Journal of Rural Studies 93 (2022) 309–317

Contents lists available at ScienceDirect

Journal of Rural Studies

journal homepage: www.elsevier.com/locate/jrurstud

Theoretical and practical research into excavation slope protection for agricultural geographical engineering in the Loess Plateau: A case study of China's Yangjuangou catchment

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ARTICLE INFO

Keywords:
Excavation slope
Gradient
Vegetation style
Agricultural geographical engineering
Loess plateau

ABSTRACT

The Loess Plateau is one of the most vulnerable areas in the world as it is extremely susceptible to soil erosion and ecological destruction. Recently, the local government carried out the "Gully Land Consolidation Project" (GLCP) in the Loess Plateau region to increase farmland area, improve rural production and living conditions. Among all the GLCP engineering constructions, slope protection engineering plays an important role in ensuring the safety of the main project, residential lives and properties, although more theoretical and technical research on comprehensive protection of engineering slopes is required. In this study, a field experiment using 12 standard runoff plots (length 4m×width 2m) was performed in Yangjuangou catchment of Yan'an City, to compare and analyze the comprehensive benefit to vegetative growth, soil erosion and engineering benefit from four vegetation styles and three levels of slope gradient (45°, 53°,63°). Results show that under different slope gradient and vegetation styles, significant differences existed in the comprehensive benefit to slopes, as well as the levels of vegetative growth, soil erosion and engineering benefit. The comprehensive benefit of the 53° slope was significantly better than that of 45° and 63° slopes. In addition, the comprehensive benefit of slopes with one or more vegetation styles was better than that of non-vegetation covered slopes. With the increase in slope gradient, the vegetative growth and slope erosion indices of vegetation average height, species richness, vegetation coverage slope, runoff production and sediment yield, showed a remarkable declining trend. Conversely, the engineering benefit index including newly-increased farmland area and excavating earthwork volume, showed an increasing trend. Recently, agricultural geographical engineering (AGE) has become an indispensable method for ecological construction and agricultural development, resulting in an increase in research in the field of geography. These findings not only have theoretical significance and enrich our understanding of the influence of gradient and vegetation styles on excavation slope protection, but also have practical significance and provide a baseline for engineering parameters and suggestions for slope protection engineering strategies.

1. Introduction

In recent decades, the developing countries have been expanding their cities to boost their economies and improve living standards, which entered a golden age of urbanization (Kan, 2016; Woods, 2007). At the same time, rural problems such as population loss, industrial decline and environmental pollution have arisen, which indicated that the rural decline gradually became a global issue (Woods, 2012; Li et al., 2015, 2016; Liu and Li, 2017a). Agricultural geographical engineering combines theoretical and engineering technology research, with the aim of solving problems in regional agricultural development and supporting rural revitalization and modernization (Liu et al., 2016; Liu, 2018). This approach can solve spatial land management issues and is regarded as an indispensable method for agricultural development and spatial restructuring (Woods, 2009; Long, 2014). The application of engineering techniques for the purpose of farmland use and development, can increase the amount of usable land, improve land utilization efficiency and actively realize a sustainable human-land relationship (Long and Liu, 2016; Liu et al., 2017). At present, due to the rapid development of social economies, science and technology, research on agricultural geographical engineering cannot solve the key issues of land use (Liu et al., 2014, 2018c). Therefore, more research and practical applications

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https://doi.org/10.1016/j.jrurstud.2019.01.020
Received 30 March 2018; Received in revised form 14 December 2018; Accepted 20 January 2019
Available online 12 February 2019

of the agricultural geographical engineering approach are needed.

The Loess Plateau is one of the main agricultural base in China, located in the middle and upper reaches of the Yellow River and covering an area of about 648,700 km^2 (Fu et al., 2011). It is an ecologically fragile zone that experiences serious levels of soil erosion (Sun et al., 2013), with the reported erosion area in the Loess Plateau reported to cover 454,000 km^2, accounting for 70% of the total area in the 1990s. Recently, the government has put increasing efforts into the agricultural geographical engineering approach, as a method to improve the ecological environment and living standards of local residents (Li et al., 2016). Since 1998, the Grain-for-Green Project (GFGP) has been implemented in the Loess Plateau, which significantly improved the rate of regional soil erosion and the ecological environment in general. However, the population-grain conflict continues to intensify as the population grows and available farmland decreases with the advancement of the GFGP, which has had negative effects on grain production (Cao et al., 2018a,b; Liu et al., 2018a). In order to consolidate the results of the GFGP and increase the usable farmland area, the Ministry of Land and Resources and the Ministry of Finance in 2014 approved the gully land consolidation project (GLCP) in Yan'an. The GLCP refers to using excavating machinery to cut gentle slopes into both sides of the gully, fill the base of the gully with cut soil and level out the new farmland. However, a large number of bare and instable slopes have formed following the implementation of GLCP, which seriously affected the stability of the principal project (Jin, 2014). The slope instability is mainly due to surface processes after surface looseness, such as rainfall, runoff and gravity erosion. Therefore, the effective implementation of slope protection technology according to the specific characteristics of different types of engineering slopes, has become a critical aspect of sustainable and steady advancement of the GLCP in Yan'an City.

