diversity

MDPI

Article

Ecosystem Service Relationships, Drivers, and Regulation Strategies in a Degraded Alpine Shrub Meadow on the Northeastern Qinghai-Tibetan Plateau

Dawen Qian [1,2,*], Bo Fan [2], Yuting Lan [2], Mengke Si [2], Qian Li [2] and Xiaowei Guo [2]

1 School of Geography and Tourism, Chongqing Normal University, Chongqing 401331, China
2 Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining 810008, China
* Correspondence: dwqian@nwipb.cas.cn

Abstract: One of the challenges of managing grasslands sustainably is the conflict between the different ecosystem services they provide. This is especially evident in the Qinghai-Tibetan Plateau (QTP) region, where fragile alpine ecosystems make balancing the needs of grassland conservation and development difficult. However, our current understanding of the relationships and drivers of ecosystem services in degraded alpine shrub meadows on the QTP is insufficient. To address this, we studied forage provisioning and water retention services in a degraded alpine shrub meadow in the northeastern QTP. We analyzed the changes and relationships between these services at different levels of degradation and identified those factors that influenced ecosystem service relationships. The results showed that the forage supply service and the water retention service of the alpine shrub meadow increased and decreased by 23.6% and 27.07%, respectively, due to degradation. The trade-offs between these two services varied depending on the degree of degradation, with light and moderate degradation showing a preference for water retention service, and heavy and extreme degradation showing a preference for forage supply. Water retention was constrained by forage supply and both services showed an exponential function form of decay. The physical and chemical properties of the soil in the alpine shrub meadow remained relatively stable during the degradation process, with only soil organic carbon (SOC), total potassium (TK), and total nitrogen (TN) decreasing significantly. SOC may have indirectly influenced the relationship between the two services by affecting water retention. This study provides insights into alpine shrub meadow management and conservation on the QTP.

Keywords: alpine shrub meadow; ecosystem service relationship; constraint effect; grassland degradation; Qinghai-Tibetan Plateau

Citation: Qian, D.; Fan, B.; Lan, Y.; Si, M.; Li, Q.; Guo, X. Ecosystem Service Relationships, Drivers, and Regulation Strategies in a Degraded Alpine Shrub Meadow on the Northeastern Qinghai-Tibetan Plateau. *Diversity* **2023**, *15*, 596. https://doi.org/10.3390/d15050596

Academic Editor: Mario A. Pagnotta

Received: 8 February 2023
Revised: 7 March 2023
Accepted: 23 April 2023
Published: 26 April 2023

1. Introduction

Ecosystem services (ES) can be defined as benefits arising from the interaction of multiple biotic or abiotic processes in an ecosystem that can be accessed directly or indirectly by humankind [1,2]. Ecosystem services can be categorized into four types: provisioning (materials and energy for humans), regulating (climate and disaster control), supporting (basic ecological processes), and cultural (social and cultural value). Grasslands cover 26% of the Earth's land surface, making them one of the most important ecosystem types on our planet [3]. They provide critical advantages for both the environment and human societies, including the conservation of biodiversity, climate and hydrological regulation, and global biogeochemical cycling [4]. Grasslands offer a range of ecosystem services, both material and non-material, that are invaluable to humans [5]. However, grassland degradation has become a severe global environmental problem, with almost half (49%) of the world's grasslands having already degraded to varying degrees [6–8]. The decline of grassland ecosystems presents a significant danger to those communities that rely on their resources, including food, fuel, fuelwood, and medicinal plants, as well as their cultural significance [9,10]. Moreover, grassland degradation has led to several ecological and environmental problems, such as the loss of carbon and nutrients, soil erosion, and biodiversity decline [5,9,10]. Consequently, conflicts between the provisioning and regulating services of grasslands are increasing, and the relationship between ecosystem services is becoming increasingly unbalanced [5,10].

