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Effects of topography and land-use patterns on the spatial heterogeneity of terracette landscapes in the Loess Plateau, China

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ABSTRACT

Terracette landscapes are common on hilly rangelands in arid and semiarid regions. Terracette structure significantly modifies the hydrological and biogeochemical processes, resulting in striking spatial patterns in soil moisture, nutrient, and vegetation distribution. However, there is still no efficient and precise method for monitoring and analyzing terracettes formation and maintenance processes. Therefore, we investigated spatial patterns and vegetation cover of these landscapes via field sampling and unmanned aerial vehicle (UAV) methods on the Loess Plateau, China. The parameters considered included land-use patterns (grazed *vs.* ungrazed) and topography (aspect: north and south, slope: 0°, 15°, 30°, and 45°). We revealed structural characteristics of terracettes, evaluated the differences between two sampling methods and explored the potential formation and maintenance mechanisms of these landscapes. The results showed that: 1) terracettes only existed in the north-30°, north-45°, and south-45° areas of grazed plots, 2) terracettes density (terracettes basic unit number/m, TBU/m) and vegetation cover differed significantly among the land-use patterns and topographies, 3) vegetation cover increased and then decreased with increasing terracettes density, with an inflection point of ~0.78 TBU/m, up to a vegetation cover of ~70%. These results could have major implications on land-use policies and environmental conservation and socioecological sustainability practices of the Loess Plateau. Finally, UAV can be used to effectively and accurately monitor and analyze terracette landscapes, and have great potential for monitoring terracettes in future studies.

1. Introduction

Terracette landscapes are common on hilly rangelands in arid and semiarid regions (Howard and Higgins, 1987; Stavi et al., 2008a), and consist of a track area with a gentle slope and a nontrack area with a slope gradient similar to that of the hillside (Goudie, 2004; Howard and Higgins, 1987; Stavi et al., 2008b). Terracette structure significantly modifies the hydrological and biogeochemical processes, resulting in striking spatial patterns in soil moisture, nutrient, and vegetation distribution, which strongly influences the foraging behavior of livestock (Bates, 1950; Hiltbrunner et al., 2012; Jin et al., 2016; Stavi et al., 2008a,b). Terracettes may have significant implications on soil and water conservation in rangelands (Jin et al., 2016), especially in arid and semiarid regions where water resource limitations and soil erosion are key factors that impact ecosystem production and sustainability (Chen et al., 2010; Jin et al., 2016). For instance, the gentler slopes of track segments, concurrent with the lower bulk density and concentrated plant structures of shoulder segments, slow down and scatter surface flow (Jin et al., 2016; Stavi et al., 2008b). These processes increase the infiltration rate and sediment capture, which in turn promote plant growth (Bromley et al., 1997; Jin et al., 2016; Wilcox et al., 1988). Moreover, the reduced rate and quantity of runoff are helpful for improving water conservation and reducing soil erosion in canyon areas (Bromley et al., 1997; Stavi et al., 2008a). However, the formation and maintenance of terracettes remain inconclusive. For example, Darwin (1881) and Bates (1950) suggested that grazing tracks on slopes were likely formed by other processes (e.g., earth slips, cracks, etc.) and subsequently used by grazing animals, while Howard and Higgins (1987) argued that grazing tracks formation is largely biogenic, and stated that the mean spacing among terracettes is dependent on the size of the grazing animal, slope of the hillside, and possibly grazing intensity. Therefore, long-term experimental corroborative evidence is

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urgently needed to quantitatively clarify the characteristics, occurrence, and development process of terracettes.

Unlike large patches in fragmented landscapes, terracettes cannot be easily identified by remote sensing methods, and are too numerous and irregular to be easily and efficiently measured *in situ* (Oikawa et al., 1988; Yi, 2017). Researchers currently use two primary methods to estimate terracettes: aerial photograph sampling and field surveys (Jin et al., 2016; Oikawa et al., 1988). Traditional aerial photograph sampling provides the opportunity for estimating terracettes at a larger scale, and several vegetation and fragmentation dynamics studies have shown that it is a reliable data source (Augustine et al., 2012; Oikawa et al., 1988; Wu et al., 2000). However, traditional aerial photographs are not only prohibitively expensive for many applications but also difficult to analyze for complex topography, even when using complex algorithms (Oikawa et al., 1988). Field surveys mainly include quadrat and belt sampling (Jin et al., 2016; Stavi et al., 2008b), since terracette landscapes exhibit large spatial and temporal variations. For example, Oikawa et al. (1988) divided cattle tracks into seven types based on spatial patterns and origins. Therefore, it is difficult to use limited field survey results to estimate entire terracette landscapes. Most studies have reported that field investigations (e.g., quadrat scale or basic landscape unit scale) are a feasible method for measuring terracettes within specific research areas (Jin et al., 2016). For example, Jin et al. (2016) used data combination of 0.5 m × 0.5 m sampling frames in each basic landscape unit as the measured value. Meanwhile, Stavi et al. (2008b, 2009) determined the impact of livestock on the microtopography and penetration resistance with straight, parallel-slope transects. However, the field sampling methods usually require large amounts of time, labor, cost, and resources (Arif et al., 2016). Additionally, ecological studies usually require long-term repeated monitoring (Jorgenson et al., 2015; Yi, 2017). Therefore, a new efficient and repeatable monitoring method is urgently needed.

Vegetation cover is defined as the ratio of the vertical projected area of vegetation to the total ground area, which is an important ecological parameter in ecosystem process and climate change studies (Lin and Qi, 2004; Zribi et al., 2003). Vegetation cover is often used to evaluate vegetation degradation and desertification (Chen et al., 2016; Jiapaer et al., 2011), and spatial patterns of vegetation cover are generally regarded as the most intuitive indicators of livestock tracks (Oikawa et al., 1988). Several recent studies have shown that vegetation cover can be easily and efficiently monitored and analyzed without destructive sampling by unmanned aerial vehicle (UAV) (Chen et al., 2016; Yi, 2017). However, few studies have adopted vegetation cover to study terracettes.