Developing slope protection technologies in view of the specific slope surface, has high theoretical and practical significance for creating a stable engineered slope, and slope protection with vegetation is one of the most important aspects. This method combines local vegetation, engineering measures and non-living plant materials to protect artificial slopes by reducing slope erosion damage and enhance the comprehensive stability of the slope (Greenwood et al., 2004). In developed regions, such as Europe and North America, research on slope protection technology is more established, in terms of both theory and practical engineering applications, forming a baseline of complete theoretical systems which have been widely used in various types of slope surface and slope protection technologies (Caviezel et al., 2014; Danjon et al., 2008; Ryzhkov et al., 2014). However, in China studies on slope protection technologies have largely focused on theoretical research, such as slope protection mechanisms (Liu et al., 2011), slope erosion mechanisms (Ai et al., 2017; Fu et al., 1994; Meng et al., 2001; Fu et al., 2004), protection benefits from different slope vegetation (Chen et al., 2007) and the root-soil system model (Yan et al., 2010; Chang et al., 2012; Zhu et al., 2014). In terms of practical aspects, few studies have focused on practical applications and technology, with most studies concentrating on slope protection around highways (Luo et al., 2013; Pan et al., 2013; Cao et al., 2018a,b), river banks (Huang et al., 2010) and in coal mine districts (Zhang et al., 2014). In addition, due to the large number of engineered slopes formed during the GLCP process in the Loess Plateau, traditional slope stability methods are expensive on implementation and in maintenance, making it difficult to carry out practical operations. In the Loess Plateau, slope protection is of great significance in ensuring the safety of agricultural geographical engineering, especially for gully land consolidation projects and subsequent sustainable land use projects, since this region has bedding permeability, disintegration and collapsibility (Qi and Hu, 2006; Chen et al., 2007; Huang et al., 2010; Feng et al., 2016). Therefore, reasonable design of excavation slope gradients and vegetation protection type, are key technical problems in effective slope engineering projects.

The aims of this study were: (1) to simulate the excavation slopes formed during the process of gully land consolidation, using a slope experiment in the Yangjuangou catchment region of Yan'an City; (2) to analyze the effects of slope gradients and vegetation styles on slope vegetative growth, erosion conditions, engineering benefits and comprehensive benefits; (3) to explore the intrinsic mechanisms and principle of slope protection and provide engineering and technical parameters to serve as a reference for future slope protection in the GLCP; (4) to explore a novel research direction in agricultural geography, to help solve the current problems in regional agricultural development and land use, using agricultural geographical engineering experiments.

2. Materials and methods

2.1. Site description

The field experiment was conducted in Yangjuangou catchment of Baota District in Yan'an City (109° 31 ′17.91 "E, 36° 41′ 48.31" N), which was located in the central part of the Loess Plateau and belonged to the northern Shaanxi Loess Hilly-Gully region (Fig. 1). The Yangjuangou catchment covers an area of 2.02 km^2, with slope gradient ranging from 10° to 30° and elevation ranging from 1050 to 1298 m. The climate in this region is semi-humid and semi-arid, and the thermal resources are abundant (Fu, 1999). The geomorphic type is dominated by loess beam and loess gully, and the valleys degree is 2.74 km/km^2. The annual mean temperature is 8.8 °C in the region. The mean lowest temperature of the coldest month (January) is −6.9 °C, while the mean highest temperature of the hottest month (July) is 22.6 °C. The mean annual precipitation is about 500 mm, with 70% falling in July to September (Wang et al., 2016). In 2013, the GLCP was implemented in Yan'an city, with a construction scale of 33,300 hectares, involving 13 districts and counties. The land consolidation project in Yangjuangou catchment is one of the subprojects of GLCP, with a construction scale of 27.84 hectares. At the end of 2014, a series of engineering measures, including land leveling engineering, rural road engineering, irrigation and drainage engineering, significantly improved the local farmland production capacity, farmland quality and land use efficiency in the region, and achieved great economic, social and ecological benefits.

2.2. Experiment design

The experimental area was a typical region of the Loess Plateau in northern Shaanxi Province (China), widely covered by loess soils with a gully density of 4–6 km/km^2. Considering differences in soil type, topography, water and heat conditions, 12 standard runoff plots were selected. Four vegetation styles and three levels of slope gradient (45°, 53°, 63° or 1:1, 1:0.75, 1:0.5 in slope ratio form) were chosen in the semi-arid Loess Plateau. Slope ratio was chosen as the variable used to ensure equal differences rather than gradient, as it is convenient for project implementation from the perspective of practical engineering application. Compared with other relevant research, the experiment setting selected for the present study has the advantage that all natural conditions, such as topography, landform, soil and water conditions, are completely based on practical engineering practice, allowing the results to be directly applicable to current engineering practice.

The experiment was carried out from October 2015 to November 2018, as shown in Fig. 1. Group A, group B and group C refer to slopes with gradients of 45°, 53° and 63°, respectively. Each slope gradient group was divided into plots for the control group (CK), *Caragana microphylla* group (CM), *Amorpha fruticosa* group (AF), and a mixed *C. microphylla* and *A. fruticosa* group (CM - AF). Overall, twelve standard runoff plots were designed including A1 - A4 (45°; CK, CM, AF, CM-AF); B1 -B4 (53°; CK, CM, AF, CM-AF); and C1 - C4 (63°; CK, CM, AF, CM-AF). All plots were 4.0 m (length) x 2.0 m (width). The aspect of all experimental slopes were in a westerly direction. The soil type of the underlying surface soil was loessial soil, with its major chemical and physical properties shown in Table 1. The surface soil and vegetative cover on all