Ecosystem service relationships refer to the study of the different types of relationships and their changing characteristics at spatial and temporal scales. These relationships include trade-offs, synergies, neutrality, and bundles between multiple ecosystem services [11,12]. Understanding these relationships can help decision-makers to manage the potential conflicts between services effectively [13]. Research on ecosystem service relationships in grasslands can be divided into two main categories, based on the means of investigation. The first category is based on remote sensing data and models. It assesses the characteristics of grassland ecosystem service relationships and their changes at global and regional scales through correlation analysis and spatial overlay analysis [14–16]. The second category is based on field investigations. It explores the effects of different grazing intensities, land management practices, and restoration measures on the relationships between the various grassland ecosystem services [17–21]. The Qinghai-Tibetan Plateau (QTP), also known as the “Roof of the World” or the “Third Pole”, is a crucial water and biodiversity conservation area in Asia and is also one of the most important grassland ranges found globally. Alpine grasslands, one of the most widely distributed vegetation types on the plateau, cover 60% of the total plateau area and serve as the material base and carrier of the ecological functions upon which herders depend for survival [22]. However, grassland degradation has become one of the key challenges on the QTP in recent years, with studies estimating that nearly 90% of grasslands on the plateau have been degraded to some extent, due to climate change and human activities [23]. The alpine shrub meadow is prevalent on the shady mountain slopes of the QTP, ranging from 2500 to 4000 m, and on the terraces of river valleys, occupying 4% of the total plateau area [24]. It consists of two vegetation types, namely, alpine shrub and alpine meadow. Alpine shrub meadows have different ecological structures and functions separate from alpine meadows, manifesting in water retention, water supply, and carbon sinks [25–27]. Usually, they are used as summer pasture, with the grazing period concentrated between June and September each year. However, the short duration and the increasing intensity of grazing have led to the degradation of alpine shrub meadows, especially in the northeastern QTP [26]. Unfortunately, there is still insufficient attention paid to this phenomenon. Currently, our understanding of the interconnections between ecosystem services in alpine shrub meadows is limited. The approach used to determine the type of relationship between these services relies primarily on correlation analysis, with little emphasis placed on identifying the causal relationships that exist. Consequently, we have an incomplete understanding of the constraints that influence the provision of ecosystem services. To address this gap in knowledge, more attention should be paid to identifying the underlying constraints that affect the relationships between ecosystem services. Scatter plots between two ecosystem services are usually distributed under a boundary line, known as the “constraint line” [28]. The constraint line represents the range or potential maximum of the distribution of response variables under the constraints or limitations of the variables on the x-axis [29]. This approach allows for the observation of the constraining effect of the constraining variable on the response variable, providing a new way to explore the interactions between ecosystem services [30,31].

Understanding the drivers of ecosystem service relationships is essential for regulating and managing ecosystem services [12]. Previous studies have mainly focused on explaining these relationships in terms of land use changes or climatic factors [32,33]. Similarly, studies on the drivers of ecosystem service relationships in grasslands have primarily focused on land management practices and grazing intensity [18,19]. However, there is still insufficient knowledge regarding the influence of environmental factors on the ecosystem service relationships of alpine shrub meadows.

In this study, we propose two hypotheses. (1) There are trade-off relationships between ecosystem services in alpine shrub meadows, which can be expressed through constraint lines. (2) Environmental factors influence the relationship between alpine shrub meadow ecosystem services. Our objectives are to characterize the types of relationships between services in alpine shrub meadow ecosystems and to clarify the main factors that influence these relationships. To achieve these objectives, we selected forage provisioning and water retention services in alpine shrub meadows of the northeastern Qinghai-Tibetan Plateau as key provisioning and regulating services. We analyzed the types of relationships between these services and their characteristics. Finally, we analyzed the influencing factors of service relationships using the soil's physical and chemical properties as environmental factors. Through this study, we aim to provide a better understanding of the complex relationships between ecosystem services in alpine shrub meadow ecosystems and to identify the factors that can be used to manage these relationships.

2. Materials and Methods

2.1. Study Site

The study site is located in Haibei Tibetan Autonomous Prefecture, Qinghai Province, China, and lies on the southern slope of the Qilian Mountains in the northeastern part of the Qinghai-Tibetan Plateau. The average altitude here is 3300 m and the average slope is less than 5 degrees. The climate of the study site is classified as a plateau continental climate, with an average annual temperature of −1.68 °C and an average annual precipitation of 590 mm [34]. The main vegetation types here are *Potentilla fruticosa* and *Korbresia humilis*, which together form an alpine shrub meadow habitat (Figure 1).