The Loess Plateau, China (630,000 km^2), features deep loess deposits and hilly terrains. It experiences among the most severe soil erosion in the world (Chen et al., 2010; Liu, 1988; Sun et al., 2001; Zheng and Wang, 2014) and has a long history of livestock grazing (Chen et al., 2010). Moreover, terracette landscapes are common in this area (Jin et al., 2016; Sun et al., 2001). Thus, a better understanding of the ecological function of terracettes is critical to inform land conservation and management policies, such as the current Returning Grazing Land to Grassland (GLG) policy to exclude grazing from substantial areas of hilly rangelands in the region, and their potential consequences (Deng and Shangguan, 2014; Jin et al., 2016). Therefore, the objectives of this study were to (1) investigate the effects of land-use patterns and topography on terracette landscapes; (2) explore the referential meaning of terracette landscapes in grazing management on the Loess Plateau, and (3) explore the feasibility of UAV to landscape monitoring and analysis. Our results could have significant implications on land-use policies and socioecological sustainability practices on the Loess Plateau.

2. Methods

2.1. Study area

The research was conducted in July 2017 in Huanxian County, Gansu Province, China (37.1°N, 106.8°E). This region has a typical continental monsoon climate and is located 1650 m a.s.l.. The mean annual precipitation is 359 mm, with more than 60% occurring from late June to mid-September, and the mean annual evaporation is 1993 mm. The mean annual temperature is 7.1 °C, with a several-month-long period of sub-zero winter temperatures, as well as summer temperatures typically above 30 °C. The annual sunshine duration is 2777 h and the frost-free period is 125 days (Chen et al., 2010). The soil at the study site was classified as loessial, and this rangeland is a typical temperate steppe according to a comprehensive and sequential classification system of grassland (Chen et al., 2010; Ren et al., 2008). The dominant species of the rangeland include *Stipa bungeana*, shrubby lespedeza (*Lespedeza bicolor*), wormwood (*Artemisia capillaris*), flaccidgrass (*Pennisetum flaccidum*), and green bristle grass (*Setaria viridis*).

2.2. Experimental design

The study plots were established in 2001. The un-grazed plots (25 m × 50 m) were built along a mountain ridge that gradually becomes steeper, with slope gradients of ~0°, 15°, 30°, and 45° (Fig. 1A, B, C, and D). Areas outside the un-grazed plots were grazed freely by Tan sheep (*Ovis aries*) throughout the year (Chen et al., 2010). Areas parallel to each un-grazed plot were selected as grazed plot (25 m × 50 m, Fig. 1). One exceptional case was the south 15°-grazed treatment area, which was smaller than 25 m × 50 m because of a reseeding experiment occupying some of the area (Fig. 1E). In addition, several other areas were used as paddocks for multi-specific stocking rate experiments (Fig. 1F; Chen et al., 2010; Chen et al., 2017), and there were some tire tracks (on the slope or flat area) from power cable construction and maintenance (on the ridge) and transport of water for the animals used in the multi-specific stocking rate experiments, which could be easily distinguished from terracette landscapes (Fig. S1).

2.3. Field sampling and data retrieval

In late July 2017, field sampling was conducted near the peak biomass season to characterize the microtopography and vegetation cover. Each plot was divided into three sub-plots equally along the ridge aspect (Fig. 2 and Fig. S2b). In each sub-plot, nine field samples were conducted using a 2-m long straight rulers to investigate the density of vegetation patches ($\text{VBU}_{\textit{Field-B}}$; including all vegetation patches, the minimum length of a bare patch was set as 10 cm) (Figs. 2–10). In addition, the density of the terracette basic unit ($\text{TBU}_{\textit{Field-B}}$; including tracks, shoulder, and interslope segments; refer to Jin et al., 2016) was measured (Figs. 2–11).

Fragmentation Monitoring and Analysis with Aerial Photography (FragMAP) was used to create a high-resolution 3D dataset using the overlapped flight path within each plot (0°, 15°, 30°, and 45°, respectively) (Yi, 2017). We used a DJI drone (Phantom 4 Professional, DJI Innovation Company, China) and Pix4Dmapper (Pix4D S.A., Lausanne, Switzerland) to generate orthomosaic photographs (Yi, 2017). We sampled the entire monitoring area (e.g., Fig. 3a) to retrieve vegetation cover information from the orthomosaic photographs. Vegetation cover was calculated using a threshold method based on excess green index (EGI = 2G-R-B; with R, G, B being red, green, and blue bands, respectively) of each pixel (Yi, 2017). In brief, the specific procedures were to (1) calculate an initial value of EGI threshold and compare it with each pixel; (2) classify each pixel in a photograph as either a green vegetation pixel or a bare pixel based on this threshold; (3) draw the contours based on the locations of green vegetation pixels using the OpenCV package; (4) overlay on and compare the contours with the original