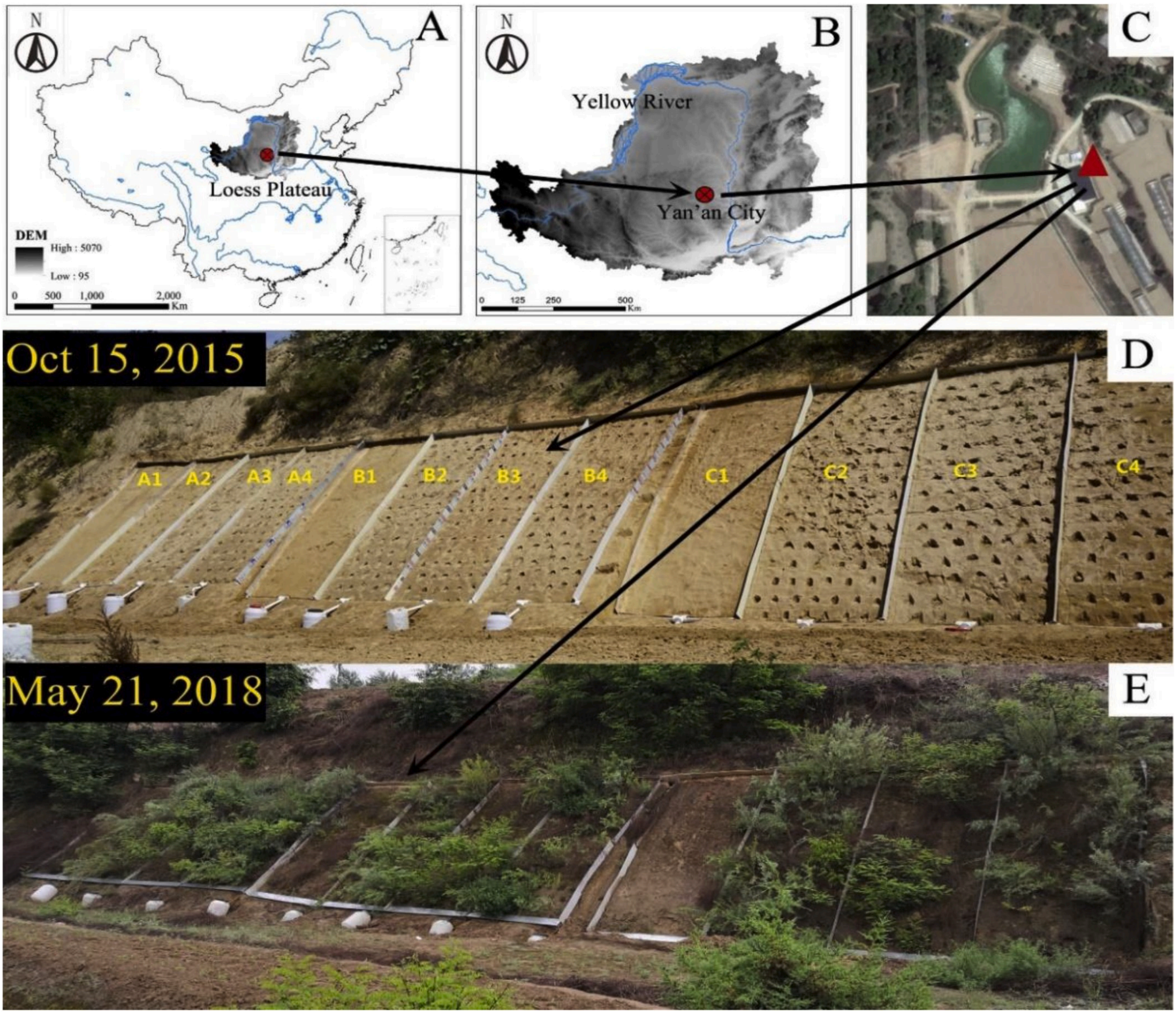

Fig. 1. Location of the experimental slope in Yangjuangou catchment of Yan'an City (A, B, C) and its general map in October of 2015 (D) and 2017 year (E).

Table 1
Selected chemical and physical properties of the slope underlying surface soil.

Soil Type	Particle Size (%)			Soil Texture	Organic Matter (%)	pH	CEC (Cmol/kg)	Available K (mg/kg)	Available P (mg/kg)	Available N (mg/kg)
	Sand	Silt	Clay							
Loessal soil	24.1	69.7	6.2	Silty loam	1.34	8.77	10.73	90.25	3.65	12.95

12 plots were severely destroyed by trampling and digging during construction and each runoff plot had an aluminum sheet installed at the lower end of the plot, which served as an outlet for collecting runoff samples. The plot border was hydrologically isolated by inserting polyvinyl chloride (PVC) boards that were inserted 15 cm underground and protruded 15 cm aboveground, to prevent runoff flowing out or into adjacent plots and splash effects.

2.3. Data collection

Vegetative growth was characterized as a parameter according to plant height, species richness and vegetative coverage, which are closely linked to the characteristics and structure of the vegetation community. In the middle of August in 2016 and 2017, five replicates of 30 * 30 cm samples were selected from each plot using the opposite angle line five spots method to obtain plant height, species richness and vegetation coverage by the ruler measurement method, visual counting method and visual estimation method (Zuo et al., 2014).

Slope erosion conditions were characterized by rill density, runoff coefficient and sediment yield. We measured rill density condition by calculating the slope rill length per unit area. Resultant surface runoff was collected and measured at 15 days intervals in 2016 and 2017 years, and runoff collections were oven dried at 105 C for 24 h to remove water. Soil material was weighed, and then sediment yield was calculated (Wu et al., 2014).

Engineering benefit was characterized by the increase in farmland area and excavated earthwork volume. As the theme of GLCP is “farmland increasing, ecological protection, people’s livelihood guarantee”, the newly-increased farmland area and excavating earthwork volume can reflect the benefit and cost of engineering project. As the excavating soil is used to fill low-lying places and make new land platforms, the excavating earthwork volume from slope excavation can effectively reduce the cost of transporting soil from the far land and save capital for the project. According to practical work of engineering project, geometric model of excavation slopes was constructed as showed in Fig. 2.