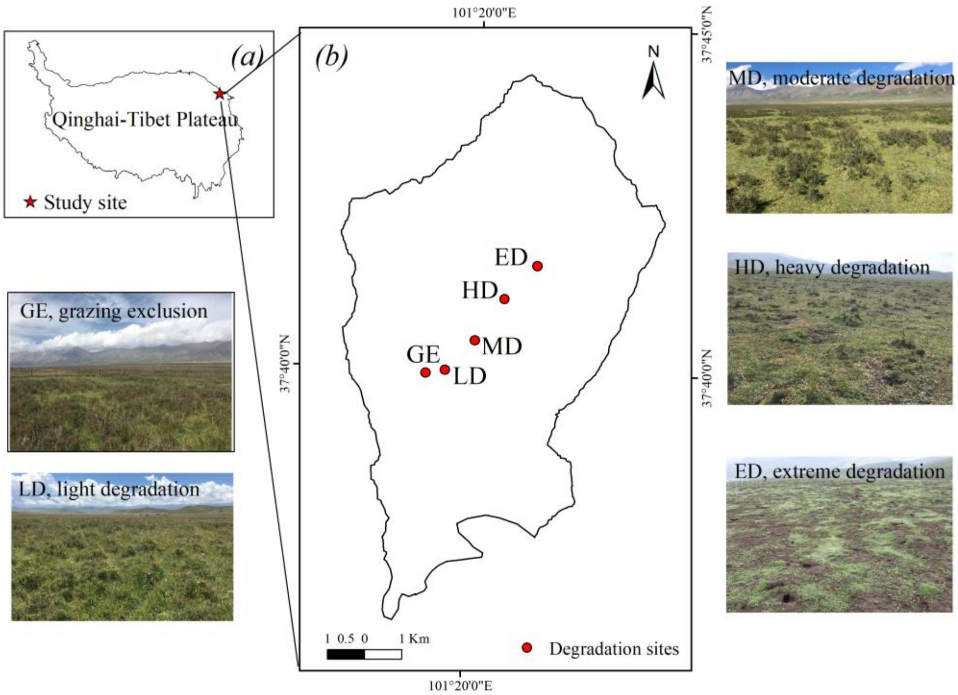

Figure 1. Location of the study site on the Qinghai Tibetan Plateau (**a**) and the sampling sites in a small watershed (**b**).

The study area is used as a summer pasture by herders, with grazing taking place from June to September each year. The area is also divided from north to south by three different grazing management systems: public pasture (no restriction on grazing intensity), communal family pasture (usually grazed by animals from 2–3 families together), and family pasture (single-family grazing animals). The main grazing animals are yaks and Tibetan sheep. The long-term practice of such different grazing management systems has led to different degrees of degradation of the alpine shrub meadow environment [26].

2.2. Field Sampling

2.2.1. Classification of Alpine Shrub Meadow Degradation Levels

We classified the degradation of alpine shrub meadow into four levels, based on *Potentilla fruticosa* shrub cover and the number of plant species: light degradation (LD), moderate degradation (MD), heavy degradation (HD), and extreme degradation (ED) (Figure 1 and Table 1) [26].

Table 1. Classification of alpine shrub meadow degradation levels.

Degradation Level	Shrub Coverage (%)	Species Number
LD	50–60	24
MD	40–50	22
HD	5–10	26
ED	0	14

Note: LD, light degradation; MD, moderate degradation; HD, heavy degradation; ED, extreme degradation.

2.2.2. Soil and Plant Sampling

We investigated the above-ground biomass in alpine shrub and alpine meadow environments through the random positioning of three 5 m × 5 m and 50 cm × 50 cm quadrats at the four degradation sites, respectively. The above-ground biomass of the alpine meadow was surveyed using the standard harvesting method, which involves cutting the plants close to the ground and separating the plant species into palatable and non-palatable forage. The above-ground biomass of the alpine shrub environment was surveyed using the standard plant method: based on the canopy size, we randomly selected three large, medium, and small shrubs in the quadrat, and subsequently cut fresh branches and leaves as edible forage [18,35]. Finally, the plant samples were taken back to the laboratory, dried for 48 h, and then weighed and recorded.

We collected both disturbed and undisturbed soil samples at depths of 0–10, 10–20, and 20–30 cm using a soil auger 7 cm in diameter and a soil bulk sampler with a stainless-steel cutting ring (5.0 cm diameter × 5.0 cm high) at three points randomly distributed across four degradation sites. The undisturbed soil samples were sieved to determine the soil bulk density (BD), soil total porosity (TP), and field capacity (FC). The disturbed soil samples were sieved to determine the soil organic carbon (SOC), soil total nitrogen (TN), total potassium (TP), total phosphorus (TK), available nitrogen (AN), available potassium (AP), and available phosphorus (AK).

