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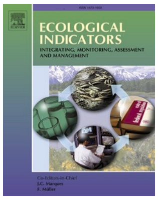

Original Articles

Impacts of alpine shrub-meadow degradation on its ecosystem services and spatial patterns in Qinghai-Tibetan Plateau

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ABSTRACT

Alpine shrub-meadow is an important ecosystem type on the Qinghai-Tibetan Plateau, providing a variety of ecosystem services while supporting the livelihoods of pastoralists. However, there is a clear lack of understanding of the changes in spatial patterns and ecosystem services of alpine shrub-meadow degradation. This study combined aerial photography and ground surveys to investigate and analyse the impact of degradation on the spatial patterns of alpine shrub-meadow and their ecosystem services, and the relationships between the spatial patterns and ecosystem services. The results showed that degradation led to fragmentation and patchiness in alpine shrub-meadow, as evidenced by a decrease in the proportion of shrub and meadow area and average patch size, as well as the complexity of patch boundaries and shapes. Light and moderate degradation reduced all ecosystem services in alpine shrub-meadow, with carbon storage, nutrient supply and water retention services decreased by an average of 27.4%, 17.3% and 13.8% respectively, while forage supply services decreased by 65.2% at heavy degradation, and the reduction in alpine meadow ecosystem services was even greater. Regulating services increased again at heavy degradation due to the accumulation and slow decomposition of plant underground roots, and rodent activity. The spatial patterns of the meadow layer were more closely related to its ecosystem services than the shrub layer, and fragmentation and patchiness were positively related to ecosystem services. Our findings suggest that the impact of degradation on alpine shrub-meadow ecosystem services may be non-linear and that the relationships between spatial patterns and ecosystem services need to be interpreted with caution and should be analysed comprehensively with a wider range of influencing factors. Our results have implications for grassland restoration and ecosystem service management on the Qinghai-Tibetan Plateau.

1. Introduction

Grassland covers 40% of the earth's surface and plays a critical role in biodiversity conservation, climate and water regulation, and global biogeochemical cycles. It provides a wide range of ecosystem services for humankind, including food provisioning, water supply and retention, carbon storage, climate regulation, pollination and cultural service (Suttie et al., 2005; O'Mara, 2012; Wilsey, 2018). Grassland degradation has spread around the world and is increasing in extent and degree, with roughly 49% of the world's grasslands already degraded to some extent (Abberton et al., 2010; Gang et al., 2014; Gibbs and Salmon, 2015). It causes enormous environmental problems and poses a great threat to humans who depend on it for food, fuel and medicine, as well as for cultural values (Bayer, 2017; Bengtsson et al., 2019; Bardgett et al., 2021).

Degradation changes the structure and function of grassland ecosystems, which in turn affects the delivery of ecosystem services (ES). For example, grassland degradation alters water supply by affecting water infiltration rates and storage capacity (Lemaire et al., 2011; Dai et al., 2020), and the loss of soil organic carbon and release of CO_2 can alter climate regulation service (Liu et al., 2018), the decline in vegetation cover and the increase in the area of bare ground will reduce the erosion prevention services of grassland (Fu et al., 2011), while the decline in productivity of grassland directly affects its fodder production services (Bengtsson et al., 2019). Various studies have analysed the loss of grassland in the agro-pastoralist zone of northern China and the impact of grazing pressure on typical grassland ecosystem services in the Inner Mongolia region of China (Li et al., 2021c; Liu et al., 2021a). Degradation and reduction of grassland in arid and semi-arid areas significantly reduces carbon stocks, biodiversity and biomass, and

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exacerbates direct conflicts between regulating services and livestock production services (Qi et al., 2017; Mbaabu et al., 2020). Degraded grassland, even after restoration, still struggle to reach non-degraded levels of biodiversity and ecosystem services (Ren et al., 2016).

The Qinghai-Tibetan Plateau (QTP), also known as the “Third Pole”, is the highest plateau in the world, with an average altitude of over 4,000 m and an area of nearly 2.5 million km^2. QTP acts as an important reservoir for water, regulating climate change and water resources in east Asia and even for the whole world (Qiu, 2008; Immerzeel et al., 2010; Yang et al., 2011; Yao et al., 2012). Alpine grassland is an important reservoir of biodiversity (Dong et al., 2017; Mi et al., 2021), and an important carbon sink on the QTP, storing a total of 7.36 Pg C in the top 1 m depth (Yang et al., 2008), with alpine meadow storing roughly 26% of the total carbon in Chinese grassland (Ni, 2002). It is also the bearer of livestock activities and an essential material basis for the livelihoods of the 5 million herders on the plateau (Harris, 2010). However, it has been observed that 90% of the alpine grassland on the QTP has been degraded in recent decades, with 35% of the area being severely degraded (Harris, 2010; Miehe et al., 2019). The degradation of alpine grassland causes a range of ecological effects and consequences, including the decline in plant diversity and productivity, reduction in soil nutrients (Liu et al., 2018), increasing greenhouse gas emission (Su et al., 2015) and the risk of soil erosion (Miehe et al., 2019), and eventually leading to the loss of the ecosystem services. There are many studies on the changes in the provisioning and regulating services of alpine grassland, such as the use of models to evaluate the spatial characteristics of the regulating services of alpine pastures on the QTP (Li et al., 2015b), of the impact of alpine grassland degradation on ecosystem services based on plot surveys (Wen et al., 2013a), and the trade-offs between ecosystem services in alpine grassland (Xu et al., 2019).

Alpine shrub-meadow is one of the most widespread vegetation types on the QTP. It is often found on the shady slopes of mountains at 2500–4000 m above sea level and on the terraces of river valleys where the water table is high, accounting for 4% of the total plateau area (Yashiro et al., 2010). Alpine shrub-meadow has different ecological structures and functions from alpine meadow, manifested in water retention, water supply and carbon sink (Li et al., 2016; Dai et al., 2021; Li et al., 2021a). It is often used as summer pastures and is important for the livelihoods of pastoralists. Thus, it has a significant role to play in the delivery of ecosystem services on the QTP. Degradation of alpine shrub-meadow has occurred due to the short grazing periods and high grazing pressure during summer, which observed in the northeastern QTP (Dai et al., 2020), however, there is currently insufficient attention to this issue, particularly in terms of knowledge of changes in its ecosystem services.