Furthermore, three function which including function of impact factor (K), newly-increased farmland area (S) and earthwork volume (V) were made according to Equations (1)–(3):

$$K = cot(\alpha) - cot(\beta) \tag{1}$$

$$S = m \times h \times (cot(\alpha) - cot(\beta)) = m \times h \times K \tag{2}$$

$$V = S \times h/2 = m \times h^2 \times (cot(\alpha) - cot(\beta))/2 = K \times m \times h^2/2 \tag{3}$$

Where K denotes impact factor, S denotes newly-increased farmland area, V denotes earthwork volume, α denotes original slope gradient, β denotes excavated slope gradient, m denotes the soil depth of excavation, h denotes original slope height.

2.4. Date processing

1) Evaluation Index System Construction. Since the objectivity and accuracy of slope stability evaluation determine the suitability of grading technology methods to a great extent, it is important to select scientific and objective evaluation methods. By comprehensive consideration of the actual situation in the area of each slope sample and data availability, and soliciting the opinions and suggestions from experts in the field, a comprehensive evaluation index system on the surface of the slope stability has been established. It mainly covers three aspects: the degree of vegetative growth (vegetation height, species richness, vegetation coverage), degree of slope surface erosion (rill density, runoff production, sediment yield), economic benefit (newly-increased farmland area, earthwork volume). Then, each index weight was determined according to the analytic hierarchy process (AHP), and the weight of each indicator of rural sustainable development was determined by interviews with experts. The comprehensive benefit evaluation index system (Table 2) was established.
2) Data Normalization Processing. The extremum standardization method was used to eliminate the difference between the index dimension, the order of magnitude and the positive and negative orientation of the index, as specified in Equations (4) and (5):

$$x_{ij}^{'} = \frac{x_{ij} - x_{jmin}}{x_{jmax} - x_{jmin}} \tag{4}$$

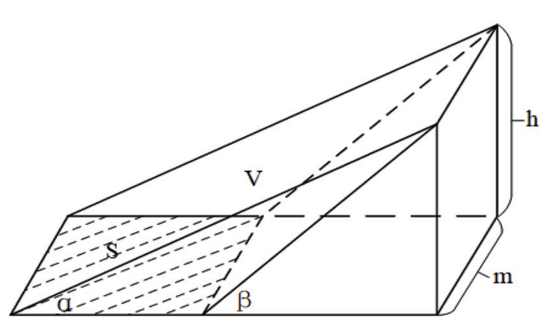

Fig. 2. Geometric model of excavation slopes.α denotes original slope gradient, β denotes excavated slope gradient, S denotes newly-increased farmland area, V denotes earthwork volume, m denotes the soil depth of excavation, h denotes original slope height.

Table 2
Evaluation index system for assessing the comprehensive slope benefit.

Target Layer	Criterion Layer	Second Grade Index	Weight	Positive/ Negative
Comprehensive Benefit Index (CBI)	Vegetative Growth Index (VGI)	Plant height	0.041	Positive
		Species richness	0.107	Positive
		Vegetation coverage	0.186	Positive
	Slope Erosion Index (SEI)	Rill density	0.250	Negative
		Runoff coefficient	0.083	Negative
		Sediment yield	0.167	Negative
	Engineering Benefit Index (EBI)	Newly-increased farmland area	0.100	Positive
		Earthwork volume	0.067	Positive

$$x_{ij}^{'} = \frac{x_{jmax} - x_{ij}}{x_{jmax} - x_{jmin}} \tag{5}$$

Where, i denotes the plot number; j denotes the index number; $x_{ij}^{'}$ refers to the normalized value of index j in plot i; x_{ij} refers to the measured value of index j in plot I; x_{jmax} and x_{jmin} refer to the maximum and minimum measured values of index j, respectively.

3) Index Calculation. The data for each slope area were collected, sorted and the comprehensive benefit of each slope was established according to Equations (6) and (7):

$$VGI_i = 10 \times \sum_{1}^{3} x_{ij}^{'} \times W_j \quad SEI_i = 10 \times \sum_{4}^{6} x_{ij}^{'} \times W_j \quad EBI_i = 10 \times \sum_{7}^{8} x_{ij}^{'} \times W_j \tag{6}$$

$$CBI_i = VGI_i + SEI_i + EBI_i = 10 \times \left(\sum_{1}^{3} x_{ij}^{'} \times W_j + \sum_{4}^{6} x_{ij}^{'} \times W_j + \sum_{7}^{8} x_{ij}^{'} \times W_j \right) \tag{7}$$

Where, i denotes the plot number; j denotes the index number; $x_{ij}^{'}$ refer to the normalized value of index j in plot I; VGI_i, SEI_i, EBI_i and CBI_i refer to the vegetative growth index, slope erosion index, engineering benefit index and comprehensive benefit of plot I, respectively; and W_j refer to the weight of index j.

3. Result analysis

3.1. Plant height, species richness and vegetation coverage

As shown in Fig. 3, in different years significant differences were observed under different gradients and vegetation types in terms of slope vegetative growth. All vegetative growth indexes in 2017 were notably higher than in 2016, while the relative difference in each year showed a similar trend, so all the following analyses are based on the data from 2017. For each growth index, the plant height, species richness and vegetation coverage in 2017 were 50.2 cm, 7.03 and 42.14%, respectively, which were significantly higher than in 2016, which were 33.9 cm, 5.92 and 27.17%, respectively ($P < 0.05$). There were significant differences in plant height, species richness and vegetation coverage in slope areas with different gradients. With increased slope gradient, there was a distinct decreasing trend in all three indices. The mean vegetation height on the 45° slope was 70.0 cm, which was the highest among the different slope gradients tested, followed by the 53° slope with a vegetation height of 42.1 cm. The 63° slope had the lowest