Soil and vegetation sampling was repeated three times at each random point, for a total of 36 soil and vegetation samples, and the investigation was conducted in early August 2020.

2.3. Laboratory Analysis

We selected two representative ecosystem services found in alpine shrub meadows: forage supply (FS) and water retention (WR). Forage supply is the main provisioning service of grasslands on the Qinghai-Tibet Plateau, providing direct benefits to humans. Water retention is a vital regulating service provided by grasslands on the Qinghai-Tibet Plateau, serving as a significant carrier for the “Asian water tower” function [36]. This can be easily quantified and investigated.

2.3.1. Forage Supply

The forage supply service of grassland is usually considered to be the most effective forage intake of livestock [18]; however, since this data is difficult to obtain, we used the difference between the theoretical maximum forage supply of grassland and the existing above-ground forage biomass as a proxy. The theoretical maximum forage supply refers to the maximum forage supply potential that can be provided by the grass without resulting in grazing disturbance. We selected a long-term grazing exclusion (GE) site near the degraded areas as a reference and took its average above-ground edible biomass over the last 5 years as the maximum forage supply.

2.3.2. Water Retention

We used soil field capacity to represent the water retention service of alpine shrub meadows. The field capacity (FC) was obtained from the water content of undisturbed soil samples at −30 kPa, using a pressure plate apparatus after saturation in tap water for 48 h (1500 F1, Soil Moisture Equipment Corp.,Goleta, CA, USA).

2.3.3. Influencing Factors

Undisturbed soil samples were collected as ring cores and were subsequently saturated with tap water for 48 h. After saturation, the samples were transferred to a flat container filled with dry sand and left for 2 h. The samples were then weighed as M_1 (g). Finally, the samples were oven-dried at 105 °C until a constant mass was achieved and weighed as M_2 (g). The soil bulk density (BD), capillary moisture capacity (CMC), soil total porosity (TP (%)), and soil capillary porosity (CP (%)) were calculated using the following equation [37,38]:

$$BD = \frac{M_2 - M}{V} \tag{1}$$

$$CMC = \frac{M_1 - (M_2 - M)}{M_2 - M} \tag{2}$$

$$TP = (1 - \frac{BD}{ds}) \times 100 \tag{3}$$

$$CP = CMC \times \frac{BD}{V} \times 100 \tag{4}$$

where V is the volume of the steel ring core (cm^3), M is the weight of the steel ring core without a soil sample (g), and ds is the soil particle density (g/cm^3) [39].

Each disturbed soil sample was air-dried at room temperature and pulverized. The dried soil samples were sieved through a 2-millimeter-diameter metal mesh sieve, which allowed for the removal of as many large particles (stones and gravel), loose plant debris, and roots as possible, to be used for the analysis of soil organic carbon (SOC) and soil nutrients.

SOC was measured using the ferrous ammonium sulfate titrimetric method [18]. The soil's total nitrogen (TN) and available nitrogen (AN) were measured using the Kjeldahl procedure and the alkali diffusion method [40]), respectively. The total phosphorus (TP) was measured colorimetrically, after wet digestion with H_2SO_4 and $HClO_4$ (UV2800A ultraviolet spectrophotometer, Shanghai, China) [41]). TK was measured by flame photometry (model 2655-00 Digital Flame Analyzer, Cole-Parmer Instrument Company, Chicago, IL, USA), after the soil was digested with perchloric and nitric acid [42]. Available potassium (AK) was extracted by NH_4OAc and was later measured by flame photometry [42]. Available phosphorus (AP) was extracted by $NaHCO_3$ and was measured by Mo-Sb colorimetry [42].

2.4. Ecosystem Service Relationship

2.4.1. Correlation Coefficient

Spearman's rank correlation was used to study the relationships between the ecosystem services of alpine shrub meadows.

2.4.2. Root Mean Square Error

The root mean square error (RMSE) was applied to estimate the magnitude of the trade-offs between two or more ecosystem services [43]:

$$\text{RMSE} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(ES_i - \overline{ES})^2} \tag{5}$$

where ESi is the relative benefit of ecosystem service i, $\overline{\text{ES}}$ is the average of all sites for ecosystem service i, and n is the number of ecosystem services.

Relative ES was calculated as follows:

$$\text{Relative } ES = \frac{ES_i - ES_{i-\min}}{ES_{i-\max} - ES_{i-\min}} \tag{6}$$

where $ES_{i\text{-max}}$ and $ES_{i\text{-min}}$ are the maximum and minimum values for the actual amount of the ecosystem service of type i in all sampling plots.

