Catena 202 (2021) 105248

Contents lists available at ScienceDirect

Catena

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Chinese zokor (*Myospalax fontanierii*) excavating activities lessen runoff but facilitate soil erosion – A simulation experiment

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ARTICLE INFO

Keywords:
Alfalfa
Subterranean rodent
Simulated rainfall
Sediments
Runoff
Soil water

ABSTRACT

The Chinese zokor (*Myospalax fontanierii*) affects the physical and chemical properties of soil and the evolution of vegetation. However, few studies have evaluated the effects of zokors on soil erosion. In this study, alfalfa (*Medicago sativa L.*) was planted in tanks to quantify the effects of zokor excavation activities on runoff and soil erosion rate. Three slope gradients of 5°, 10°, and 15° were set, two soil tanks (with and without a zokor) were used for each gradient, and six soil tanks were prepared in total. Laboratory simulated rainfall was applied using a side-spray simulation system, and the rainfall intensity was set to 80 mm h^{-1} with the rainfall duration of 60 min after runoff generation. Results showed that the soil bulk density of fresh zokor mounds was 0.82 ± 0.02 g cm^{-3}, which was 39% lower than that of the soil matrix (1.35 g cm^{-3}). The vegetation coverage decreased to 32%, 45%, and 43% respectively, after 3 days of disturbance by zokor, compared with 87%, 90%, and 92% in the tanks without zokor. The presence of zokor reduced the runoff rate by 88% on the lowest gradient to 21% on the steepest gradient, and increased the water infiltration and soil water storage within 90 cm depth. The soil mounds and herbivorous tunnel changed the microtopography and consequently the runoff pathway, increased the sediment yield, and intensified soil erosion, especially at a steep slope gradient. Although the activity of zokors does not directly increase soil erosion, and the tunnel system can facilitate water infiltration and lessen runoff, the mounds they create provide loose and erodible materials. The destruction of vegetation by zokors would facilitate soil erosion and reduce the benefit of vegetation restoration. This study provides insights into the effects of subterranean rodents on soil erosion in the Loess Plateau.

1. Introduction

Soil erosion is one of the most serious environmental problems in the world and is considered as the greatest threat to land degradation and crop yield (Lal, 2003; Luetzenburg et al., 2020). Soil erosion leads to soil loss, decrease in organic matter and nutrients, decrease in soil fertility, water pollution, and reservoir siltation (Poesen, 2018). The Loess Plateau is of concern because of serious soil erosion (Zhou et al., 2013; Chen et al., 2015; Dou et al., 2020). In 2013, the vegetation coverage of the Loess Plateau had reached 60% (Chen et al., 2015). The increase in vegetation coverage can effectively reduce soil erosion (Hou et al., 2014). However, improper vegetation restoration and excessive water consumption of vegetation can increase the distribution of the dry soil layer (Wang et al., 2010; Zhou et al., 2013; Chen et al., 2015; Jia et al., 2019), which reduces vegetation and degrades the soil ecosystem.

Subterranean rodents are special mammals that have adapted to living in underground tunnel environments. They mainly live in grasslands (Zhang et al., 2003; Yu et al., 2017) and arid and semi-arid shrubs (Eldridge and Whitford, 2014) and are distributed all over the world (Davidson and Lightfoot, 2008; Fleming et al., 2013; Hagenah and

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https://doi.org/10.1016/j.catena.2021.105248
Received 11 April 2020; Received in revised form 1 February 2021; Accepted 7 February 2021

Bennett, 2013; Lindtner et al., 2019). Their excavation activities, underground foraging, and excretion have direct and indirect, short-term and long-term impacts on ecosystems (Zhang et al., 2003). These rodents can affect soil texture (Galiano et al., 2014), water holding capacity (Wilson and Smith, 2015), nutrient dynamics (Miranda et al., 2019), and plant communities (Kang et al., 2007; Wang et al., 2008) and can establish habitats for other species (Davidson et al., 2008). They play an important role in ecosystem dynamics and are known as "ecosystem engineers" (Reichman and Seabloom, 2002).

Zokors (*Myospalacinae*) live underground all year long and is a subterranean rodent endemic to East Asia (Fan and Shi, 1982; Zou et al., 2020). Owing to the insufficient information on the morphological features and the convergent and parallel evolution induced by the special lifestyles of zokors, the controversies in zokor morphological classification appeared at the family and genus levels (Zou et al., 2020). Chinese zokor (*Myospalax fontanierii*) (Fig. 2B) mainly lives in the Loess Plateau and can be found in farmlands, grasslands, and woodlands (Sui et al., 2014). These rodents have a body length of 171–217 mm and a body weight of 285–443 g (Han et al., 2005). For the sake of brevity, the zokor mentioned below refers to the Chinese zokor (*M. fontanierii*). In general, zokors have a lifespan of 3–4 years and reproduce once a year from April to May. The length of gestation is approximately 30 days with an average of one to six (mostly two to three) pups each pregnancy per breeding female. A newborn zokor can reproduce in the second year. Except for the breeding period, zokors live alone, and each zokor builds its own burrow. Different from herbivores on the ground, zokors dig tunnels to find food; this activity consumes a considerable amount of energy (Vleck, 1979; Reichman and Seabloom, 2002). Thus, these animals have a large appetite and year-round activity (Zhang et al., 2003). Zokors are adaptable and mainly feed on the underground parts of plants, thus harming crops and trees (Xie et al., 2014). They dig tunnels in the ground and then pile up the excavated soil on the surface, thereby forming exposed mounds that cover a part of above-ground plants and change the microtopography. Zokors lack natural enemies (snakes or weasels) and are a main rat pest in the Loess Plateau. To ensure the safety of crops and benefit vegetation restoration, farmers often use chemical poisons and mousetraps to kill these animals. According to the 140 monitoring points of rodent damage in agricultural areas in China, the density of Chinese zokor in the farmlands of Gansu and Shaanxi provinces in 2019 were 8 and 10 per hectare, respectively (Guo et al., 2019). Fan and Gu (1981) investigated the Liupan Mountain forest and found that the density of Chinese zokor reached 25–50 per hectare. The density is high in woodlands and grasslands without disturbance by humans. More than 320–400 million zokors can be found on the Loess Plateaus with an area of almost 40 million hectare (Sui et al., 2014). Thus, these animals inflict considerable damage to agriculture and agroforestry.