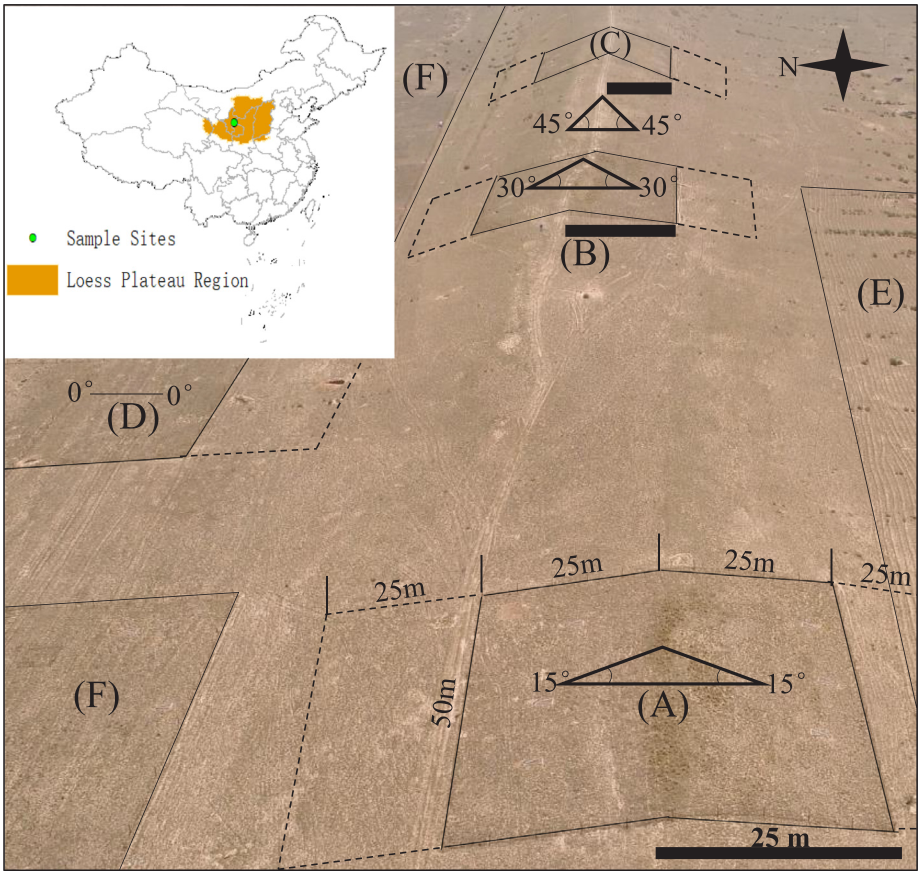

Fig. 1. Map depicting the location of the Loess Plateau in China and the experimental design of the sample plots. (A-D) The 15°, 30°, 45°, and 0° 17-year-old un-grazed (25 m × 50 m, solid line) and gazed plots (25 m × 50 m, dotted line), (E) Reseeding experiment area, (F) Areas used as paddocks for multi-stocking rates experiments (simulated as warm season pastures).

photograph; and (5) if the contours did not fit with the shape of the vegetation patches, then the threshold was adjusted and the process repeated from procedure 2 until the contours fit well with the vegetation patch in the original photograph (Fig. 2). Meanwhile, terracettes were clearly identified based on the belt distribution of bare areas (e.g., Fig. 2a and b; Yi, 2017). In this study, we focused on the tracks for grazing (i.e., parallel and conjunctive tracks) rather than those related to migration (Oikawa et al., 1988) or artificial tracks derived from long-term field sampling around the fencing. The resampling (i.e., retrieved information of vegetation cover and terracettes from the orthomosaic photographs) area was 15 m × 20 m (Fig. 3 and Fig. S2b) to avoid these problems. Based on the 2017 aerial images of similar areas surrounding

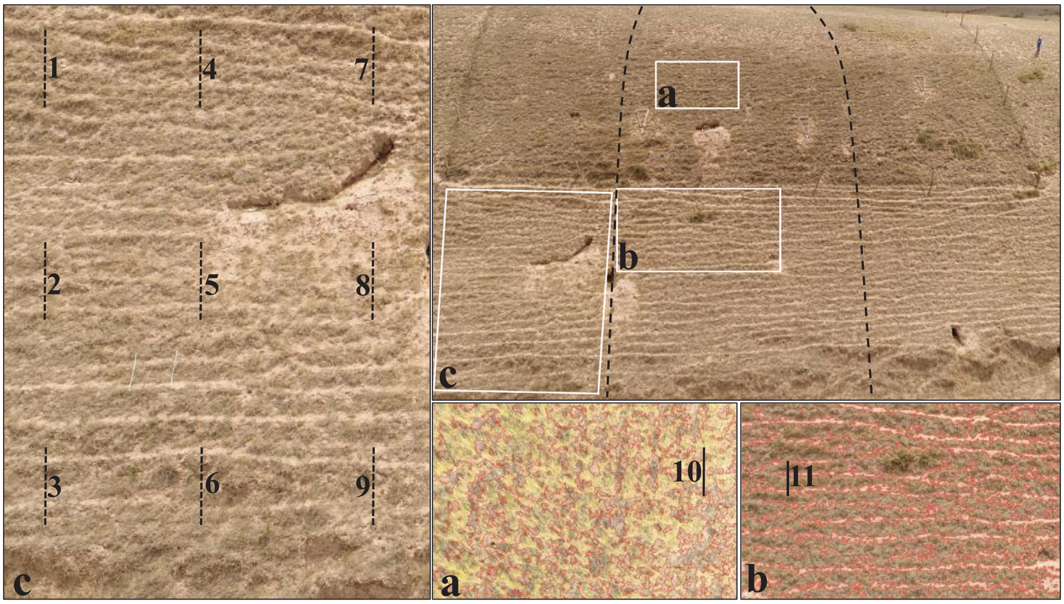

Fig. 2. Field sampling methods and terracette landscapes identification based on the Nor-45° un-grazed and grazed cases. (a, b) Examples of identified terracettes related to grazing (Oikawa et al., 1988) based on small-scale fragmentation derived from image recognition software developed independently by Yi (2017). (c) Nine 2-m field samples (1–9) used to investigate the characteristics of spatial heterogeneity of each sub-plot; 10 and 11 illustrate general vegetation patches and terracette basic units, respectively.