RMSE quantifies the average difference between the standard deviation of individual ecosystem services and the mean standard deviation of ecosystem services, describing the degree of dispersion from the average. A larger RMSE value indicates a greater trade-off between different services, i.e., benefits are more skewed toward certain services.

2.4.3. Constraint Lines Extraction

In this study, constraint lines were extracted using the segmented quantile regression approach proposed by Mills et al. [29]. The specific steps of the method include: (1) dividing the range of values of the x-axis variables into equal sizes; (2) extracting the 99.95th quantile in each column as the boundary point; (3) selecting the appropriate regression model as the constraint line based on the shape of the scatter plot and the greatest goodness-of-fit (R^2) value. This study uses a constraint line to investigate the non-linear relationship between two ecosystem services in alpine shrub meadows, as well as the constraining effect of forage supply on water retention.

2.5. Analysis of the Influencing Factors for Ecosystem Service Relationships

Since the key to understanding ecosystem service relationships is in how regulating services respond to changes in provisioning services under direct human disturbance, we indirectly analyze the impact of environmental factors on ecosystem service relationships by investigating the relationships between soil properties and water retention service.

We used Spearman's rank correlation coefficients to test the relationship between soil attributes and water retention services. We also applied multiple linear regression (MLR) analysis to examine the relationship between soil properties and water retention. The adjusted coefficient (adjusted R^2) indicates the predictive ability of the MLR model. The relative importance of the different soil properties to WR was measured using a standardized coefficient (beta).

3. Results

3.1. Changes in the Water Retention and Forage Supply Services of Alpine Shrub Meadows at Different Degradation Levels

Forage supply and water retention services in the alpine shrub meadows showed opposite trends with increasing degradation, with forage supply continuing to increase and being significantly higher than other degradation levels at ED, while water retention continued to decrease from 35.7% at LD to 26.0% at ED (Figure 2)

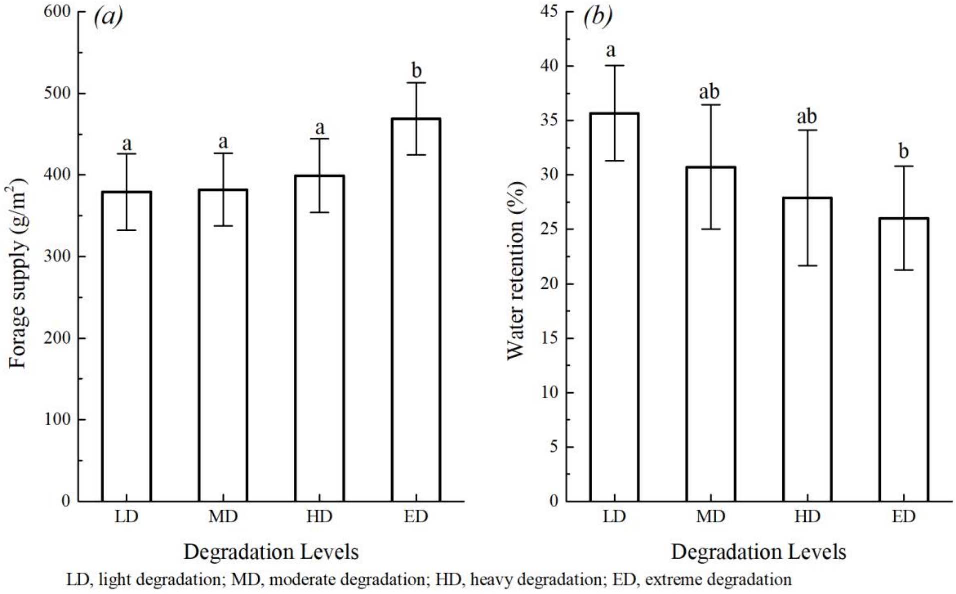

Figure 2. Changes in forage supply (**a**) and water retention (**b**) services in the alpine shrub meadow under different levels of degradation. Note: lower-case letters represent significant differences ($p < 0.05$) in ecosystem services at different levels of degradation; error bars represent 95% confidence intervals.

3.2. The Relationship between Water Retention and Forage Supply Services in the Alpine Shrub Meadow at Different Degradation Levels

A significant ($p < 0.05$) negative correlation was found between forage supply and water retention services in the degraded alpine shrub meadow (the correlation coefficient is −0.423). This means that the relationship between the two services is expressed as a trade-off under degradation.