Grassland degradation also causes changes in surface spatial patterns, such as soil cracking, fragmentation of grassland patches and the expansion of black soil beach (Qin et al., 2018; Niu et al., 2019; Song et al., 2020). The spatial pattern of grassland is the most direct response to changes in plant communities, soils and topography, such as vegetation cover, which is a simple pattern indicator that captures the degradation of grassland. However, the spatial pattern information of degraded grassland is not well described and understood in previous studies. Traditional ground-based surveys have the disadvantages of being time-consuming and costly, as well as damaging the ground surface, while satellite remote sensing data have overcome these problems to some extent, but their application is still limited due to the coarse spatial and temporal resolution (Qin et al., 2020). The rapid development of unmanned aerial vehicle (UAV) technology in recent years has opened up new opportunities for ecological research, with the advantages of rapid revisits, high spatial resolution and low cost, which make up for the shortcomings of traditional satellite remote sensing data and ground-based surveys (Anderson and Gaston, 2013; Manfreda et al., 2018). UAV can identify spatial pattern characteristics of micro-patches and specific feature types (e.g., rodent burrows) in alpine grassland (Anderson and Gaston, 2013; Qin et al., 2018; Tang et al., 2019). However, there is still a lack of quantitative studies of spatial pattern changes in alpine shrub-meadow with complete degradation sequences.

Changes in grassland ecosystem services are influenced by biotic or abiotic factors such as plant communities, soils, hydrology and animals. Degradation affects ES provision indirectly by altering these elements. Spatial patterns, as a direct response to grassland degradation, are shaped and changed with implications for grassland ecosystem services (Wen et al., 2013b; Zhang et al., 2020). Various studies have analysed the relationship between the spatial pattern of alpine grassland and soil properties (Qin et al., 2018; Zhang et al., 2020; Li et al., 2021b) and plant community structure (Song et al., 2020), but the relationship between the spatial pattern of degraded alpine shrub-meadow and its ecosystem services is still poorly understood. The study of the relationship between landscape patterns and surface temperature and air pollution in urban ecology is intended to investigate the impact of urban spatial patterns on ecological functions, and to provide a reference for improving the urban environment for human habitation (Xu et al., 2021; Gao et al., 2022). Similarly, if we explore the spatial patterns of degraded alpine grasslands in relation to their ecosystem services, and identify the key pattern indicators and their characteristics that influence ecosystem services, we can contribute to the enhancement of alpine grassland functions.

This study attempts to test two hypotheses: (1) the degradation of alpine shrub-meadow alters their ecosystem services; and (2) there is a correlation between the spatial pattern of alpine shrub-meadow and its ecosystem services. This study takes a typical degraded alpine shrub-meadow in the northeastern QTP as an example, and analyses changes in spatial patterns and ecosystem services through UAV and ground surveys. The objectives of this study were to quantitatively characterise the spatial pattern of degraded alpine shrub-meadow and ecosystem services at different levels of degradation, and to reveal the relationships between the two. The research results will provide a guideline for the restoration and management of degraded grasslands on the QTP.

2. Method and data

2.1. Study site

The study area is located on the northeastern part of the Qinghai-Tibetan Plateau, in the middle of the piedmont alluvial fan on the southern slopes of the Qilian Mountains, with flat topography and a slope of $< 5^\circ$, and an average altitude of 3320 m. The region has a typical plateau continental climate, with only two seasons: the warm season is cool and brief, and the cold season is cold and long. The average annual temperature is $-1.68\ ^\circ$C, with an extreme maximum of 27.8 °C and an extreme minimum of $-37.1\ ^\circ$C. The average annual precipitation is 590.1 mm, with most of the precipitation occurring between May and September, accounting for 80% of the annual precipitation (Cao et al., 2007). The main vegetation type is alpine shrub-meadow with two-layer structure, *Potentilla fruticosa* as the dominant species in the upper layer and an herbaceous layer dominated by *Korbresia humilis* in the lower layer.

The study area is used as a summer pasture by herders and is grazed from early June to mid-September each year. The grazing livestock are yaks and Tibetan sheep, together with a significant number of plateau pika (*Ochotona curzoniae*) in areas of severe grassland degradation. From north to south, grazing management has been divided into communal pastures (no control of livestock numbers at all), joint family pastures (usually 2–3 families grazing together) and family pastures (single-family grazing), separated by fences. According to our interviews with herders, such grazing management has been practised for at least 30 years, which has led to the degradation of alpine shrub-meadow and causing changes in surface landscapes and plant community structure (Dai et al., 2020).

2.2. Degradation classification of alpine shrub-meadow

The degree of alpine shrub-meadow degradation was classified as light degradation (LD), moderate degradation (MD) and heavy degradation (HD) using the cover of *Potentilla fruticosa* shrub, the number of plant species and the cover of bare soil. The three degraded sites were located in family pastures, joint family pastures and public pastures, respectively. In addition, a grazing exclusion site (100 m × 100 m) was selected as non-degraded (ND) alpine shrub-meadow (enclosed for more than 4 years) (Table 1) (Dai et al., 2020) (Fig 1).

Table 1
Classification of alpine shrub-meadow degradation levels.

Degradation level	Shrub coverage (%)	Species number	Bare soil coverage (%)
ND	50–60	24	–
LD	40–50	22	–
MD	5–10	26	–
HD	0	14	30–40

2.3. Field sampling

2.3.1. Sample plot setting for UAV and ground survey

We placed three plots (100 m × 100 m) in each degraded sample site, which were equidistantly distributed at an approximate interval of 50 m (Qin et al., 2019). In each plot, we placed three quadrats along the diagonal within it (Fig. 2), with three replicates. In addition, nine quadrats are evenly distributed in the ND in an "S" shape. Aerial photography and ground survey were carried out simultaneously, with the ground survey quadrat located in the centre of the aerial photography quadrat. The size of the aerial photography quadrat was 30 m × 30 m, and the size of the ground survey quadrat was 5 m × 5 m (for alpine shrub) and 0.5 m × 0.5 m (for alpine meadow), the total number of quadrats was 36.