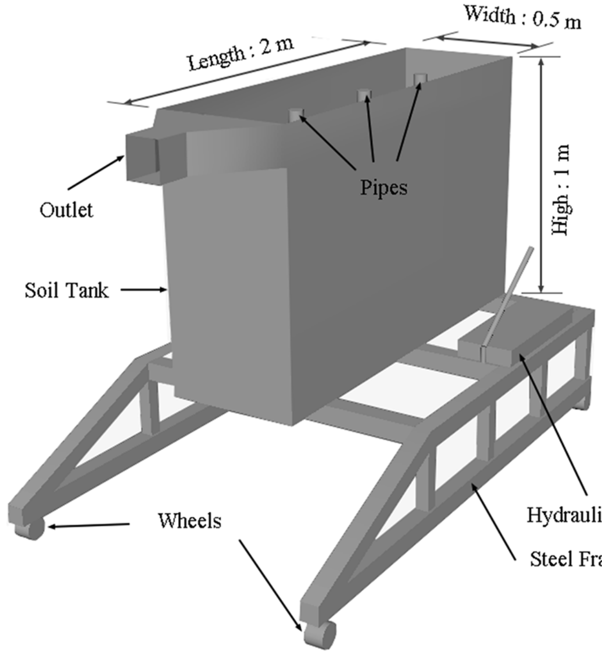

Fig. 1. Tank (2.0 m long, 0.5 m wide, and 1.0 m deep) used to evaluate the effects of zokor excavation activities on soil moisture and soil erosion.

Bioturbation alters soil processes and increases water and nutrient cycling. However, the role of animals as geomorphic agents of soil erosion has not been paid enough attention (Gabet et al., 2003; Butler, 2007). The long-term effects of continual animal disturbance on soil structure and pedogenesis are unknown (Hancock et al., 2015, 2017). Orgiazzi and Panagos (2018) proposed that soil ecological factors should be considered in the soil erosion model (the revised universal soil loss equation). Seitz et al. (2015) demonstrated that the presence of soil meso- and macrofauna increases initial soil erosion in a subtropical forest of China. Soil meso- and macro fauna can fracture and forage leaf litter, slacken and process soil surface and thus reducing the protection of litter to soil surface and promoting soil erodibility. And they believed that the effects of these fauna groups on sediment discharge should be considered in soil erosion experiments. Compared with these meso- and macrofauna soil-burrowing animals, such as springtails and mites (Seitz et al., 2015), earthworms (Orgiazzi and Panagos, 2018) or ants (Cerdà and Jurgensen, 2011; Li et al., 2019b), subterranean rodents have a larger body and are more destructive to soil surface structures. These rodents can destroy the soil surface integrity by digging tunnels and bringing deep soil to the surface, thereby changing the soil's physical structure and chemical nutrient composition (Reichman and Seabloom, 2002). Miranda et al. (2019) reported that desert rodents (*Ctenomys*) promoted the establishment of nutrient patches, which promoted plant growth. However, Harris (2010) believe that subterranean rodents are the main reasons for pasture degradation. Wilson and Smith (2015) found that the disturbed bare soil of plateau pika increases water infiltration and has a potential impact on the hydrological function of the Qinghai–Tibet Plateau. Gophers decrease runoff and erosion compared with bare slope but promote the infiltration of surface pollutants into deep soil (Hakonson, 1999). However, Li et al. (2013) reported that the excavation activities of burrowing rodents are the major causes of soil erosion. Animal burrowing activity is one of the major slope processes in humid deciduous forested areas and is responsible for most of the downslope material transport (Imeson, 1976). Although some studies have focused on subterranean rodents, their impact on soil erosion remains poorly understood. The increase in vegetation in the Loess Plateau (Chen et al., 2015) provides enough food for subterranean rodents, such as Chinese zokor, which may cause the rapid growth of rodent populations. Chinese zokor disturbs the soil, damages vegetation, and reduces the benefits of afforestation, which may further increase the risk of erosion.

In the present study, laboratory-simulated rainfall experiments under different slope gradients of 5°, 10°, and 15° were conducted. This work aimed to (1) analyze the effects of zokor excavation on soil and plants and (2) explore the mechanism of zokor excavation on soil moisture profile, runoff rate, and soil erosion rate.

2. Methods and materials

2.1. Rainfall simulator

The simulated rainfall was conducted in the rainfall-simulation laboratory of the State Key Laboratory of Soil Erosion and Dryland Farming in Yangling City, Shaanxi Province, China. A side-spray rainfall simulation system was used to apply rainfall. The system can be set to any selected rainfall intensity ranging from 30 mm h^{-1} to 150 mm h^{-1} by adjusting the nozzle size and water pressure (Shen et al., 2016). The rainfall system can effectively simulate the size and distribution of

Fig. 2. Hole-catching mousetrap (A). A close-up of a zokor (B). A zokor digging burrows (C). Soil excavated by a zokor (D). Eaten alfalfa and broken soil surface (E). Zokor mound after rainfall (F). Collapsed tunnel and exposed entrance of the tunnel (G). Zokor's traffic tunnel in the natural habitat (H).

natural raindrops (Li et al., 2019b) and we calibrated the simulator with standard rain gauges before the rainfall simulation to guarantee stable rainfall patterns. Additionally, the raindrop falling height is up to 18 m; thus, all raindrops can reach the final speed of natural raindrops when they reach the soil surface (Zhou et al., 2002). In this study, uniform rainfall intensity (80 mm h^{-1}, a high magnitude-low frequency intensity commonly occurring in the research area in summer) was adopted, and the rainfall duration after runoff generation was 60 min.

2.2. *Soil and soil tank*

The soil was collected from bare land at a depth of 0–50 cm in Xibo village (34°20′ N, 108°24′ E; altitude of 521 m) of Yangling City, Shaanxi Province, China. This area is characterized as a warm temperate semi-humid zone and has four distinct seasons with a mean annual precipitation of 637 mm and a mean annual temperature of 12.9 °C. Most of the precipitation is concentrated from July to October in the form of rainstorms, and the annual average evaporation is 884 mm. The collected soil was air dried and passed through a 2 mm sieve to remove weeds and small stones. The soil has a clay–loam texture (sand, 39.6%; silt, 36.1%; and clay, 24.3%), with pH 7.8, electrical conductivity of 227 μs cm^{-1}, and organic matter content of 3.6 g kg^{-1}, and is classified as cumulic anthrosol (FAO/UNESCO) (Li et al., 2019b).