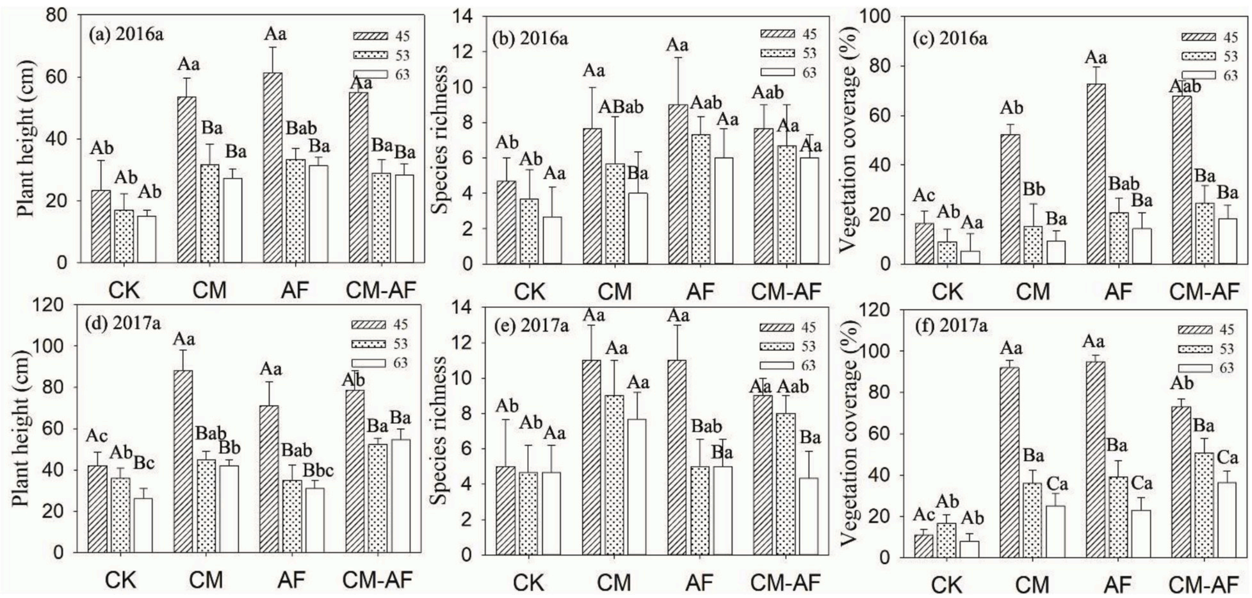

Fig. 3. Vegetative growth Index including plant height (a, d), species richness (b, e) and vegetation coverage (c, f) under different gradients and vegetation types in the Yangjuangou catchment area, in Shaanxi Province in 2016 and 2017.Note: Different capital letters indicate significant differences at P < 0.05 level among different gradient. Different lowercase letters indicate significant differences at P < 0.05 level between vegetation types.

vegetation height, at only 38.4 cm. In terms of the species richness index, no significant differences were observed between the 53° slope and the 45° and 63° slopes, but the species richness of the 45° slope was significantly higher than that of the 63° slope. For the vegetation coverage index, the value established at the 45° slope was 67.8, which was significantly higher than the other two sample regions, which were 35.6 for the 53° slope and 23.1% for the 63° slope, between which no significant differences existed.

Significant differences were observed in plant height and vegetation coverage in slope areas according to different vegetation types, while no significant differences were observed for species richness (P < 0.05). The average plant height across all experimental sites was 50.17 cm, with the smallest being 34.7 cm at the CK site and the largest being 61.9 cm in the CM-AF site. Compared to the control site, the average plant height increased significantly in AF, CM and CM-AF, increasing by 31.8%, 68.6% and 78.5%. In terms of the vegetation coverage index, the vegetation coverage of sites was also significantly improved as compared to the CK group, increasing by 328.9% at the CM site, 340.2% at the AF site and 348.6% at the CM-AF site. The vegetation species richness, however, showed no significant differences according to different vegetation types.

3.2. Rill density, runoff coefficient and sediment yield

Fig. 4 shows the rill density of each slope under different gradient and vegetation types, in 2016 and 2017. The rill density of each plot in 2017 was much higher than the equivalent plot in 2016 (P < 0.05), showing that the rill density exhibited an increasing trend over time. In terms of the gradient, the 53° plot had the minimum rill density, which was significantly lower than that of 45° and 63° slopes, with average values of 73.0, 121.5, 73 and 121.0, respectively. As the gradient increased, the rill density initially decreased and then increased, which indicates that a critical gradient exists between 45° and 63° slopes, in which the rill density could reach its minimum value. In terms of vegetation types, no significant differences were observed in the rill density among plots with vegetation (CM, AF and CM-AF). However, compared to the CK group, the average rill density decreased obviously in CM, AF and CM-AF, decreasing by 9.4%, 11.2% and 8.2%, respectively.

Fig. 5 shows the runoff coefficients and sediment yields for all test plots under different gradients and vegetation types. The mean value of runoff coefficient and sediment yield for all plots in 2017 were 34.8% and 15.3g/m^{-2}, respectively, which were significantly lower than those in 2016 of 40.9% and 17.1 g/m^{-2}, respectively, indicating that the degree of soil and water erosion in each plot gradually improved over time.