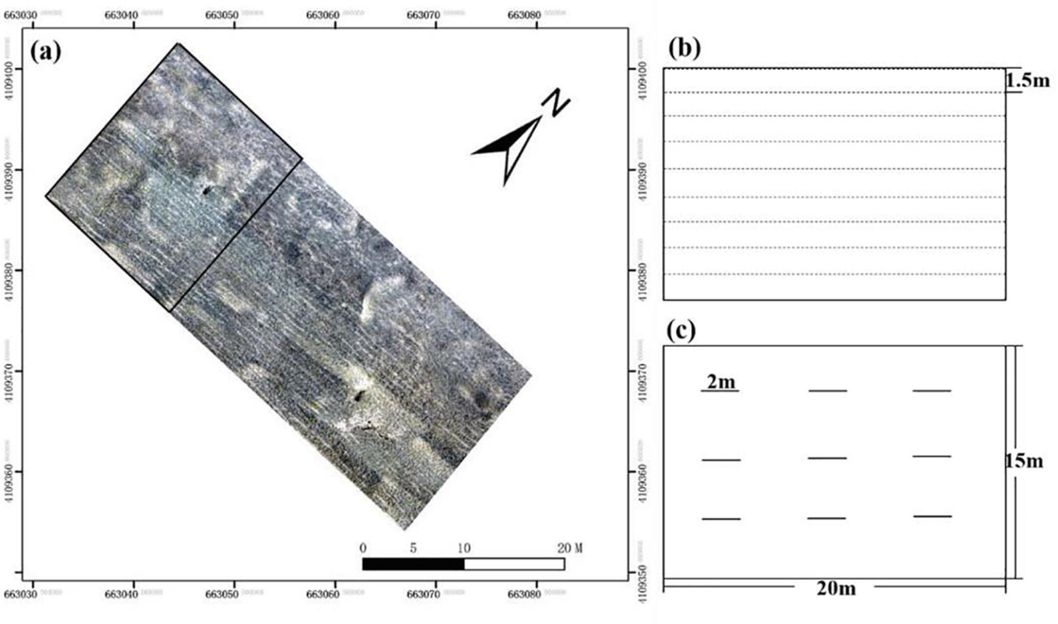

Fig. 3. Data resampling and retrieval based on orthomosaic photographs. (a) The orthomosaic photographs used for resampling and retrieval using the Nor-45°-grazed case as an example. (b) Resampling along ten parallel lines. (c) Resampling based on the field sampling method.

the sample area (Fig. S2a), we confirmed that terracettes were widely distributed on side slopes with higher gradients (including the fenced areas of 30° and 45° in the present study, especially the north slopes), except the narrow flat area at the top of ridges before the fences were set up (e.g., Fig. S2a-4). To avoid sampling on ridgetops, areas within 7 m of ridgetops were excluded from filed sampling and analysis of the images from orthomosaic photographs (Fig. S2b).

To verify the accuracy of the method used to sample the orthomosaic photographs (Sou-45°, Nor-30°, and Nor-45° of grazed plots) for the terracette study, we retrieved information on the terracettes from the orthomosaic photographs using the same method for field sampling ($TBU_{UAV\text{-}B}$; Figs. 2c and 3c). Meanwhile, we sampled along ten parallel lines in the orthomosaic photographs in 1.5-m intervals to investigate the terracettes structure at a plot scale ($TBU_{UAV\text{-}L}$; Fig. 3b). Based on the dataset collected from the field sampling and ten parallel line sampling methods, we analyzed the impact of the use of different belt layouts and groups of belts on the accuracy of terracettes estimated at a plot scale. Four scenarios were used: (1) one belt (fifth belt); (2) three belts (first, third, and ninth belts); (3) five belts (first, third, fifth, seventh, and ninth belts); and (4) nine belts (all the nine belts in a plot) (see Fig. 2c and 3c).

2.4. Statistical analysis

The statistical analyses were performed with R ver. 3.4.1 (R Development Core Team, 2013). A goodness-of-fit test (Shapiro-Wilk test, UNIVARIATE Procedure) indicated that the vegetation cover was normally distributed. We used a general linear mixed model to fit these data and the variable interactions between land use (i.e., grazed *vs.* ungrazed), slope aspect and slope gradient. To select the final regression models, which indicated the relationships between sampling methods, and between terracette density and vegetation cover, likelihood ratio

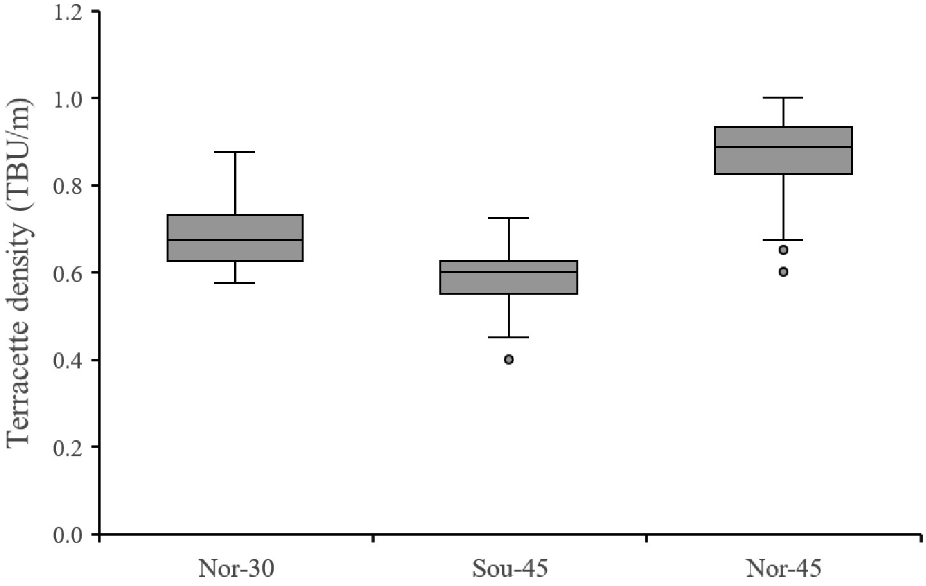

Fig. 4. Characteristics of the terracettes in the North-30°, North-45°, and South-30° grazed plots.