The soil tank (2 m long, 0.5 m wide, and 1.0 m deep) was placed on a steel frame with wheels for easy movement, and a hydraulic lift was used to adjust the angle of the tank (Fig. 1). A total of 351 holes (0.5 cm in diameter) were drilled at the bottom of the tank to facilitate drainage. To obtain the target soil bulk density (1.35 g cm^{-3}) similar to that in the field, the soil water content was measured before packing the tank, and the required soil weight was calculated. First, two layers of medical gauze were laid at the bottom of the tank to prevent soil leakage and to ensure air and water permeability at the same time. Then, a 5 cm thick layer of sand was packed at the bottom of the tank as a filter layer for drainage to prevent the soil from blocking the holes. During the packing process, the soil layer was packed in 10 cm increments, and the filling height of soil was 90 cm. A total of 0.9 m^3 soil was filled into the tank. Three pipes (100 cm long and 2.8 cm in diameter) were installed in the soil of each tank (Fig. 1) to measure soil water contents at depths of 10, 20, 30, 50, and 90 cm with a PR2–6 probe (Cambridge, UK, Delta-T Device, Ltd.). After filling, alfalfa (*Medicago sativa L.*) was planted with row spacing of approximately 15 cm (12 rows in total), and the row of alfalfa was perpendicular to the length direction of the tank. After the emergence of alfalfa, the seedlings were thinned out, and the final density of alfalfa was controlled similar to that in the field (final coverage about 90%). The tanks were placed outdoor and exposed to rainfall and solar radiation. When natural rainfall was insufficient, an appropriate amount of water was replenished by a flower sprinkler to ensure alfalfa growth. Alfalfa was managed and harvested according to the farmers' habits in the field, and the laboratory-simulated rainfall experiment was conducted the next year. In this experiment, three slope gradients of 5°, 10°, and 15° were set, two soil tanks (with and without a zokor) were used for each gradient, and six soil tanks were prepared in total.

2.3. *Source of zokors*

The Chinese zokors used in this study were captured by hole-catching mousetrap (Fig. 2Aa) in a farmland of Gansu Province, where zokors piled up a great deal of mounds on the ground. The hole-catching mousetrap can be connected to the zokor tunnel to simulate the tunnel's environment. We selected new soil mounds and then excavated around them to find traffic tunnels at a depth of 18–25 cm. The tunnels where zokors often move were clean and dust-free. There were many small pits on the inner wall of the tunnel, which can be used to judge the direction of the zokor nest. Before being connected to the tunnel in the direction near the zokor nest, a soil wall was built on the inner surface of the hole-catching mousetrap by spraying a water film and then evenly spreading a layer of fine soil, which was able to eliminate the smell of mousetrap and simulate the tunnel environment. Then, the mousetrap was connected tightly to the zokor tunnel and fixed. Afterward, the switch was set (Fig. 2Ab). When the zokors come out of the nest to find food and enter the mousetrap, the switch will be triggered, locking the zokors inside. If the zokors find that the tunnel is damaged, they will push soil to plug the gap where air is leaking and will be locked inside when they enter the mousetrap.

The captured zokors were transferred into iron cages (25 cm long, 15 cm wide, 15 cm deep, and aperture: 0.5 cm) and brought back to the laboratory. Three zokors with virtually identical body size (approximately 20 cm long) were selected and placed individually in each soil tank. The iron cage was placed on the soil surface, and the iron cage door was opened to ensure that the zokor can come out of the cage. After the zokor entered the soil tank, it began to dig holes to build a shelter (Fig. 2C). Wire cages without a bottom (2 m long, 0.5 m wide, 0.4 m deep, and aperture: 0.5 cm) were used to cover the soil tank to prevent the zokors from escaping, and provide unlimited growth space for the alfalfa. Alfalfa in the tank served as food for the zokors, and no other food was added. Simulated rainfall was conducted 3 days after the zokors entered the soil tank to better show the effects of zokor mounds and tunnels on water infiltration and soil erosion.

2.4. Experimental measurements

A PR2-6 probe was used to measure the soil water content profiles in the tanks before the zokors were placed inside, and the soil water content profiles were measured again 24 h after the simulated rainfall. The time to runoff generation was recorded, and runoff samples were collected in 5 L buckets thereafter. Then, the runoff volume was measured. The samples were measured at 2 min intervals throughout the entire rainfall duration. For every soil tank, 30 samples were collected in total. The samples were allowed to stand for 24 h to settle the soil particles. Then, the supernatant was removed, and the wet soil was dried at 105 °C and weighed to calculate the soil erosion rate. A week later, soil samples from the fresh mounds in the tanks were collected to measure the soil bulk density.

2.5. Data analysis

The following equations were used to calculate the soil erosion rate, runoff rate and sediment concentration:

$$E_r = \frac{W}{A \times T} \tag{1}$$

$$R = \frac{D}{T} = \frac{V}{A \times T} \times 10^3 \tag{2}$$

$$SC = \frac{W}{V} \times 10^{-3} = \frac{E_r}{R} \tag{3}$$

In the three equations, *Er* is the soil erosion rate (g m^{-2} min^{-1}); *W* is the dried soil weight of the sediment (g); *A* is the horizontal projection of the soil slope (m^2, equal to slope area × cos (5°, 10°, or 15°)); *T* is the sampling duration (min, 2 min in this study); *R* is the runoff rate (mm min^{-1}); *D* is the runoff depth (mm); *V* is the runoff volume (m^3) for each sample; and *SC* is the sediment concentration (kg m^{-3}).

The four measurements were repeated each time when the soil moisture content profiles were determined, and the mean values and standard deviation of these measurements were used to analyze the effects of zokors on soil water content profiles. θ_k (cm^3 cm^{-3}, k denotes different soil depth in cm) was used to calculate the soil water storage (*SWS*, mm). The following equation was used to calculate the *SWS* values within 90 cm:

$$SWS\ (0 - 90\ cm) = 100 \times (\theta_{10} + \theta_{20} + 1.5 \times \theta_{30} + 3 \times \theta_{50} + 2.5 \times \theta_{90}) \tag{4}$$

Data were processed and analyzed using Excel 2016. The figures were created using Origin 9.0 software (Origin Lab, Northampton, ME, USA) and Photoshop CS 6.0 (Adobe Systems Corporation, San Jose, USA).