2.3.2. Aerial photography

For each plot, a UAV (Phantom 4 Pro, DJI Innovation Company, China), controlled by DJI GS PRO software, was used to take photographs of the quadrats at a height of 30 m, with the camera looking down vertically. The Phantom 4 Pro has a camera with a 1/2.3″ CMOS sensor and 20 million pixels, the lens is 24 mm (35 mm format equivalent) with a wide (84°) field of view angle. We chose clear weather and light winds for our aerial photography work, which was carried out at around 12 a.m. on August 22–23, 2020. The flying height is 30 m, and the forward-overlap was set to 80%, and the side-overlap was 50% to yield an image covering about 37 m × 30 m, with a ground resolution of 1.5 cm per pixel.

2.3.3. Soil and plant sampling

In each quadrat of ND, LD and MD, the above-ground biomass survey was conducted in shrub and meadow at 5 m × 5 m and 50 cm × 50 cm respectively, while in the HD quadrat, it was conducted in the meadow and bare soil patches at 50 cm × 50 cm. The aboveground biomass of alpine meadow and bare soil was obtained by the standard harvesting method, and the plant species were divided into palatable and non-palatable forages. Above-ground biomass of alpine shrub was obtained using the standard plant method: three shrubs of large, medium and small stature were randomly selected within the quadrat according to their canopy size, and all fresh branches and leaves of the whole shrub were harvested as edible forage. Finally, they were brought back to the laboratory and dried at 65 °C for 48 h before being weighed and recorded.

Soil samples of 0–10, 10–20 and 20–30 cm were obtained near each plant survey quadrat, using a 7 cm diameter soil auger, and replicated three times per quadrat, for a total of nine replicates per sample plot. A small number of soil samples were first sealed in aluminium boxes and taken back to the laboratory to obtain the soil moisture content by drying method (Cui et al., 2019). The remaining soil samples were tested in the laboratory for soil organic carbon and soil total nitrogen respectively. Soil organic carbon was tested by the ferrous ammonium sulfate titrimetric method, and total soil nitrogen was tested using the semi-micro Kjeldahl method (Wu et al., 2017).

2.4. Data processing

2.4.1. Ecosystem services of alpine shrub-meadow

We used palatable aboveground biomass (PGAB), soil organic carbon (SOC), soil total nitrogen (TN) and soil water content (SWC) to represent forage supply service (FS), carbon storage service (CS), nitrogen supply service (NS) and water retention service (WR) in alpine shrub-meadow, respectively.

2.4.2. UAV data processing and surface type classification

The raw UAV photos were pre-processed using Agisoft PhotoScan to generate orthoimages, and then the images were classified into alpine shrub, alpine meadow and bare soil based on an object-oriented classification method. The classification process was based on eCognition 9.0 software and included two processes: multi-resolution segmentation and threshold method classification.

The multi-resolution segmentation had a segmentation scale of 15, and a shape and compactness parameter of 0.5, which were obtained by trial and error. Threshold method refers to a step-by-step classification process by selecting indicators that reflect key information about the image object, such as spectral, spatial and textural characteristics (Table 2), and combined with the thresholds of these indicators and the principles of the decision tree to classify images. Specific threshold ranges were obtained by comparing the accuracy of the target features and their classification results, and eventually obtaining empirical thresholds that are appropriate for different features. Those classification errors that are difficult to avoid and occur randomly during the automatic classification process are modified directly using the manual editing toolbar in the eCognition 9.0 software and finally exported as a vector file, which is processed comprehensively in the GIS software to obtain the final classification result.

320 ground truth samples of different landscape types (160 alpine meadow, 120 alpine shrub and 40 bare soil) randomly generated by GIS software were selected and identified in 45 quadrats to evaluate the classification accuracy. The results show that the average overall accuracy was 93.59 % and the Kappa coefficient was 0.91; these values satisfied the research requirements.

2.4.3. Selection and calculation of landscape pattern metrics

We selected eight landscape pattern metrics (LPMs) representing attributes of the landscape such as dominance, fragmentation, disturbance and connectivity (Table 3). The R package *landscapemetrics* (Hesselbarth et al., 2019) was used to calculate the LPMs.

2.5. Statistical analysis

All data in this study are presented as the average ±95% confident interval. A one-way analysis of variance (ANOVA) and a post hoc test of the Student-Newman-Keuls (SNK) test were performed using R 3.5.3 to compare averages of landscape patterns and ecosystem services across the different degradation stages at the $p < 0.05$ level. Spearman's rank correlation was used to study the relationship between the landscape patterns and ecosystem services of alpine shrub-meadow.