The trade-off between forage supply and water retention showed a decrease, followed by an increase, with a continuous decrease in LD, MD, and HD and an increase in ED (Figure 3). The relationship between forage supply and water retention services at LD and MD is mostly above the reference line, with water retention dominating the trade-off relationship at these levels. About half of the HD areas and most of the ED areas have relationships below the reference line, with forage supply dominating the trade-off relationships below these levels (Figure 4).

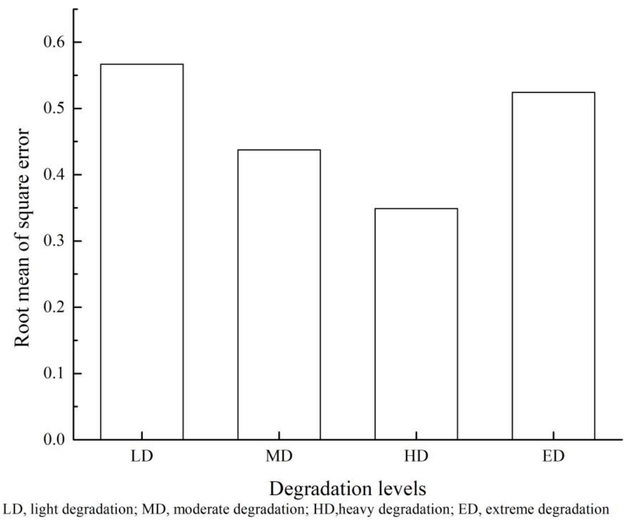

Figure 3. Changes in RMSE for forage supply and water retention services in the alpine shrub meadow.

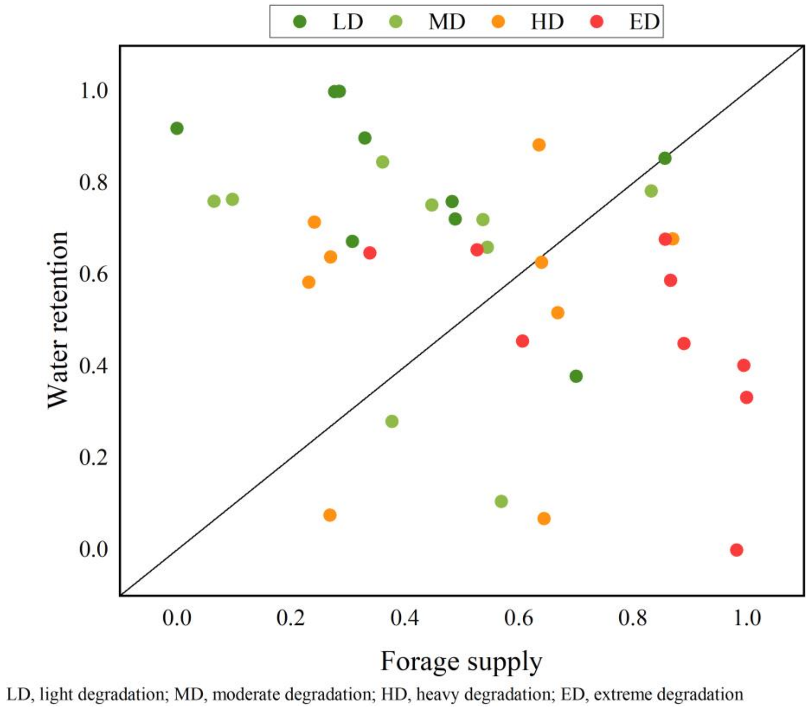

Figure 4. Scatterplot of the relative forage supply and water retention services in the alpine shrub meadow.

The constraint relationship between forage supply and water retention services in alpine shrub meadows can be described as a decaying exponential function, with a model fit R^2 of 0.484. The rate of decline of water retention services gradually increased as forage supply services increased, i.e., the constraining effect of forage supply on water retention increased (Figure 5).