Table 1
Alfalfa coverages in the six tanks. The mean runoff rate, soil erosion rate, and sediment concentration at 5°, 10°, and 15° in control treatments (A–C) and treatments with a zokor with a rainfall intensity of 80 mm h^{-1} for 60 min.

Value	5°		10°		15°	
	With a zokor	Without	With a zokor	Without	With a zokor	Without
Alfalfa coverages	32%	87%	45%	90%	43%	92%
Mean runoff rate (mm min^{-1})	0.04	0.32	0.20	0.35	0.23	0.29
Mean soil erosion rate (g m^{-2} min^{-1})	0.11	0.21	1.32	0.73	6.64	1.71
Mean sediment concentration (kg m^{-3})	2.24	0.85	6.91	3.04	29.95	7.06

3. Results

3.1. Zokor bioturbation in 3 days

In this study, zokors began to dig holes and build shelters immediately after being placed in the tank. All three zokors produced mounds on the ground (Fig. 2D and F), and broken alfalfa roots were found in the soil mounds (Fig. 2F). The alfalfa coverages in the three tanks (5°, 10°, and 15°) without disturbance were 87%, 90%, and 92%, respectively. Conversely, the alfalfa coverages in the three tanks (5°, 10°, and 15°) with a zokor after 3 days were 32%, 45%, and 43%, respectively (Table 1). The initial formation of zokor mounds covered and smothered the alfalfa, and some alfalfa were eaten by these rodents (Fig. 2E). During rainfall, the mounds were partially eroded, and some of the entrances of the tunnel system were exposed (Fig. 2G). The soil bulk density of the mounds was 0.82 ± 0.02 g cm^{-3}, which was 39% smaller than that of the soil matrix (1.35 g cm^{-3}). The soil in the zokor mounds was relatively loose with large porosity (69%). The soil integrity was destroyed by the soil ridge produced by the zokors when digging the transverse tunnels, especially those near the soil surface (Fig. 2D and E). The tunnel arch was relatively stable; however, part of the tunnel collapsed, and the damaged transverse tunnel formed small puddles, which could develop into interconnecting surface ditches during rainfall. The runoff could be intercepted when a water retaining ditch formed on the slope.

Field observations indicated that the tunnel system was generally composed of mounds on the ground, herbivore tunnel, traffic tunnel, blind tunnel, and nest. The herbivore tunnel with a small diameter and a rough inner wall, forming a twisted cracked soil beam on the surface, was used for foraging plants. The traffic tunnel is a channel connecting the nest, and the herbivore tunnel and can be divided into temporary and permanent traffic tunnels. The traffic tunnel has a diameter of approximately 8–12 cm (Fig. 2H) and a smooth inner wall. The temporary traffic tunnel is located 18–25 cm away from the surface, and the permanent traffic tunnel is situated 30 cm below the surface. In case of rainfall, rainwater can enter the tunnel system and infiltrate into the deep soil along the underground tunnel system (Fig. 2G).

3.2. Effects of zokor excavation activities on runoff and soil loss

Surface runoff occurred in all tanks under the rainfall intensity of 80 mm h^{-1}. No significant difference was observed in the start time of the runoff between the tanks with and without a zokor. Under the slope gradients of 5°, 10°, and 15°, the mean runoff rate of control treatment was 0.32, 0.35, and 0.29 mm min^{-1}, which were 706%, 70%, and 29% higher than those of plots with a zokor (0.04, 0.20, and 0.23 mm min^{-1}) (Table 1). The runoff rate increased with the increase of slope gradient in the zokor treatment. However, in the control plots, the runoff rate first

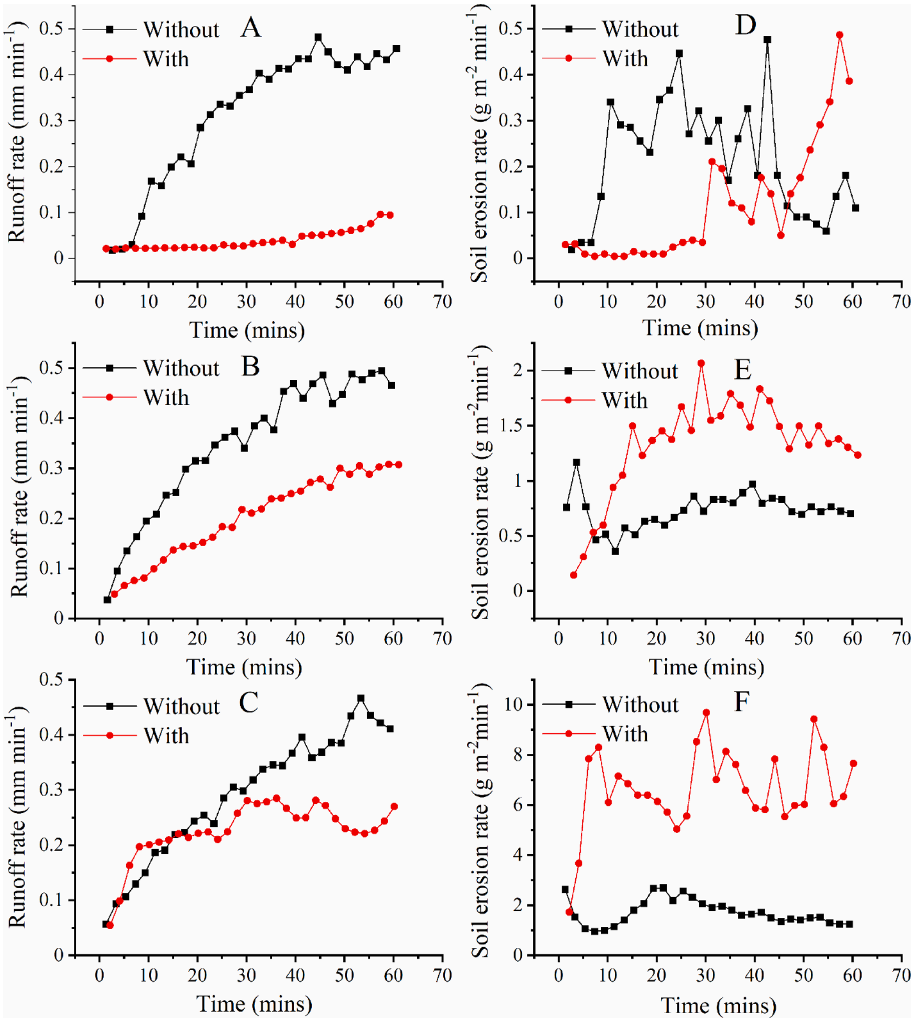

Fig. 3. Variation in runoff rate (A–C) and soil erosion rate (E–G) during rainfall with a rainfall intensity of 80 mm h^{-1} under the slope gradient of 5° (A and E), 10° (B and F), and 15° (C and G) at 2 min intervals in the tanks with and without a zokor. The mean runoff rate (D) and the mean soil erosion rate (H).