3. Results

3.1. Spatial pattern characteristics of degraded alpine shrub-meadow

Before HD, the number of patches (NP) and patch density (PD) of

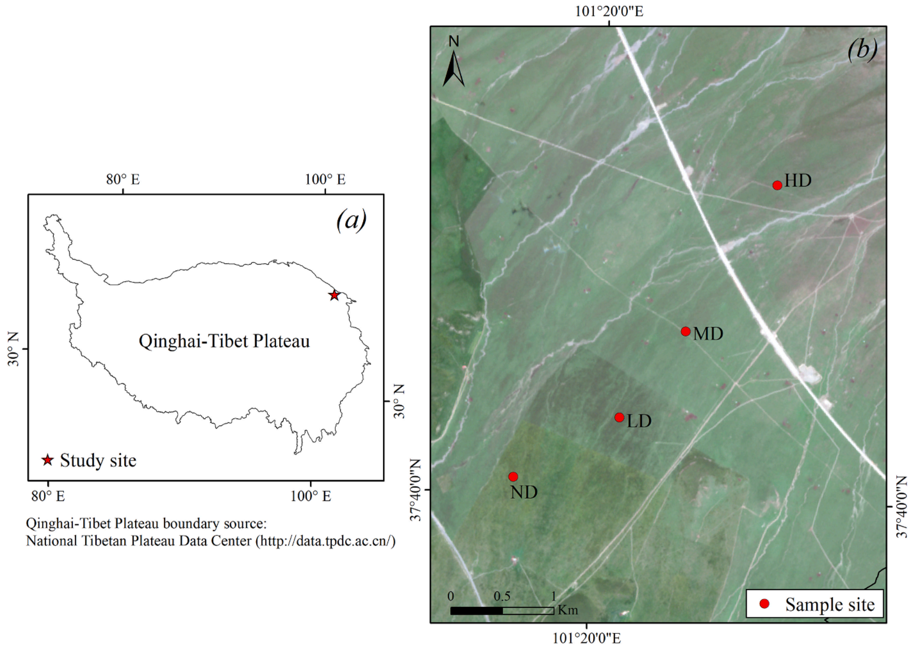


Fig. 1. Study site location. Note: ND (Non-degradation), LD (light degradation), MD (moderate degradation) and HD (heavy degradation).

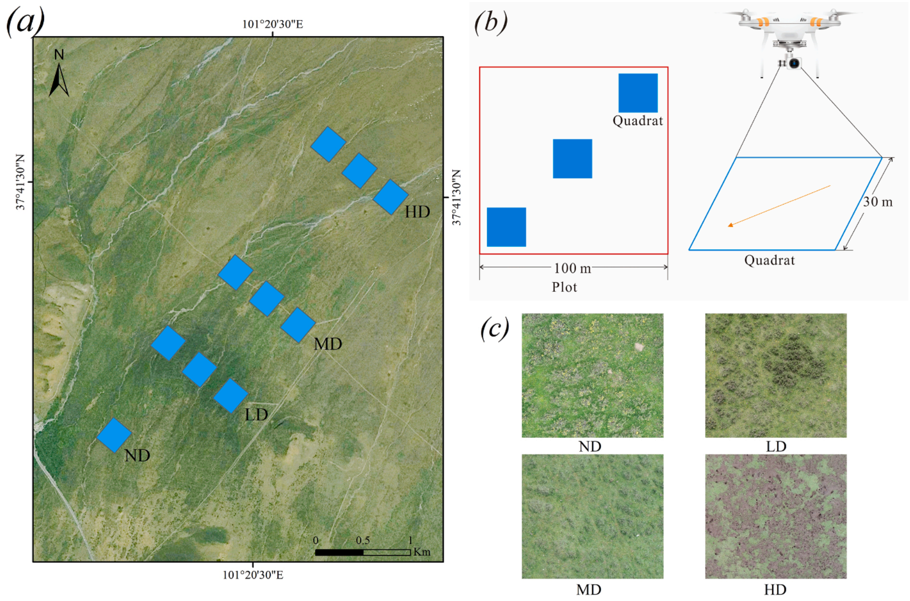


Fig. 2. Field sampling and UAV aerial photography. Note: a, b and c represent the location of the sample plots, aerial photography schematic and photographs of the surface landscape at different levels of degradation, respectively. ND (Non-degradation), LD (light degradation), MD (moderate degradation) and HD (heavy degradation).

Table 2
Feature parameters for surface type classification.

Features	Feature characteristics	Major purpose
Spectral information	Mean brightness	To classify alpine shrub and alpine meadow
	Excess green (EXG)	To classify vegetation and non-vegetation, alpine shrub and alpine meadow
Geometry information	Shape index	To classify alpine shrub and alpine meadow

alpine meadow decreased continuously, while they followed opposite trends in alpine shrub (except for a slight decrease in the PD at MD). At HD, the alpine shrub has completely disappeared from the surface and has been replaced by alpine meadow and bare soil, while the number and density of alpine meadow patches have increased rapidly (Fig. 3).

The percentage of landscape (PLAND) and the largest patch index (LPI) of alpine meadow and alpine shrub followed similar trends at different degradation levels. They did not change significantly at ND and LD, but at MD, PLAND of alpine shrub rapidly decreased to 6.3%, and alpine meadow increased to 93.7%, consisting almost of an individual patch. The average area (Area_MN) of alpine meadow patches increased rapidly to 3.94 m^2 at MD, while alpine shrub decreased to 0.02 m^2. At HD, the proportion of bare soil area increased rapidly to 39.1%. At this

Table 3
Calculation of the selected landscape metrics and their interpretation.

Metric/acronym	Calculation/unit/description	Indication
ED (Edge Density)	Calculation: the edge density equals the sum of all edges of class *i* in relation to the landscape area. Unit: m/m^2 Description: equals ED = 0 if only one patch is present (and the landscape boundary is not included) and increases, without limit, as the landscapes becomes more patchy	Fragmentation Disturbance
ENN_MN (Mean of Euclidean Nearest-Neighbor Distance)	Calculation: ENN equals the distance (m) to the nearest neighbouring patch of the same type, based on shortest edge-to-edge distance. Unit: m Description: approaches ENN_MN = 0 as the distance to the nearest neighbour decreases, i.e. Patches of the same class *i* are more aggregated. Increases, without limit, as the distance between neighbouring patches of the same class *i* increases, i.e. patches are more isolated.	Connectivity
LPI (Largest Patch Index)	Calculation: it is the percentage of the landscape covered by the corresponding largest patch of each class *i*. Unit: % Description: largest patch index at the class level quantifies the percentage of total landscape area comprised by the largest patch. As such, it is a simple measure of dominance.	Dominance
PD (Patch Density)	Calculation: PD equals the number of patches of the corresponding patch type divided by total landscape area. Unit: Number/m^2 Description: increases as the landscape gets more patchy. Reaches its maximum if every cell is a different patch.	Fragmentation
AREA_MN (Mean of patch area)	Calculation: the metric summarizes each class as the mean of all patch areas belonging to class *i*. Unit: m^2 Description: approaches AREA_MN = 0 if all patches are small. Increases, without limit, as the patch areas increase.	Composition Patch-structure
NP (Number of patches)	Calculation: number of patches in the landscape of patch type Unit: None Description: NP equals the number of patches of the corresponding patch type.	Fragmentation
PLAND (Percentage of landscape)	Calculation: proportion of the landscape occupied by patch type Unit: % Description: PLAND equals the percentage the landscape comprised of the corresponding patch type.	Dominance
LSI (Landscape shape index)	Calculation: LSI equals 0.25 times the sum of the entire landscape boundary and all edge segments within the landscape boundary involving the corresponding patch type, including some or all of those bordering backgrounds, divided by the square root of the total landscape area. Unit: None Description: a standardized measure of total edge or edge density that adjusts for the size of the landscape.	Disturbance

point, the LPI and Area_MN of alpine meadow declined rapidly as bare soil divided the alpine meadow patches (Fig. 3).