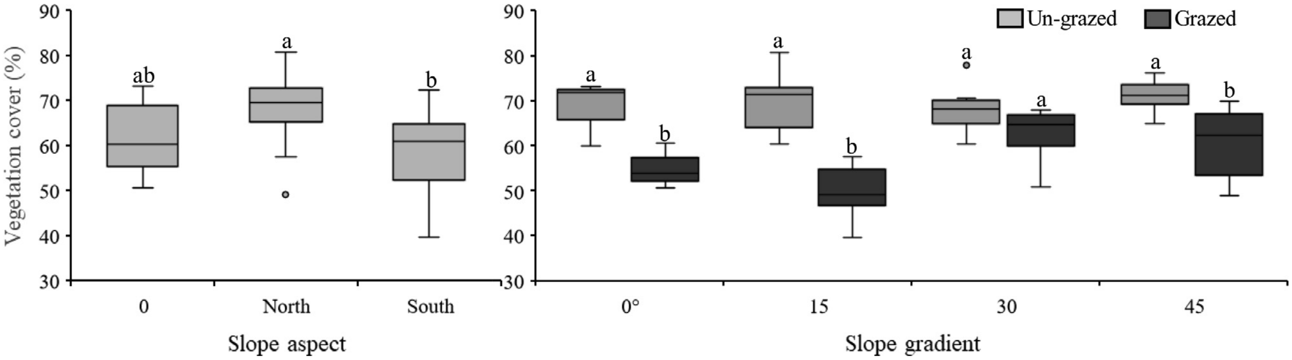

Fig. 5. Characteristics of vegetation cover under (a) specific slope aspects, and (b) specific slope gradients and land use patterns.

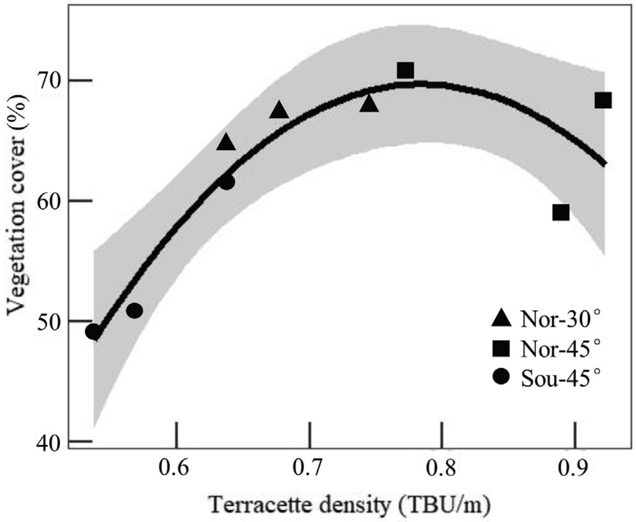

Fig. 6. Relationship between vegetation cover and terracette density. The solid line indicates statistical significance for the relationships. The shaded areas show the 95% confidence interval of the fit.

tests were used to compare the simple linear regression and polynomial regression models (n = 9, ggplot2 package in R). The effects of slope aspect and gradient on terracette density and differences among TBU$_{Field-B}$, VBU$_{Field-B}$, TBU$_{UAV-B}$, and TBU$_{UAV-L}$ were examined with a *t*-test, and differences among means were considered to be significant at the $P < 0.05$ level. The coefficient of determination (R^2 and *P* values) was used to evaluate the performance of different sampling methods (TBU$_{Field-B}$ and TBU$_{UAV-L}$).

3. Results

3.1. Effects of land-use patterns and topography on terracettes

No terracette landscapes were identified in un-grazed plots. There were terracette landscapes in the Nor-30°, Nor-45°, and Sou-45°grazed plots, but none in the other topographic settings (Table 1).

TBU$_{UAV-L,}$ terracette density measured along ten parallel lines in orthomosaic photographs; VBU$_{Field-B}$, vegetation patch density measured in nine 2-m sampling belts in the field; TBU$_{UAV-B}$ and TBU$_{Field-B}$ indicate terracette density measured based on the 2-m sampling belts in orthomosaic photographs and in the field, respectively; values with different lowercase letters are significantly different between sampling methods at the $P < 0.05$ level, mean ± SD.

The structures of the terracettes differed, and terracette density followed the order Sou-45° < Nor-30° < Nor-45° ($P < 0.05$, Fig. 4).

3.2. Relationship between vegetation cover and terracettes

There was lower vegetation cover on south slopes than on north slopes (Table 2 and Fig. 5). There was an interaction between land-use pattern and slope gradient (Table 2). Finally, the 17-year-old un-grazed had increased vegetation cover (Table 2 and Fig. 5).

With increasing terracette density (based on the Sou-45°, Nor-30°, and Nor-45° grazed datasets, where terracette density = TBU/m calculated as the average value of ten belts in the present study; Fig. 3b), vegetation cover increased below ~7.8 TBU/m and then decreased (Fig. 6, R2 = 0.82, $P = 0.007$). The maximum vegetation cover was ~70%.