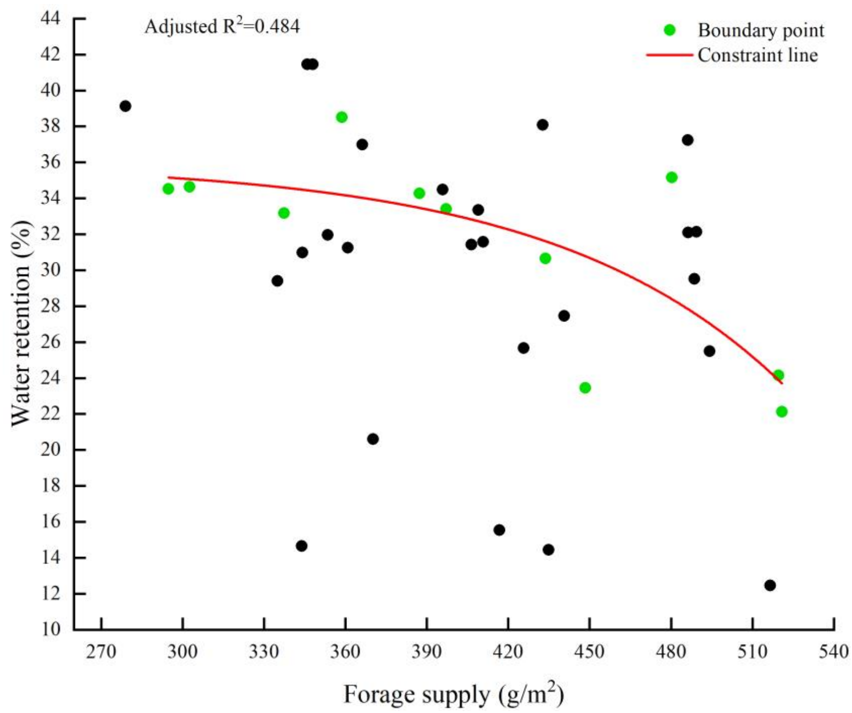

Figure 5. The constraint relationship between forage supply and water retention services in the alpine shrub meadow.

3.3. Influencing Factors of the Ecosystem Service Relationship in the Alpine Shrub Meadow

The effects of alpine shrub meadow degradation on soil bulk density and capillary porosity were not significant, while the changes in SOC were relatively pronounced, with a significant decrease at the MD level. The effects of alpine shrub meadow degradation on soil nutrients were variable, with significant effects on TN and TK, but not on the other indicators. TN and TK decreased significantly at the MD and HD levels, respectively (Figure 6).