The edge density (ED) and landscape shape index (LSI) of the alpine meadow showed more fluctuating changes at different levels of degradation, decreasing from ND to MD, and increasing again at HD (Fig. 3). The ED of the alpine shrub showed a decreasing trend, while LSI showed a decreasing and then increasing trend. The ED and LSI of the bare soil were greatest at HD (Fig. 3). The linear distance (ENN_MN) between the alpine meadow patches reaches a minimum at MD, while the linear distance between the alpine shrub patches was increasing (Fig. 3).

3.2. *Ecosystem services changes to the degradation of alpine shrub-meadow*

3.2.1. *Ecosystem services changes of alpine meadow*

Soil organic carbon (SOC) at 0–30 cm soil depth in alpine meadow decreased with increasing soil depth at ND and HD, while it decreased before it increased at LD and MD. At 0–10 cm and 10–20 cm soil depths, SOC decreased significantly at LD and MD and then increased again to a maximum at HD. At 20–30 cm, the variations in SOC between the different levels of degradation were not significant (Fig. 4-a).

Soil total nitrogen (TN) at 0–30 cm soil depth in alpine meadow showed a decrease followed by an increase at different levels of degradation. The TN in the 0–10 cm soil depth reached a minimum at LD, which was significantly lower than that in MD and HD, while it reached a maximum at HD. At 20–30 cm it was also significantly lower at MD than at other levels and was greatest at ND (Fig. 4-b).

Soil water content (SWC) in alpine meadow decreased gradually at 0–30 cm soil depth, with relatively little variation between soil depths. SWC at 0–10 cm soil depth decreased significantly at LD and MD and reached a minimum at MD, while it continued to increase to a maximum at HD. SWC at 10–20 cm and 20–30 cm had similar characteristics to the 0–10 cm SWC (Fig. 4-c).

The palatable aboveground biomass (PAGB) in alpine meadow decreased continuously with increasing degradation and was significantly lower at HD than in other levels (Fig. 4-d).

3.2.2. *Ecosystem services changes of alpine shrub*

SOC of alpine shrub showed a decrease followed by an increase at different soil depths in LD and MD, and reached a maximum at 20–30 cm soil depth at ND and LD. SOC decreased at LD in 0–10 cm and increased again at MD, but none of the changes was significant. The trend was the same for 10–20 cm, while SOC continued to decrease at 20–30 cm soil depth and reached a minimum at MD, but again the change was not significant (Fig. 5-a).

TN in alpine shrub gradually decreased at different soil depths, it reached its lowest at LD in 0–10 cm soil depth, while it varied little at 10–20 cm and significantly reduced at LD in 20–30 cm (Fig. 5-b).

SWC in the alpine shrub showed a continuous decrease at different soil depths, and it was only significantly lower at MD than ND in 10–20 cm soil depth. It varied little between the different levels of degradation at other soil depths (Fig. 5-c). The PAGB in the alpine shrub was significantly reduced at MD (Fig. 5-d).

3.2.3. *Ecosystem services changes of bare soil*

The SOC and TN of the bare soil decreased as the depth of the soil

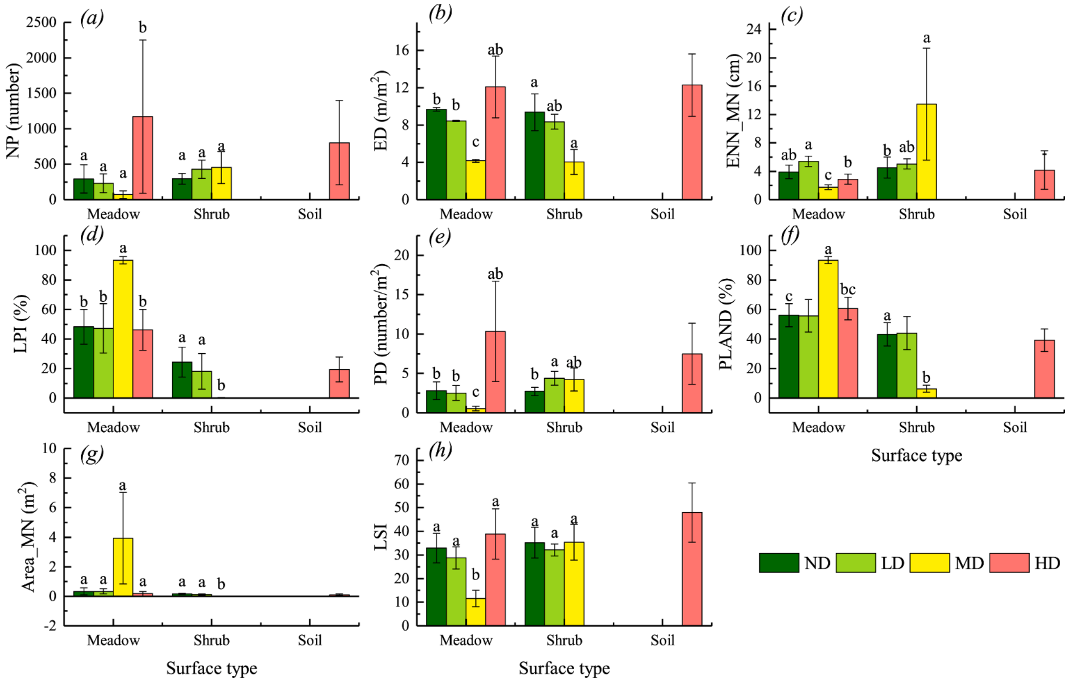


Fig. 3. Changes in the spatial pattern of alpine shrub-meadow at different levels of degradation Note: a to h represents NP, ED, ENN_MN, LPI, PD, PLAND, Area_MN and LSI of different surface types. Lower case letters represent significant differences ($P < 0.05$) in landscape patterns for the same surface type at different levels of degradation and error bars represent 95% confidence intervals.