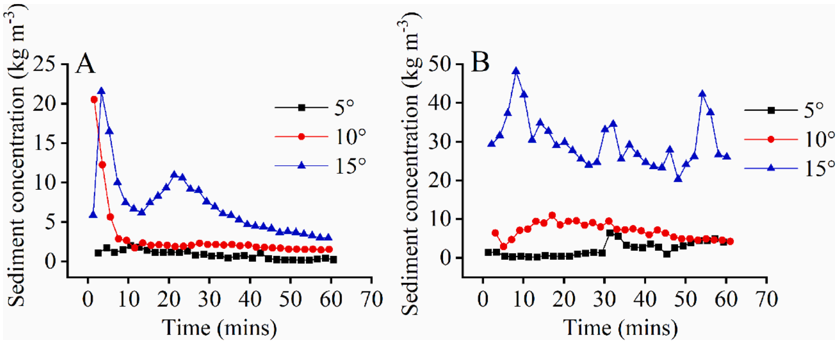

Fig. 4. Variation in sediment concentration during rainfall with an intensity of 80 mm h^{-1} at 5°, 10°, and 15°at 2 min intervals in the tanks without (A) and with a zokor (B).

increased and then decreased. At the beginning of the simulated rainfall experiment, the runoff rate between the tanks with or without a zokor was not different. With the progress of the rainfall experiment, the runoff rate increased. The control plots always had higher runoff rate than the tanks with a zokor, except for a short period time in the plots with 15° gradient (Fig. 3C).

Although the excavation activity of zokors reduced the runoff rate, the soil erosion rate increased, especially when the slope was steep. At plots with 10° and 15° gradients, the soil erosion rates were 1.32 and 6.64 g m^{-2} min^{-1}, which were 81% and 288% greater than those of the control plots (0.73 and 1.71 g m^{-2} min^{-1}). However, at the slope of 5°, the erosion rate in the zokor treatment was only 0.11 g m^{-2} min^{-1}, which was lower than that in the control treatment (0.21 g m^{-2} min^{-1}). The slope gradient had an obvious effect on the soil erosion rate. With or without a zokor, the soil erosion rate increased with the increase in the slope gradient. The sediment concentration of runoff also increased as the slope increased, and the zokors further promoted the sediment concentration (Fig. 4). The mean sediment concentrations of the runoff

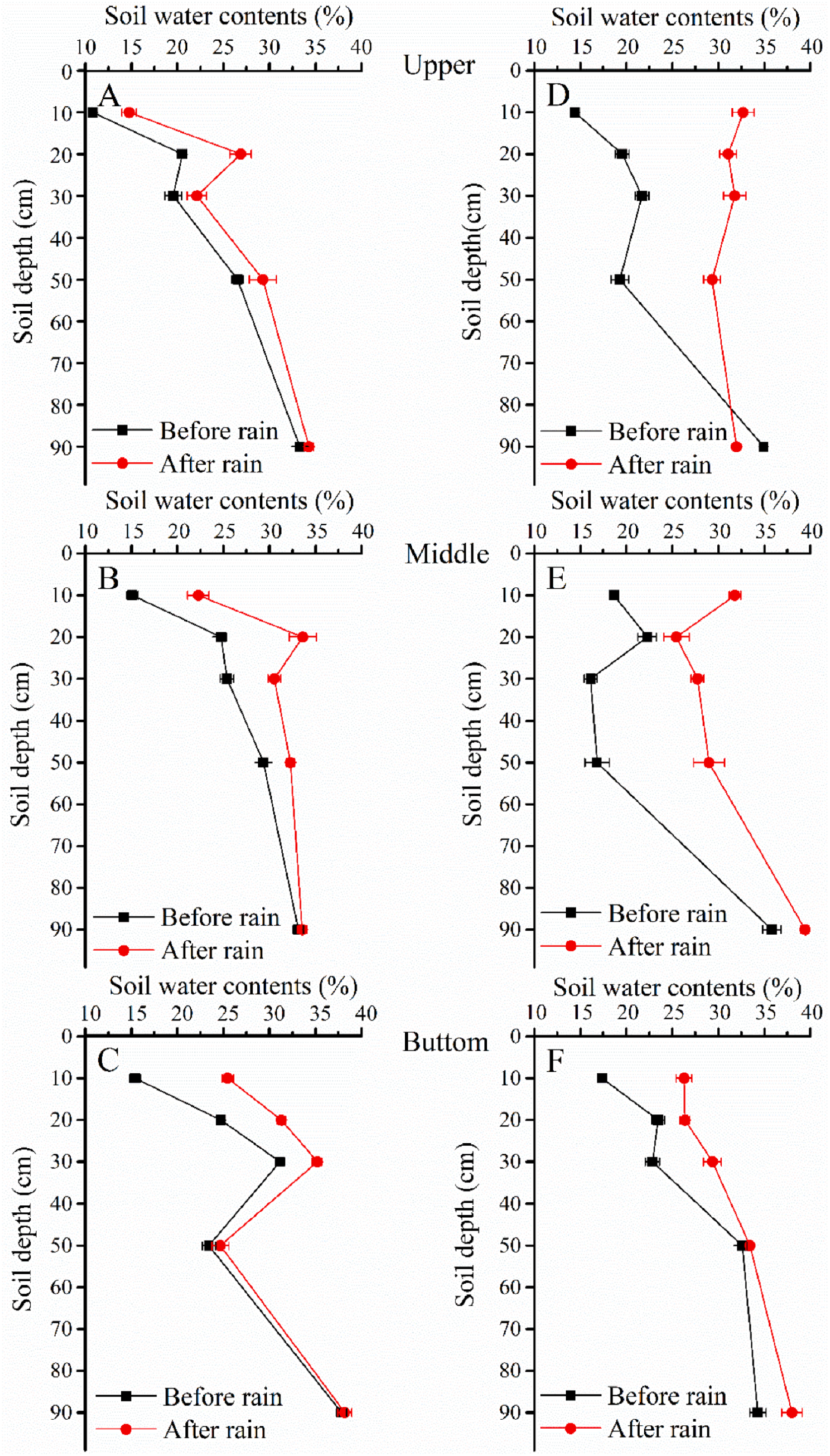

Fig. 5. Soil moisture profiles under the degree of 5° at the depths of 10, 20, 30, 50, and 90 cm in control treatments (A–C) and treatments with a zokor (D–F).

in tanks with a zokor at 5°, 10°, and 15° gradients were 2.24, 6.91, and 29.95 kg m^{-3}, which were 164%, 127%, and 279% greater than those of the control plots, respectively (0.85, 3.04, and 7.06 kg m^{-3}) (Table 1).