3.3. Differences among sampling methods at a plot scale

There was no significant difference between TBU$_{UAV-B}$ and TBU$_{Field-B}$ (Table 1). Nevertheless, the terracette density (TBU$_{UAV-L}$, TBU$_{UAV-B}$, and TBU$_{Field-B}$ based on nine sampling belts) of Sou-45°-grazed plots was smaller than the density of VBU$_{Field-B}$ (Table 1). TBU$_{UAV-L}$ and TBU$_{Field-B}$ (based on nine sampling belts) did not differ significantly at a plot scale (although the standard deviation of TBU$_{Field-B}$ was larger; Table 1). All four sampling scenarios exhibited a significant linear relationship between TBU$_{UAV-L}$ and TBU$_{Field-B}$ ($P < 0.05$). However, the R^2 of the regression models between TBU$_{UAV-L}$ and TBU$_{Field-B}$ were below 0.85. Furthermore, R^2 increased and P decreased with increasing number of sample belts used to estimate the terracettes (Fig. 7).

The solid lines indicate statistical significance for the relationships. The shaded areas show the 95% confidence interval of the fit.

4. Discussion

4.1. Effects of land-use patterns and topography on terracette maintenance

Terracettes formation and maintenance have long been discussed (Bates, 1950; Darwin, 1881; Howard and Higgins, 1987; Jin et al., 2016). In this study, we found no terracettes in the 17-year-old fencing plots; however, grazed plots had terracettes, especially on higher slope gradients (Table 1). Associated with the original conditions: 1) the local herdsman and former owner of the sampling areas noted that there were "livestock tracks" on the side slopes before they had been fenced, and 2) the aerial photographs taken around the sampling areas revealed terracettes on the ridges, except the narrow flat areas on the top (e.g., Fig. S2a-4). Hence, we speculate that the 17-year-old grazing exclosure resulted in the disappearance of these landscapes. Furthermore, we conclude that animal grazing has a critical role in maintaining terracette landscapes which associated with spatially heterogenous patterns, in agreement with the perspectives of Jin et al. (2016) and Howard and Higgins (1987). Furthermore, the terracette densities differed with respect to slope aspect (e.g., Nor-45° and Sou-45°) and slope gradient (e.g., Nor-45° and Nor-30°, although it was not significant at the

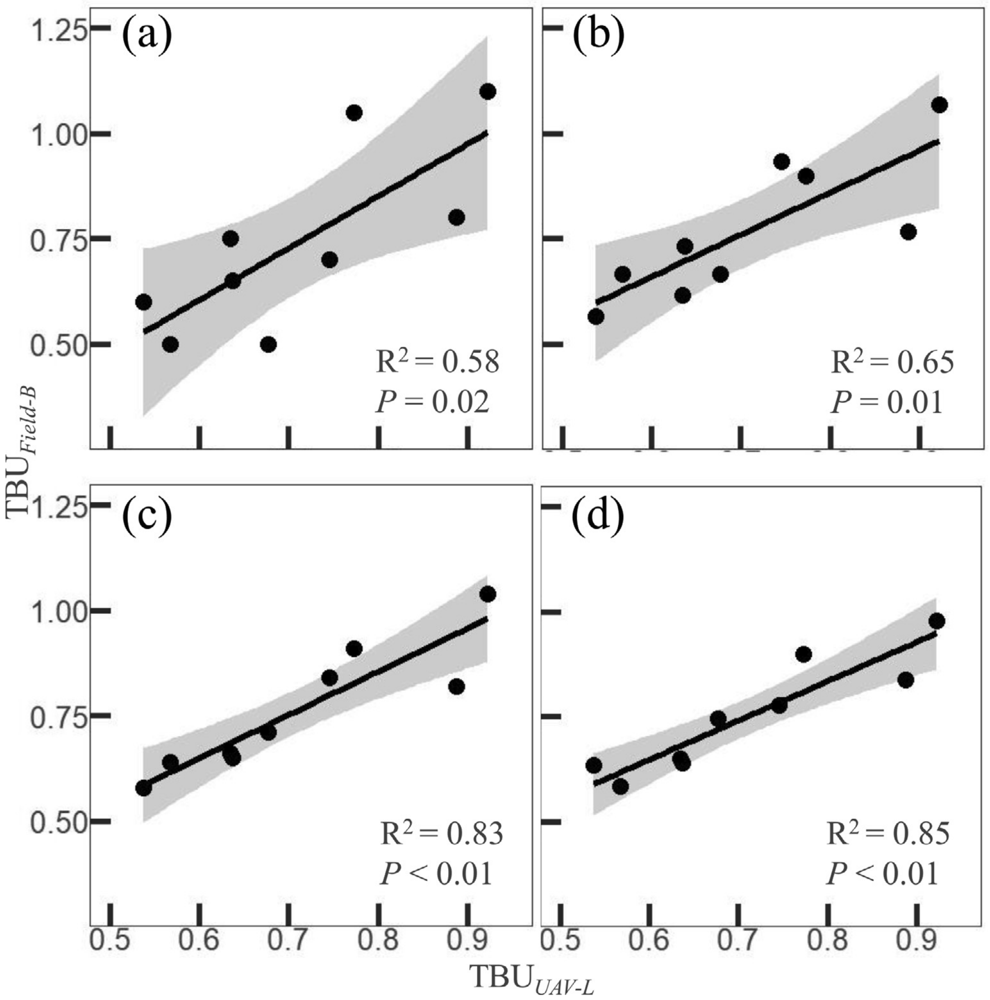

Fig. 7. Relationships between estimated terracette density based on orthomosaic photograph resampling (TBU_{UAV-L}) and traditional field sampling ($TBU_{Field-B}$) at a plot scale using (a) one; (b) three; (c) five; and (d) nine belts, respectively.