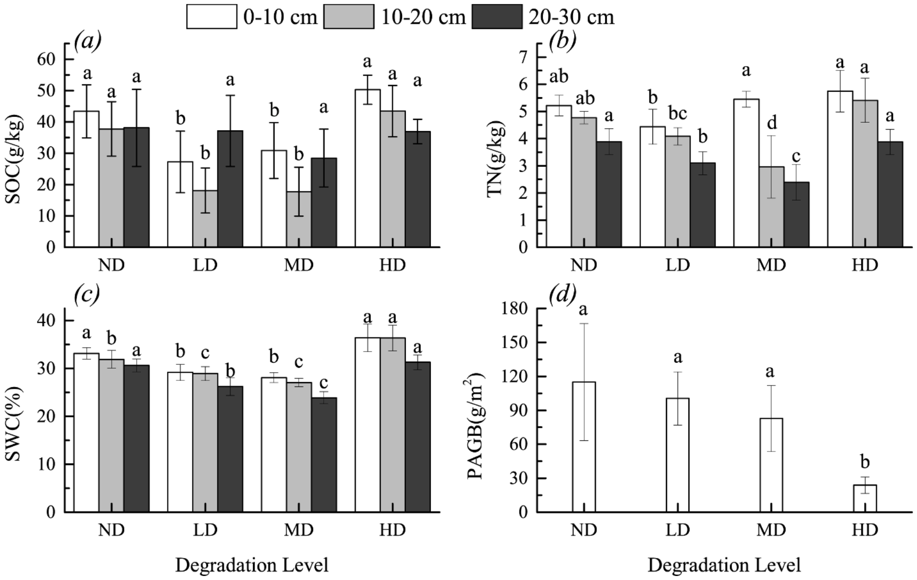


Fig. 4. Changes in alpine meadow ecosystem services at different levels of degradation. Note: a to d represents soil organic carbon, total nitrogen, soil water content and palatable aboveground biomass of alpine meadow at different degradation levels. ND, LD, MD and HD indicate non-degraded, light degradation, moderate degradation and heavy degradation, respectively. Lower case letters represent significant differences ($P < 0.05$) in ecosystem service for the same soil depth at different levels of degradation and error bars represent 95% confidence intervals.

layer deepened, while SWC reached its maximum at 10–20 cm, where PAGB was 23.70 g/m^2 (Fig. 6).

3.3. *The relationship between the spatial patterns and ecosystem services of degraded alpine shrub-meadow*

Except for nutrient supply (NS), other ecosystem services of alpine meadow were significantly correlated with the most landscape pattern features, with water retention (WR) and carbon storage (CS) have greater correlation coefficients with landscape patterns. Most landscape pattern features were significantly correlated with WR, CS and FS, while NP has the closest relationship with the ecosystem services of alpine meadow, followed by LSI, ED and PD (Fig. 7).

NP, LSI, ED and PD were significantly positively correlated with water retention and carbon storage services, while LPI, PLAND and Area_MN were significantly negatively correlated with them. Forage supply was significantly negatively correlated with NP and PD and weakly correlated with other landscape patterns, while nutrient supply was only weakly and significantly negatively correlated with ENN_MN.

Compared to alpine meadow, the ecosystem services of alpine shrub were not as closely related to landscape patterns, with each service only significantly correlated with one or two landscape patterns. The carbon storage of alpine shrub has significant positive and negative correlations with ED and PD, respectively. There is a significant negative correlation between nutrient supply and ENN_MN. Water retention and forage supply services, on the other hand, were significantly and positively

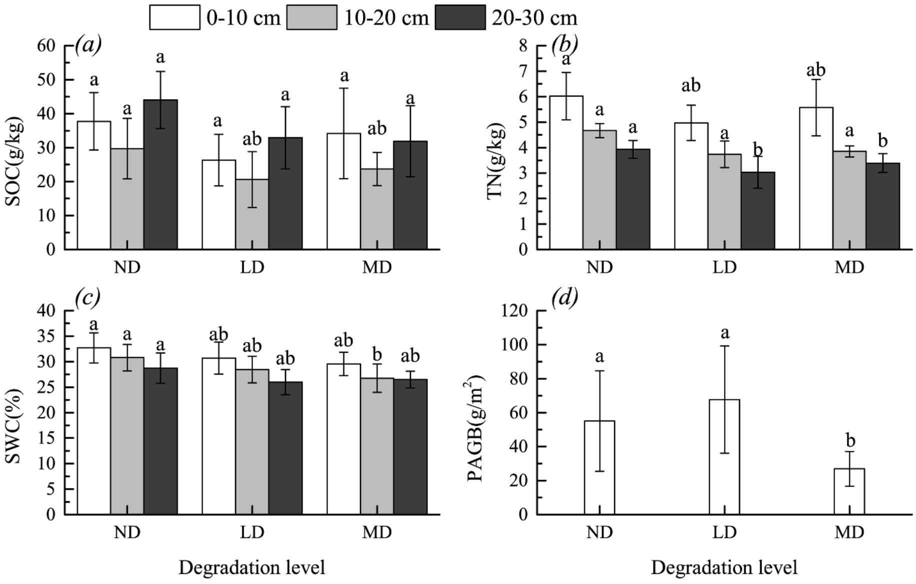


Fig. 5. Changes in alpine shrub ecosystem services at different levels of degradation. Note: a to d represents soil organic carbon, total nitrogen, soil water content and palatable aboveground biomass of alpine shrub at different degradation levels. ND, LD, MD and HD indicate non-degraded, light degradation, moderate degradation and heavy degradation, respectively. Lower case letters represent significant differences ($P < 0.05$) in ecosystem service for the same soil depth at different levels of degradation and error bars represent 95% confidence intervals.