3.3. Soil water content profile

Fig. 5 shows the soil moisture profiles at 5° with depths of 10, 20, 30, 50, and 90 cm in control treatments and treatments with a zokor. Figs. 6 and 7 show the profiles at 10° and 15°, respectively, and Table 2. shows the variation in soil water storage. The soil water distribution and the water storage in soil at a depth of 0–90 cm were used to evaluate the contribution of zokor activity to soil moisture (Figs. 5–7 and Table 2). After the simulated rainfall, the soil water content increased significantly ($P < 0.01$) compared with that before the rainfall, and the soil water content of shallow layers remarkably increased compared with the deeper soil layers (Figs. 5–7). The soil water content in the plots with zokors was increased significantly ($P < 0.05$) compared with that in the control plots.

SWS was significantly ($P < 0.01$) increased in all tanks after the rainfall (Table 2). The plots with zokors showed significantly ($P < 0.01$)

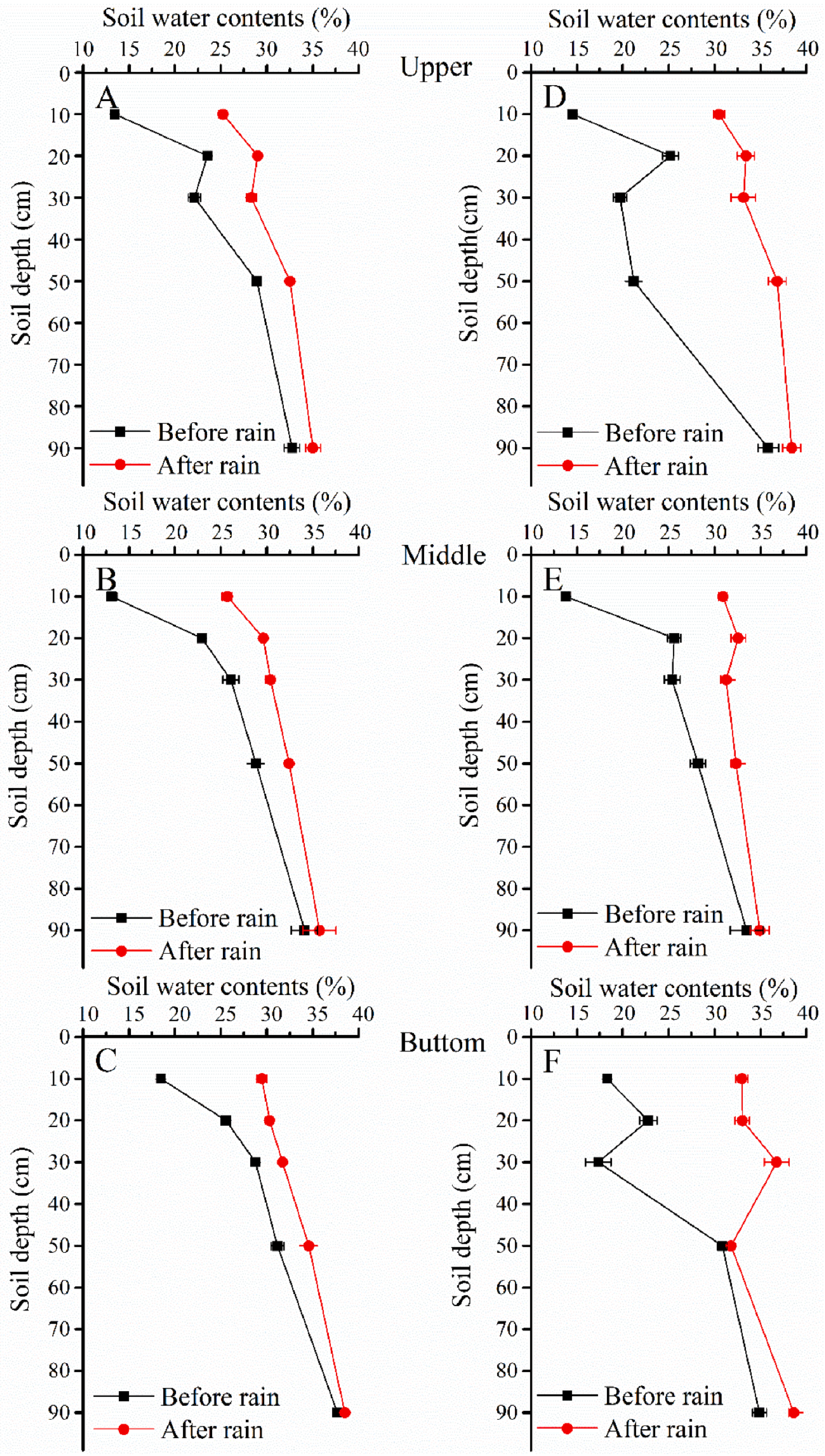

Fig. 6. Soil moisture profiles under the degree of 10° at the depths of 10, 20, 30, 50, and 90 cm in control treatments (A–C) and treatments with a zokor (D–F).

increased *SWS* compared with the control plots, especially at the low slope gradient. The mean increment of *SWS* in tanks with a zokor at 5°, 10°, and 15° slope gradients were 63.8, 54.4, and 52.8 mm, respectively, which were considerably higher than those in the control treatments (29.2, 38.7, and 36.5 mm). The zokor mounds and tunnel systems have a pronounced effect on *SWS* when the slope was low. However, the slope gradient had no significant effect on *SWS*. The mean increment of *SWS* decreased with the increase of slope gradient in the zokor treatment; however, in the control plots, the mean increment of *SWS* initially increased and then decreased.