$P < 0.05$ level) (Fig. 4). This was in agreement with the results of Howard and Higgins (1987) that the spacing among the terracettes varied with changes in the hillside slopes. Therefore, we can reasonably speculate that the formation and maintenance of terracettes are largely attributed to the activities of livestock, which can be regarded as ecosystem engineers (Gilad et al., 2004; Jones et al., 1994), although we could not elucidate the complete formation process based on the present study.

The pattern of variations in terracette structure among the grazed and un-grazed plots in different topographic setting (Table 1 and Fig. 4) suggest that both topography and grazing affect terracettes. In the present study, the study area featured greater potential evaporation than rainfall, and lower soil water content and higher surface temperature on the south slope than the north slope. Moreover, the differences increased with increasing slope based on monitoring of these fields in 2010–2011 (Duan, 2011) and monitoring data in 2013–2015 (unpublished data, Hu, personal communication). This could result in harsh environments on south hillslopes, reducing vegetation growth

Table 1

Densities of vegetation patches and terracette basic units in grazed and un-grazed plots with different aspect and slope.

Land-use pattern	Aspect	Slope	TBU_{UAV-L}	TBU_{UAV-B}	$TBU_{Field-B}$	$VBU_{Field-B}$
Grazed		0°				1.3 ± 0.3a
	North	15°				1.6 ± 0.3a
		30°	0.7 ± 0.1a	0.7 ± 0.2a	0.7 ± 0.2a	0.7 ± 0.2a
		45°	0.9 ± 0.1a	0.9 ± 0.2a	0.9 ± 0.2a	0.9 ± 0.2a
	South	15°				1.6 ± 0.3a
		30°				1.7 ± 0.4a
		45°	0.6 ± 0.1b	0.6 ± 0.2b	0.6 ± 0.2b	1.1 ± 0.3a
Un-grazed		0°				1.2 ± 0.2a
	North	15°				1.6 ± 0.3a
		30°				1.2 ± 0.4a
		45°				1.4 ± 0.4a
	South	15°				1.6 ± 0.3a
		30°				1.6 ± 0.4a
		45°				1.6 ± 0.4a

Table 2

Summary of the analysis of variance on vegetation cover on land-use pattern (un-grazed *vs.* grazed) with additional factorial treatments of aspect and slope. Bold values are significant at $P < 0.05$.

Source	Df	F	P
Land use pattern	1	51.629	**< 0.001**
Aspect	1	5.588	**0.025**
Slope	3	7.614	**< 0.001**
Land use pattern × Aspect	1	0.001	0.981
Land use pattern × Slope	3	3.356	**0.033**
Aspect × Slope	2	0.102	0.904
Land use pattern × Aspect × Slope	2	0.866	0.431

and forage supply for livestock foraging, and the lower vegetation cover on the south slope confirmed this (Fig. 5a). Moreover, low forage supplies could cause a decrease in livestock dwelling time in these areas, and more frequent occurrences of animals veering from the track to browse and ingest more food per unit time (Jin et al., 2016; Manousidis et al., 2016). It is difficult to develop mound-like structures (Bochet et al., 2015; Jin et al., 2016) to form bands of fertility (Jin et al., 2016; Stavi et al., 2008a). Therefore, it is understandable that no terracettes existed on flat (0°), low-slope (15°) or Sou-30° areas. Meanwhile, there were less developed tracks in the Sou-45° area ($\text{TBU}_{UAV\text{-}L} < \text{VBU}_{Field\text{-}B}$; Table 1) and well-developed tracks in the Nor-30° and Nor-45° areas in this experiment (Table 1). These findings agree with the perspective of Jin et al. (2016) of a positive feedback loop of the maintenance of the track structure.

4.2. *Relationship between terracettes and vegetation cover*

Grazing exclosures, as one of the most important methods of restoring degraded grassland, are widely applied in arid, semiarid, and alpine regions (Deng and Shangguan, 2014; Wu et al., 2009; Zhao et al., 2014). The direct results are to increase the vegetation cover of degraded pastures, which could help improve vegetation biomass and moisture content (Qiu et al., 2001; Sternberg et al., 2000; Wu et al., 2009). Our results were in agreement with previous studies that grazing exclosures resulted in higher vegetation cover values among aspects and slopes, except for case of 30°; Fig. 5). Meanwhile, along with the increases in vegetation cover, terracette disappeared after the 17-year-old fencing, and the average vegetation cover was 70% ± 6% (Fig. 5).

In the present study, we found that the vegetation cover increased up to ~70% and then decreased with increasing terracette density (Fig. 6). Considering the topographic characteristics associated with humidity and temperature, the results may suggest that terracettes help keep vegetation in good condition. However, this could change after the terracette density reaches a critical value (0.78 TBU/m in this study). The mechanism could involve the initial redistribution of vegetation, rather than reduction, induced by the terracettes (Oikawa et al., 1988; Stavi et al., 2008a), which then may be reversed after the terracette density reaches a critical value. In the first phase, the induction of vegetation redistribution may include complex physiological and biochemical processes (Bates, 1950; Jia et al., 2013; Stavi et al., 2008a). For example, Jin et al. (2016) revealed that soil organic carbon and total nitrogen were significantly higher in the shoulder segment than the track and interslope segments. Meanwhile, with gentler slopes, the track segments could receive about 1.4 times the precipitation per unit of surficial area than the nontrack segments, and the water captured under the tracks could contribute to plant growth in the shoulder segment due to hydrotropism (Eapen et al., 2005; Jin et al. 2016; Takahashi, 1997). Bates (1950) stated that trampling by the feet of ungulates induced redistribution of some grasses with growing points above the soil surface. Probably associated with increased grazing intensities, terracette density increased, and vegetation cover reached a maximum at an intermediate terracette density. Intermediate terracette densities may correspond to moderate competition- and disturbance-level gradients (Grime, 1973; McNaughton, 1983; Oba et al., 2001). That is before reaching a maximum, the benefits of soil and water conservation (which are critical factors for vegetation cover in arid areas) increase with increasing terracette density. However, after the maximum, vegetation cover began to decline. One possible reason is that the increase in bare areas (i.e., track and interslope segments) develops faster than the vegetation cover derived from the benefits of soil and water conservation. Another potential reason could be the higher foraging intensity within the limited areas of the shoulder segment (Grime et al., 1987; McNaughton, 1983), even under preferable hydrothermal conditions (e.g., the case of Nor-45°-grazed in the present study).