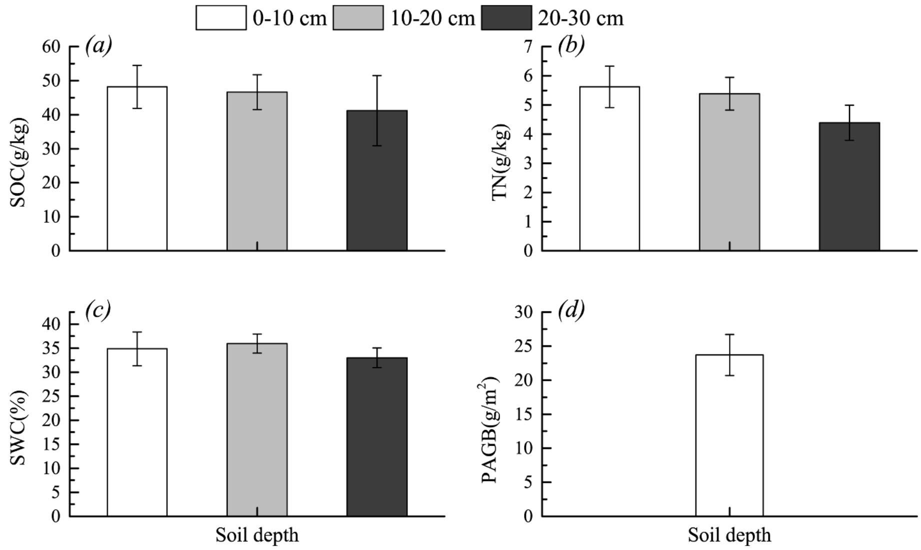
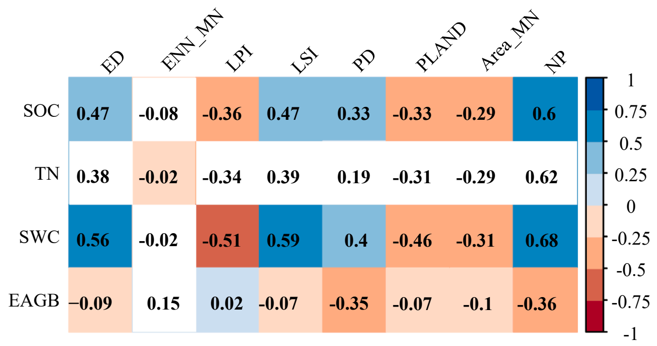


Fig. 6. Ecosystem services of bare soil in the heavy degradation level. Note: a to d represents soil organic carbon, total nitrogen, soil water content and palatable aboveground biomass of bare soil. Error bars represent 95% confidence intervals.



	ED	ENN_MN	LPI	LSI	PD	PLAND	Area_MN	NP
SOC	0.47	-0.08	-0.36	0.47	0.33	-0.33	-0.29	0.6
TN	0.38	-0.02	-0.34	0.39	0.19	-0.31	-0.29	0.62
SWC	0.56	-0.02	-0.51	0.59	0.4	-0.46	-0.31	0.68
EAGB	−0.09	0.15	0.02	-0.07	-0.35	-0.07	-0.1	-0.36

Fig. 7. The relationship between the spatial patterns and ecosystem services of alpine meadow. Note: coloured boxes represent significant correlations ($P < 0.05$).

	ED	ENN_MN	LPI	LSI	PD	PLAND	Area_MN	NP
SOC	0.43	-0.33	0.31	0.3	-0.16	0.2	0.36	-0.33
TN	0.28	-0.24	0.3	0.37	-0.08	0.13	0.21	-0.3
SWC	0.28	-0.21	0.49	0.13	-0.08	0.28	0.38	-0.52
EAGB	0.09	-0.27	0.04	0.09	0.18	0.26	0.08	-0.22

Fig. 8. The relationship between the spatial pattern and ecosystem services of alpine shrub. Note: coloured boxes represent significant correlations ($P < 0.05$).

correlated with LPI and LSI respectively, although the latter relationship was weaker (Fig. 8).

4. Discussion

Grassland degradation is often followed by fragmentation and patchiness (Harris, 2010; Liu et al., 2018). In this study, degradation drastically altered the spatial pattern of alpine shrub meadow, leading to fragmentation and complex patch boundaries and shapes. Using satellite and drone monitoring, previous studies have also found that grassland degradation at different spatial scales has also experienced fragmentation. For example, Li et al. (2020) suggest that spatial heterogeneity is a good indicator of the extent of grassland degradation. Prishchepov et al. (2021) found that Russian steppe experienced fragmentation from 1990 to 2018 due to anthropogenic or non-anthropogenic disturbances. Li et al. (2021b) suggest that external disturbances, mainly rodent population density, can cause fragmentation in alpine meadows.

Due to the small size of the study area, differences in environmental factors such as climate and topography are limited, while the different grazing regimes practised in the area are the main cause of the degradation of alpine scrub meadows and the changes in their spatial pattern, with prolonged uncontrolled grazing in public pastures leading to the most severe degradation occurring. The direct cause of fragmentation of alpine scrub meadows is the foraging and trampling by domestic animals during overgrazing (Sun et al., 2019). In addition, significant numbers of plateau pika (*Ochotona curzoniae*) activity have been observed in public pastures, and their range of behaviours have increased the number and size of bare soil patches (Qian et al., 2021).

Grassland degradation has generally caused a decline in ecosystem services, and this paper found that light and moderate degradation has led to a loss of various ecosystem services in alpine shrub-meadow. Grassland degradation has led to the loss of various ecosystem services such as biodiversity maintenance, carbon storage, nutrient regulation, and water conservation services, as evidenced by studies in regions such as Inner Mongolia and the QTP (Bai et al., 2012; Wen et al., 2013a; Wang et al., 2014; Fan et al., 2019).