4. Discussion

As ecosystem engineers, subterranean rodents can excavate and disturb the soil, remarkably change the soil texture, and increase the local landscape heterogeneity (Davidson and Lightfoot, 2008; Lindtner et al., 2019). Chinese zokors have particular digging strategies according to soil texture. If the soil is relatively loose, these rodents will not create mounds on the ground; instead, they will compact soil on the side wall using their hard nose and strong muscle strength. When the soil is hard, these rodents will create mounds on the ground. Extrusion compaction

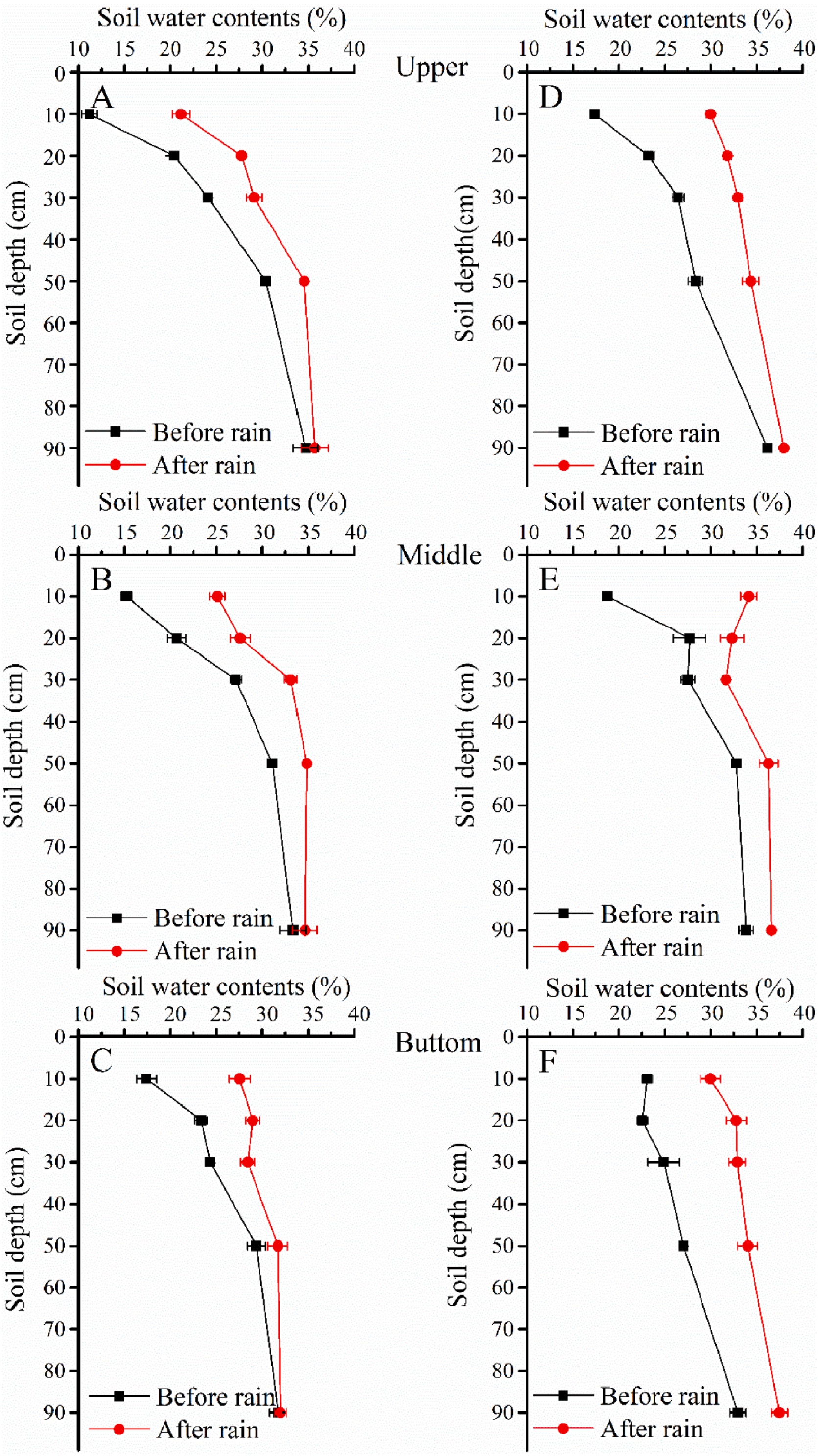

Fig. 7. Soil moisture profiles under the degree of 15° at the depths of 10, 20, 30, 50, and 90 cm in control treatments (A–C) and treatments with a zokor (D–F).

can improve the mechanical properties of the tunnel, strengthen the tunnel, reduce the permeability of the tunnel side wall (Li et al., 2001), and cause the water flowing into the tunnel system to flow along the tunnel to the deep soil layer. During the non-mating period, zokors live alone and create their own burrows. A large number of horizontal tunnels (herbivore tunnel) near the surface are excavated to forage plants. When food is scarce around the nest, zokors abandon the old nest and transfer to an area rich in food and build a new nest. These animals are highly reproductive and lack natural enemies, and they are currently the main rat pest in the Loess Plateau (Sui et al., 2014). Zokors can drag the surface vegetation into underground storage, thus bringing a large amount of organic matter into the deep soil and accelerating soil nutrient exchange. They build a separate chamber underground as a toilet. This process can form a “fertilizer island” in soil, change the soil properties, and increase soil nutrient and water heterogeneity, thus affecting plant distribution (Fleming et al., 2013).

In this study, zokors began to dig tunnels after they were placed into the soil tank. When they were in the soil, the entrance of the soil pit was

Table 2
Variation in soil water storage (*SWS*; in mm) within 90 cm soil depth in the upper, middle, and bottom plots in the treatments without and with a zokor after 80 mm h^{-1} rainfall for 60 min under the slope of 5°, 10°, and 15°.