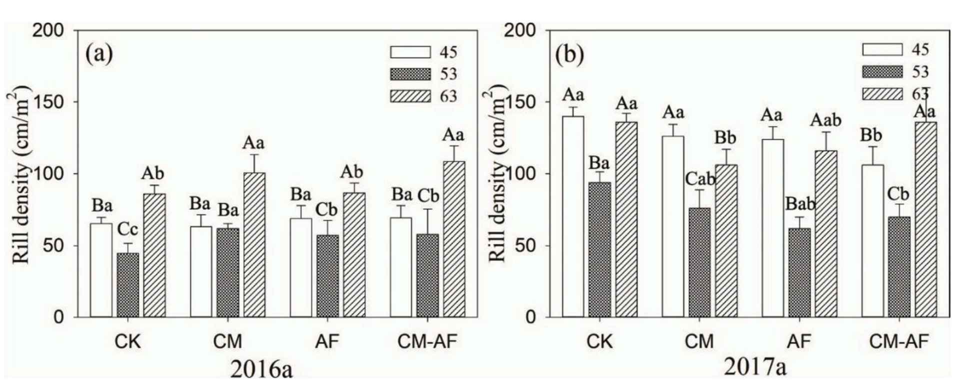

Fig. 4. Analysis of rill density (a, b) under different gradient and vegetation types in 2016 and 2017. Different capital letters indicate significant differences at P < 0.05 level among different gradient. Different lowercase letters indicate significant differences at P < 0.05 level between vegetation types.

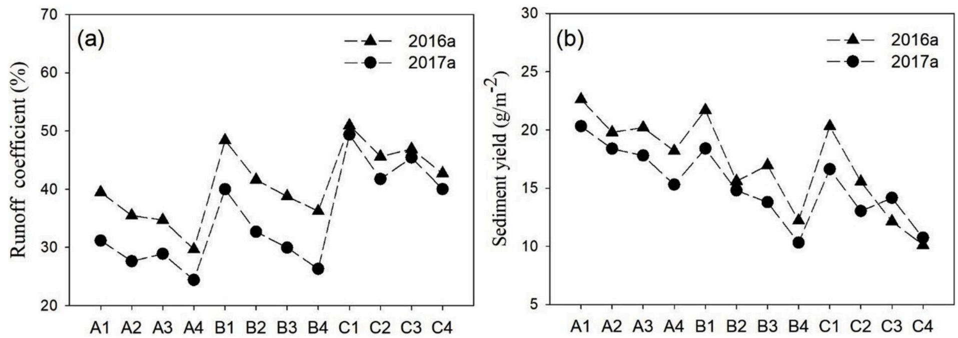

Fig. 5. Analysis of slope runoff coefficients (a) and sediment yields (b) in all plots in 2016 and 2017. A1 - A4, B1 -B4 and C1 - C4 denote CK, CM, AF and CM-AF sites, with slope gradients of 45°, 53° and 63° respectively.

Meanwhile, the relative trend in runoff coefficient and sediment yield in all plots in 2016 and 2017, were relatively consistent. Therefore, the data in 2017 was taken to illustrate the degree of soil erosion across all plots. The runoff coefficients and sediment yields were closely related to gradient and vegetation types. With an increase in gradient, the runoff coefficient of plots increased gradually, with mean values for 45°, 53° and 63° plots of 28.0%, 32.2% and 44.1%, respectively, indicating that the rainfall infiltration capacity of plots with 45° angles were relatively stronger than other plots. However, the relationship between sediment yield and gradient in each plot followed the opposite trend to that of the runoff coefficients, with mean sediment yields of 18.0 g/m^{-2}, 14.3 g/m^{-2} and 13.6 g/m^{-2} in 45°, 53° and 63° slopes. In terms of vegetation type, the runoff coefficients were ranked in the descending order: CK > CM > AF > CM-AF, with the sediment yield of each plot following the same trend.

3.3. Newly-increased farmland area and earthwork volume

According to the typical design report of GLCP in Yan'an, the GLCP should be carried out on the farmland with gentle slope below 15°. Meanwhile, the project should try to choose the land with good soil quality, flat terrain and great accessibility, which is also close to the village. The slope gradient of the excavated slope is closely related to the volume of excavating engineering and the area of new farmland. For the same slope, the larger the excavated slope is, the larger the area of new farmland and excavation volume is, resulting in reduced project costs as the excavated soil can be used to fill low-lying places and turn them into new farmland. The area of newly-increased farmland and the excavated soil volumes were calculated for different original gradients (α, ranging from 5° to 45° at 5° intervals) and excavated gradient (β, 45°, 53° and 63°), respectively(Table 3). With an increase in the original gradient, the area of new farmland formed and the volume of excavated soil decreased continuously, while an opposing trend was observed with increased excavation gradient. Therefore, with the increase in the excavated slope, the area of newly-increased farmland and the volume of excavated soil would increase, which could significantly reduce the cost of construction in gully projects and increase the area of newly-increased farmland.

3.4. Comprehensive benefit analysis

As shown in Fig. 6, the VGI, SEI, EBI and CBI indices of all plots in 2016 and 2017, were evaluated according to the comprehensive benefit evaluation index system. The overall trend for all indicators was relatively consistent across both years and therefore, data analysis was conducted on the basis of the data in 2017. The average CBI of all slopes was 4.6, among which B4, B3 and B2 sites were the highest, with CBI values of 7.2, 6.7 and 5.8 respectively. In contrast, A1, B1 and C1 had the lowest CBI values of 1.1, 3.5 and 2.7, respectively. The CBI of the 53° slope was significantly higher than those of the 45° and 63° slopes, with average values of 5.8, 3.9 and 4.0, respectively. In terms of vegetation types, the CBI of the CM-AF group was the highest at 5.6, followed by the CM and AF groups, with CBIs of 5.2 and 5.1 respectively. The control group had the lowest value, with a CBI of only 2.4.

Different trends were observed in the sub-system evaluation of each plot, under different gradients and vegetation types. With increased gradients, the VGI of the slope gradually decreased and the SEI showed an initially increasing and then decreasing trend, while the engineering benefit index gradually increased. In terms of vegetation types, the VGI and SEI of plots with vegetation cover were significantly higher than those of the CK group, while the EBI showed no correlation with vegetation type.