Grassland degradation on QTP has reduced plant diversity and productivity (Liu et al., 2018), particularly the proportion of edible forage has declined significantly. Grassland degradation also reduces soil organic carbon and total soil nitrogen, with depletion rates that can reach 48 and 39% respectively (Liu et al., 2021b). Possible reasons for this include a decline in the amount of plant residues and root exudates as a source of soil organic matter, the destruction of soil aggregates leading to accelerated decomposition of soil organic matter (Dong et al., 2012; Abdalla et al., 2018) and a reduction in the number of leguminous species (Li et al., 2015a; Wang et al., 2015). In addition, grassland degradation can reduce soil moisture by changing physical properties such as soil texture and soil bulk density (Li et al., 2015a).

However, ecosystem services have also shown resilience in the face of grassland degradation, for example, this paper finds that the regulating services of shrub meadow increase again during the HD stage, and, not coincidentally, similar phenomena are found in other parts of the QTP. Studies have shown that soil organic carbon and soil water-holding capacity has remained high in the black soil beach at the heavy degradation stage of alpine meadow on the QTP (Zhang et al., 2018; Guo et al., 2019; Wang et al., 2019).

Plant root decay and decomposition may be responsible for the increase in soil organic carbon. The well-developed underground root system of alpine meadow, especially those represented by *Kobresia* meadow accumulates and thickens the meadow during the degradation process, forming the so-called grass felt layer, while the decomposition of dead roots and apoplastic matter further leads to an increase in soil organic carbon (Gill and Jackson, 2000; Rasse et al., 2005; Miehe et al., 2019; Dai et al., 2020). Changes in the physical properties of the soil caused by rodent activity may be responsible for the increase in soil moisture. At the HD stage of the alpine shrub-meadow, significant numbers of plateau pika can be observed and a range of disturbances lead to a decrease in soil compaction and soil bulk density, an increase in soil porosity that leading to an increase in water infiltration capacity and thus an increase in soil moisture (Dai et al., 2019; Dai et al., 2020). In addition, most studies have demonstrated a positive correlation between soil organic carbon and soil moisture in grassland (Yang et al., 2014; Dai et al., 2020) all of which contribute to the abnormal increase in ecosystem services in alpine shrub-meadow under the HD stage.

The plant communities and surface landscapes have changed dramatically during the degradation of alpine shrub-meadow and the provisioning services have continued to decline, while other regulating services have not continued to decline or even collapse, suggesting that grassland ecosystems are resilient (Teng et al., 2020). Therefore, in the restoration or management of degraded grassland on the QTP, a comprehensive assessment of their ecosystem service status should be carried out so that targeted measures can be taken, and more near-natural restoration measures can be adopted (Du et al., 2020; Liu et al., 2020).

This study found that the carbon storage and water retention services of alpine meadow are more closely related to its spatial patterns. Spatial pattern features representing fragmentation and disturbance (NP, PD, LSI and ED) were positively correlated with both services, while spatial pattern features reflecting size and dominance (PLAND and LPI) were negatively correlated with the services. The majority view is that landscape fragmentation has a negative effect on ecosystem services (Mitchell et al., 2015), while increased area dominance benefits ecosystem services (Yohannes et al., 2021). This is a direct result of the fact that the ecosystem services of alpine meadow were higher when the landscape is fragmented and less dominant (at the ND and HD stages) and lower when the alpine meadows become dominant and the patch size is larger (at the MD stage).

In this study, the interpretation of ecosystem service changes through spatial patterns is limited, especially the pattern characteristics at small scales monitored by drones. The root causes of changes in ecosystem services in alpine scrub meadows are complex effects of changes in the structure and biomass of above- and below-ground plant parts, as well as feedback from soil physicochemical properties to external disturbances, while spatial patterns may play an insignificant role. Therefore, the extent to which multiple factors influence ecosystem services should be explored in depth to distinguish the true role of spatial patterns.

In this paper, one provisioning service and three regulating services of alpine shrub-meadow were selected, but other services, such as biodiversity conservation service or cultural service, was not considered. Future studies could include more ecosystem services to assess changes in alpine shrub-meadow ecosystem services more comprehensively. In addition, this study lacks an in-depth analysis of changes in ecosystem services and the mechanisms by which they interrelate with landscape patterns. In particular, how changes in soil physical properties and vegetation below-ground root condition led to abnormal increases in ecosystem services at the HD level. Therefore, the physical and chemical properties of the soil, the structure of the plant community and the condition of the underground root system should be investigated in detail in future studies in order to provide a complete explanation of the mechanisms of change in ecosystem services.

5. Conclusion

This paper investigated and analysed the impact of alpine shrub-meadow degradation on its spatial pattern and ecosystem services on the Qinghai-Tibetan Plateau using ground surveys and aerial photography by UAV, and the relationship between the two. Degradation leads to fragmentation and patchiness of alpine shrub and alpine meadows: a decrease in the proportion of area and average size, as well as an increase in the distance between patches. Ecosystem services continue to decline in light and moderate degradation, while regulating services increase again in heavy degradation. The spatial pattern of alpine meadows is more closely related to their carbon storage and water retention services, but fragmentation and patchiness have a positive relationship with these services. This study indicates that the ecosystem services of alpine shrub meadows are resilient in the face of degradation and that a comprehensive assessment of their status is needed to develop targeted restoration measures. The relationship between spatial patterns and ecosystem services needs to be interpreted with caution, and a clear understanding of the true role of spatial patterns needs to be clarified through a more comprehensive analysis of multiple factors. The results of this study have implications for ecosystem service management and degradation restoration in alpine grassland on the Qinghai-Tibetan Plateau.

CRediT authorship contribution statement

Dawen Qian: Conceptualization, Methodology, Writing – original draft. **Yangong Du:** Supervision, Project administration, Funding acquisition. **Qian Li:** Resources, Writing – review & editing. **Xiaowei Guo:** Formal analysis, Validation. **Bo Fan:** Visualization, Data curation. **Guangmin Cao:** Supervision, Project administration, Funding acquisition.

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.

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Appendix A. Supplementary data

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