Treatments	Plots	5°			10°			15°		
		Before rain	After rain	Increment	Before rain	After rain	Increment	Before rain	After rain	Increment
Without zokor	Upper	221.5	248.4	26.9	238.9	282.0	43.1	245.6	285.5	39.9
	Middle	249.0	282.5	33.5	247.0	287.7	40.7	253.2	293.4	40.2
	Bottom	251.8	279.0	27.3	274.9	307.3	32.4	244.6	274.0	29.4
	Mean	240.7	270.0	29.2	253.6	292.3	38.7	247.8	284.3	36.5
With zokor	Upper	211.7	290.7	79.0	222.6	273.3	50.7	255.7	309.1	53.4
	Middle	205.2	284.4	79.2	245.9	294.8	*48.9*	283.3	326.8	43.5
	Bottom	268.7	302.0	33.3	259.3	322.8	63.5	261.5	322.8	61.4
	Mean	228.5	292.4	63.8	242.6	297.0	54.4	266.8	319.6	52.8

blocked with loose soil. All the three zokors produced mounds of 7–15 cm in height on the soil surface, which were similar to the “small mounds” in the field survey (Liu and Li, 1984). In the present study, zokors were still active after the simulated rainfall and developing further mounds. Wang and Fan (1987) estimated that a plateau zokor can deposit at least 1024 kg year^{-1} of soil at the soil surface on the alpine meadows. One year after mound formation, the morphological characteristics were stable, and the height of the mounds was mostly 7–8 cm (He et al., 2006). Zhang et al. (2003) found that the soil bulk density of mounds produced by plateau zokors in the Qinghai–Tibet Plateau was much smaller than that of the surrounding soil. This phenomenon was also observed in this experiment. A transverse herbivorous tunnel, which was close to and formed a fold on the surface, was made by zokors to find food. Herbivorous tunnels may collapse when humans and animals trample on them or during heavy rainfall (Liu and Li, 1984), and the surface soil will enter the deep soil layer (Reichman and Seabloom, 2002). In the present study, the herbivorous tunnel collapsed during rainfall.

Vegetation plays an important role in water infiltration and soil conservation (Gyssels et al., 2005; Chen et al., 2015; Li et al., 2018a). However, zokors destroy vegetation uniformity, reduce vegetation coverage, and increase the bare ground, thus increasing the risk of soil erosion. In this study, the aboveground part of alfalfa was dragged into the tunnel when zokors found the roots (Fig. 2E). After 3 days of foraging and covering the mounds, the coverage of alfalfa in the three soil tanks decreased rapidly. The initial formation of mounds smothered live plants, some alfalfa was eaten, and an average of 0.5 m^2 of alfalfa was foraged or covered. Subterranean rodents, such as plateau pikas or zokors, are the main reasons for pasture degradation in the Qinghai–Tibet Plateau (Harris, 2010). The runoff rate of bare land (Li et al., 2019b) was 131% greater than that of alfalfa coverage under the rainfall intensity of 80 mm h^{-1} at the slope gradient of 15°. The vegetation coverage reduced the runoff and erosion rates compared with bare land, but zokor damaged the alfalfa and reduced vegetation coverage, thereby accelerating the erosion rate.

The excavation activities of zokor increased infiltration and changed the runoff path, thereby reducing runoff. With the progress of rainfall, the infiltration rate of soil decreased as the surface became wet or saturated, whereas the mound of zokors was loose and well infiltrated. More water infiltrated into the mound, which then entered the deep soil layer. The mounds uplifted the soil surface, changing the microtopography. The surface ridge formed by the herbivorous tunnel blocked the runoff, prolonged the runoff path, and further enhanced water infiltration. When the herbivore tunnel collapsed, it formed interconnected surface ditches, which accelerated the accumulation of surface water. Then, the water rapidly entered into the deep soil along the tunnel. During rainfall, zokor tunnels may become underground pipes and allow surface water to enter the deep soil layer (Reichman and Seabloom, 2002). The infiltration rate of the area with ant nest was approximately 20 times higher than that without nest (Li et al., 2017). The horizontal burrows of mole crickets (*Gryllotalpa unispina*), which are similar to the herbivorous tunnel of zokors, can also intercept rainfall and promote runoff reduction and infiltration (Li et al., 2018b). However, the zokor tunnel is much larger than the mole cricket tunnel. In this experiment, the disturbance of zokors increased the surface heterogeneity and complicated the runoff process. Meanwhile, vegetation is also an important factor that reduced runoff.

According to Reichman and Seabloom (2002), excavation by subterranean rodents is one of the main sources of soil erosion, and the low bulk density of soil mounds promotes soil erosion. Tunnel excavation and mound deposition transformed the standard model for the movement of soil downslope from linear (Gabet, 2000) to nonlinear (Reichman and Seabloom, 2002). In the present study, the small bulk density of zokor mound could provide sediment source for soil erosion, the mounds were eroded to varying degrees, and raindrops compacted the surface of mounds. The disturbance from zokor destroyed the surface integrity, increased the surface heterogeneity, and complicated the erosion process. The collapsed tunnel system promoted the surface soil to enter the deep layer, thereby intensifying the loss of surface soil. The soil of the zokor mounds on the slope moves down the slope during rainfall; Imeson (2017) reported that burrowing animals (voles and moles) are directly or indirectly responsible for most of the material transport on a wooded slope in the Luxembourg Ardennes. When the tunnel collapses, continuous ditches are formed. Rainwater accumulates along the ditch, washes the soil, and enters the deep soil layer, thus forming a shallow gully on the surface. Although the activity of zokors does not directly cause erosion, it destroys the soil surface structure and reduces vegetation coverage, and thus exacerbates soil erosion under the rain. Li et al. (2019a) reported that plateau zokors enhance the soil erosion rate, which for the zokor mound was 1.8 times higher than that of degraded meadows and 17.7 times higher than that of intact meadows. The slope gradient is also an important factor affecting soil erosion (Gong et al., 2018). With the increase in the slope gradient, less energy is needed to push the sediment, thereby increasing the runoff sediment content and erosion rate. In view of vegetation restoration in the Loess Plateau, the population of zokors may increase rapidly (personal observation). More attention should be given to the effect of zokors and other native subterranean rodents on erosion, especially at the steep slope gradient.

5. Conclusion

The excavation activities of the Chinese zokor reduced the runoff rate but promoted soil erosion, especially on the steep slope. The tunnel system of zokors changed the runoff pathway and increased water infiltration, thereby decreasing the runoff rate and increasing *SWS* within 90 cm. Collapsed tunnel systems further intercepted the runoff and promoted the surface soil entering into the deep layer, thereby intensifying the loss of surface soil. The zokor mounds on the soil surface changed the surface microtopography and provided loose and erodible materials, promoting the soil loss during rainfall. In addition, zokors reduced vegetation coverage and further increased the risk of soil erosion. The comprehensive impact of zokors on vegetation and soil environment should be paid more attention, particular in field experiments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (41807011 and 42007006), the Opening Foundation of the State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau (A314021402-1717), and the Strategic Priority Research Program of Chinese Academy of Sciences, Grant No. XDB40000000.

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