Although rangeland management practitioners appear aware that terracette landscapes respond and reflect grazing strategies (e.g., the density of terracettes decreased after the implementation of the GLG policy, and personal communication with the local herdsman). However, to date, no quantified criterion exists for reference. Although more factors should be considered, the threshold (0.78 TBU/m, 70%) can be considered as a direct principle of this, because vegetation cover is similar to the average un-grazed value under suitable environments (Figs. 5 and 6). Studies have revealed several advantages of terracettes (Jin et al., 2016; Stavi et al., 2008a). Given their microtopography and possible hydrotropism, Jin et al. (2016) argued that terracettes provide water to plants along the shoulder segment through both surface runoff and groundwater. Meanwhile, they induce animal grazing in ways that reduce energy expenditure and increase foraging efficiency (Jin et al. 2016; Lachica et al., 1997). Tracks typically follow near-horizontal orientations and have high water conserve capacities (Jin et al., 2016; Oikawa et al., 1988). Associated with lower bulk densities and concentrated plant structures, shoulder segments help slow down and store surface runoff, and reduce water loss and soil erosion (Stavi et al., 2008b). Moreover, the track segment associated with a higher bulk density may increase the mechanical stability of the loessial structure, reducing the occurrence of geological disasters (Li et al., 2009).

In general, existing terracettes with appropriate grazing can balance environmental conservation and husbandry productivity to benefit the sustainability of arid and semiarid grassland systems.

4.3. *Advantages of UAV for terracette landscape study and monitoring*

Terracette landscapes are widespread on hilly rangelands in arid, semiarid, humid, and alpine regions (Jin et al., 2016; Radcliffe, 1968; Stavi et al., 2008a; Watanabe, 1994). Studies have shown that terracette structure affect the physical and chemical properties of soil (Hiltbrunner et al., 2012; Jin et al., 2016; Stavi et al., 2008a), as well as vegetation composition and productivity (Jin et al., 2016; Joshi et al., 2006). Therefore, measuring the characteristics of terracette structure and monitoring their changes are necessary.

Traditionally, the spatiotemporal dynamics of terracettes have been monitored with aircraft photographs (Oikawa et al., 1988). However, the use of aircraft is usually associated with high cost, low flexibility (e.g., limited by the air route, weather, height, and resolution), and low accuracy (e.g., the tire tracks in the present study would have been easily mistaken for terracettes without the high-resolution images) (Fig. S1). Field sampling represents another traditional method (Jin et al., 2016; Stavi et al., 2008a), and require large investments in labor, time, and financial support. Furthermore, this method can cause man-made disturbances during the course of long-term monitoring. For example, the legible tracks around the fencing, even in the flat area, were caused by repeated walking of shepherds, as well as field vegetation and soil sampling. Ecological studies usually require long-term repeated monitoring (Jorgenson et al., 2015); however, traditional methods have significant limitations for long-term repeated monitoring.

Differing from traditional methods, UAV monitoring can more accurately monitor landscape fragmentation and pasture characteristics at a suitable scale (Sternberg, 2012; Yi, 2017). The FragMAP tool generates orthomosaic photographs containing detailed geographical information based on the 'mosaic' flight path (Yi, 2017). Thus, it makes resampling and retrieval of necessary information from the resulting orthomosaic photographs effortless (Fig. 3). Moreover, the information is reliable at belt and quadrat scales (Table 1), and it is more accurate to estimate at a plot scale (Fig. 7). Meanwhile, the multi-scale estimation can be more accurate for judging the presence or absence of terracette landscapes (e.g., they could be identified at a plot scale for Sou-45°, but this was difficult at belt and quadrat scales). For each set of way points, multiple flights can be undertaken at different times to realize repeated monitoring (Yi, 2017). Moreover, the application of FragMAP can greatly decrease the field work time and intensity. For example, the FragMAP field work required only one-tenth of the time required for traditional field sampling. Furthermore, the field work resulted in no human disturbances and the variety of sampling methods helped improve the accuracy of the results (Fig. 6).

Overall, UAV has the key advantage of a high frequency of monitoring at multiple scales, which could help studies of the dynamics of terracettes and their ecological function with low investment and no human disturbance (Chen et al., 2016; Colomina and Molina, 2014; Yi, 2017). As a limitation of the UAV method, based on the mosaic flight path, it is difficult to identify and monitor changes in plant species composition and soil characteristics, which are important parameters for determining the formation and maintenance of terracette landscapes. Hence, we recommend further exploration of UAV-based methods to resolve these issues and to better understand the maintenance of these landscapes and the key mechanisms underlying the formation and maintenance processes of terracette landscapes.

5. Conclusions

Livestock trampling is likely the fundamental process that maintains the structure of terracette landscapes; it may also be an important mechanism, modulated by topography, for terracette landscape formation. Along with hydrothermal conditions, vegetation cover increased and then decreased with decreasing space among terracettes, with a threshold of ∼0.78 TBU/m, while that of vegetation cover was ∼70%. UAV technology could effectively and accurately monitor and analyze terracette landscapes at a low cost with no disturbance. Therefore, UAV technology can be used for long-term repeated monitoring to clarify terracette formation processes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.105839.

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