4. Discussion

4.1. Effect of gradient on VGI and SEI of excavation slopes

The experimental slopes assessed in this study were designed to simulate the excavation slopes in gully land consolidation projects, which were different from most previous studies that designed for natural slopes and therefore may have different effects on vegetative growth and the erosion of slope surfaces. This study demonstrates that the slope gradient had significant effects on VGI and SEI, which is similar to the findings of previous studies (Koulouri and Giourga, 2007; Mohammad and Adam, 2010; Carroll et al., 2000). With an increase in gradient, all vegetative growth index values gradually reduced, which is consistent with the findings of other previous studies (Wang et al., 2017a,b). This phenomenon may be the result of the high soil texture, low soil moisture and the stability of soil and water storage capacities when the slope gradient is large, leading to relatively poor vegetative growth conditions (Mclsaac et al., 1987). When the gradient is relatively small, the soil is more porous and the rainfall flow rate is reduced, resulting in a higher soil moisture content which is more suitable for the

Table 3
K values under different original (α) and excavated (β) slope gradient.

Original gradient (α)	Excavated gradient (β)								
	5°	10°	15°	20°	25°	30°	35°	40°	45°
45°	10.43	4.67	2.73	1.75	1.05	0.73	0.43	0.19	0
53°	10.68	4.92	2.98	1.99	1.30	0.98	0.67	0.44	0.25
63°	10.92	5.16	3.22	2.24	1.54	1.22	0.92	0.68	0.49

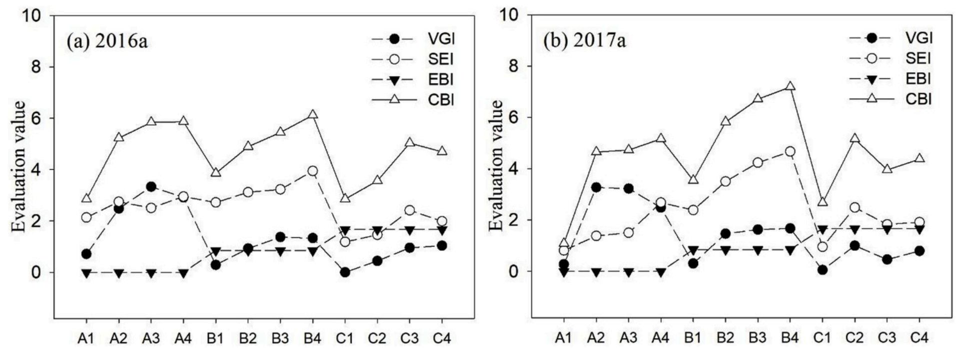

Fig. 6. Analysis of vegetative growth index (VGI), slope erosion index (SCI), engineering benefit index (EBI) and comprehensive benefit index (CBI) under different gradients and vegetation types in 2016 (a) and 2017 (b).

growth of vegetation root systems (Wang et al., 2017a,b).

Slope gradients can also strongly impact slope erosion conditions, as with increased slope gradients the catchment area decreases and the water runoff rate increases, which leads to a reduction in erosion. When the slope increases to a critical value, at which point the gravitational force and rainfall impact force of soil particles on the parallel to the slope are greater than the shear resistance of the soil, the soil is more likely to be eroded (He et al., 2016; Qin et al., 2017). With increased slope gradient, the slope rill density initially presented a downward trend as surface soils of smaller slope plots is porous and therefore, vulnerable to rainfall erosion (Xu et al., 2011). When a critical gradient value was reached, the rill density showed an increasing trend. With increased steepness of slopes, the soil particles are more vulnerable to erosion due to gravity and rainfall impact. Runoff production and sediment yield are important indicators when evaluating the comprehensive stability of slope surfaces, which can directly reflect the erosion status of a slope (Zhang et al., 2015). In general, when the slope steepness is larger than 33, the decrease in the area of the plan relative to the actual surface area means that the rainfall intensity effectively decreases, reducing the erosion. However, the erosion due to gravity will increase at the same time. Therefore, the erosion conditions of slopes with 43° and 63° gradients were distinctly more serious than that of slope 53°. With increased slope gradient, the length and the catchment area of the slope decreased and the runoff rate decreased accordingly. In addition, the slope length decreased resulting in a reduction in runoff and sediment yield (Liu et al., 2000). With the same slope length, as the slope increases the water flow speeds up, resulting in the infiltration time and the infiltration volume being reduced, resulting in more runoff (Kateb et al., 2013; Xu et al., 2017).

4.2. Effect of vegetation styles on VGI and SEI of excavation slopes

All of the assessed index values of CM, AF and CM-AF plots were significantly higher than those of non-vegetation covered plots, with the exception of the engineering benefit, which showed no relationship with vegetation style. Meanwhile, the vegetative growth conditions had a close relationship with the degree of soil erosion, with improved vegetative growth being associated with reduced runoff and sediment yields (Fu et al., 1994, 2004; Zheng et al., 2004). This is because vegetation on slope surfaces can intercept precipitation, improve the infiltration rate of water flow, relieve raindrop splash erosion, reduce the runoff rate and increase evapotranspiration, which can consequently reduce runoff and improve soil erosion conditions (Kateb et al., 2013; Wang et al., 2011).

In nature, vegetation is one of the factors to maintain the balance between the destructive power of landscape instability and the constructive or regenerative power of landscape stability (Braud et al., 2001). The mechanism of slope protection with vegetation mainly includes three aspects, which are (1) anchoring soil slope bodies by the root system of woody plants; (2) reinforcement action by the root system of herbaceous plants; and (3) conservation of soil and water by surface plants (Braud et al., 2001; Qi and Hu, 2006). In the long term, vegetation cover has significant hydrological effects, such as intercepting rainfall, slowing down the flow velocity of runoff and filtering, which significantly supports slope protection. Over time, carefully selected and implemented bioengineering techniques are bound to be more sustainable because vegetation is self-regenerating, able to respond dynamically and naturally to changing site conditions without compromising or losing the engineering characteristics of the selected vegetation (Rickson and Morgan, 1995). Rooting conditions on excavation slopes are limited, unless the soil is sufficiently fragile itself. Caragana microphylla and Amorpha fruticose are locally successful slope shrubs, which are drought resistant (Pan et al., 2013). The root system of C. microphylla are more developed with improved drought resistance, while the crown layer of A. fruticose is relatively more developed and can significantly reduce rainfall erosion. In combination with local natural conditions, small shrubs such as A fruticose and C. microphylla are suggested to be planted on these slopes, with a grass planting density of around 15 kg per hectare.

4.3. Implications for GLCP and agricultural land engineering

In this study, the effects of slope gradients and vegetation types were assessed on comprehensive slope benefits including vegetative growth, slope erosion and engineering benefit. These results show that significant differences exist in vegetative growth, slope erosion and engineering benefit among different gradients and vegetation types, resulting in different comprehensive benefits. Among all plots, B4 (53°, CM-AF), B3 (53°, AF) and B2 (53°, CM) had the highest CBI values, while A1(45°, CK), B1(53°, CK) and C1(63°, CK) had the lowest CBI values. The three slope gradients can be ranked by descending CBI value as: 53°>45°>63°, while the four vegetation types can be ranked by descending CBI value as: CM-AF > CM > AF > CK. As part of slope protection, ecological and engineering benefits, as well as project costs should be considered. Therefore, in addition to improving the vegetative growth index and erosion index in this study, the newly cultivated land area and excavated soil volumes were also included as part of the evaluation model of comprehensive benefit degree, allowing this research to directly provide technical parameters for slope engineering, which is of high value in practical applications. The effective scientific and engineering parameters for slope protection are as follows: the slope gradient should be controlled at around 53°; it is necessary to choose plant species with characteristics of fast growth rates, strong drought tolerance and developed roots. It has also been proposed that technologies should be adopted for soil spraying or organic matter spraying, to create a living environment suitable for vegetative growth.

Generally, agricultural geographical engineering is considered to be a key factor of modern agricultural development, ecological construction and sustainable land use (Liu et al., 2016). This approach plays an important role in improving the quality of cultivated land, restoring land degradation, utilizing wasteland and restoring land ecology, as emphasized by the national strategy of science and technology innovation in land and resource use (Liu et al., 2018a). After implementing the "Grain-for-Green" project in the Loess Plateau, the coordinated management of slope and gully land, ecological protection and improved agricultural production was achieved via the "Gully Land Consolidation Project". By the end of 2017, the GLCP had cumulatively implemented 18 980 hm^2 of work, costing 22.59 billion yuan (Liu and Li., 2014). The integration and innovation of agricultural geographical engineering and soil and water conservation measures in China, support the achievements of the Grain-for-Green Project, forming the foundation of agricultural development, promoting sustainable land use and advancing ecological regeneration (Liu et al., 2013, 2015, 2018b). In addition, the use of engineering technology, as well as integrating and optimizing regional factors, assist ecological conservation and rural sustainable development in ecological fragile regions, providing an effective approach and practical baseline to use science, technology and management to solve regional problems (Liu and Li., 2017b).

5. Conclusion

This paper analyzes the comprehensive benefits to vegetative growth, soil erosion and engineering benefit from four vegetation styles and three levels of slope gradient (45°, 53°,63°) in the Loess Plateau, by performing a plot test using observed vegetative growth and slope erosion data, in combination with relevant models. The aim of this study was to develop protection technology used in excavation slopes in the GLCP, which is important as a reference to guide local slope protection projects. Results show that the CBI of 53° slopes were significantly higher than those of 45° and 63° slopes. With increased slope gradient, the VGI and SEI parameters, such as vegetation average height, species richness, vegetation coverage of slope, runoff production and sediment yield index, showed a declining trend. Conversely, the engineering benefit index including newly-increased farmland area and excavated earthwork volume, showed an increasing trend with increased slope gradient. In addition, slopes with a single vegetation type or a mixture of various vegetation types were more stable than those with no vegetation coverage, while there were no significant differences between the CM, AF, and CM-AF groups.

Slope protection is of high significance when ensuring the safety of agricultural geographical engineering, especially for gully land consolidation projects and subsequent sustainable land use in the Loess Plateau. These results provide useful reference engineering and technical parameters for slope protection in future gully land consolidation projects. In order to protect excavation slopes, it is suggested to choose plant species with fast growth, drought tolerance and developed roots, while the slope gradient should be controlled at around 53°. In addition, agricultural geographical engineering is an indispensable method for agricultural development, which can solve spatial land management issues using engineering methods, although it requires more theoretical and application research. Field experiments and demonstration, as an important technology, can further promote and deepen relevant theoretical and practical research of agricultural geographical engineering. The findings of these slope trials as part of an agricultural geographical engineering assessment, have only been performed in recent years in China and the slope parameters have been limited to slope gradient and vegetation style. As trials continue in the future, the slope vegetative growth, slope erosion and engineering benefit among different gradient and vegetation types may change and therefore, long-term positioning monitoring is required on slope plots to explore the influential mechanism of a range of vegetation under different treatments conditions.

Acknowledgements

This study was supported by National Key Research and Development Program of China, No. 2017YFC0504701; National Natural Science Foundation of China, No.41471143; National Natural Science Foundation of China, No.41571166.

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