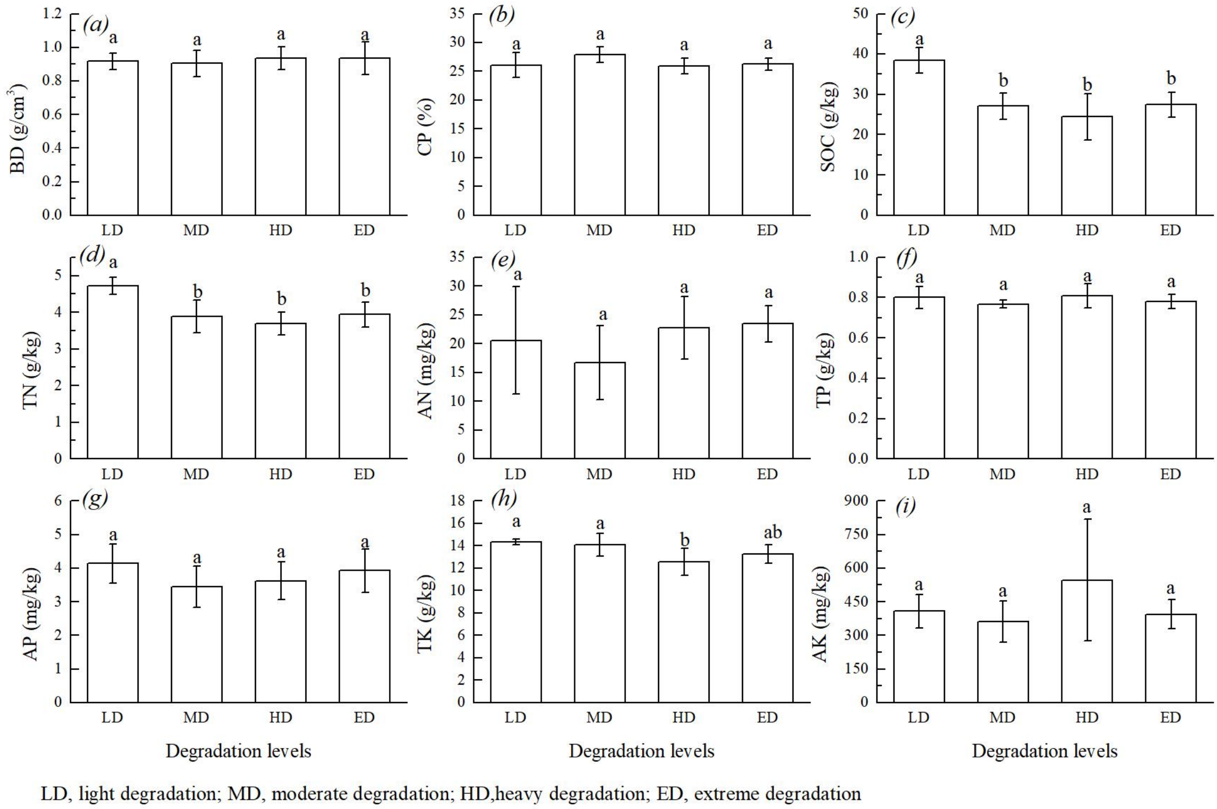

Figure 6. Changes in the soil properties of the alpine shrub meadow at different levels of degradation. Note: (**a**–**i**) represent soil bulk density (BD), capillary porosity (CP), soil organic carbon (SOC), total nitrogen (TN), available nitrogen (AN), total potassium (TP), available potassium (AP), total phosphorus (TK), and available phosphorus (AK) of the alpine shrub meadow at different degradation levels. Lower-case letters represent significant differences ($p < 0.05$) in ecosystem services at different levels of degradation; error bars represent 95% confidence intervals.

There were significant positive correlations between water retention and TK ($p < 0.05$) and SOC ($p < 0.01$), respectively. There were also correlations between the different environmental factors, with negative correlations between TK and CP ($p < 0.01$), positive correlations between SOC and TN ($p < 0.01$), and positive correlations between AP and TN, CP, and SOC and TK ($p < 0.05$) (Figure 7).

The multiple linear regression analysis revealed that AK and SOC were the primary factors influencing water retention in alpine shrub meadows. Based on the analysis, a model equation was established as follows: WR = $-0.015 \times$ AK + $0.393 \times$ SOC + 25.032 (Table 2).

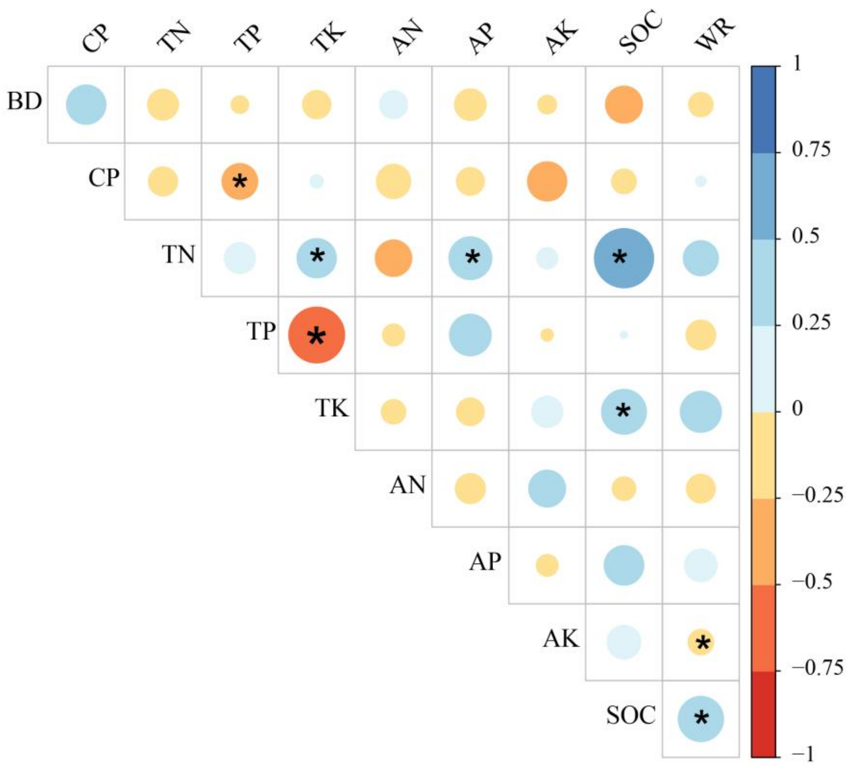

Figure 7. Correlation coefficients between the water retention service of the alpine shrub meadow and the influencing factors. Note: Soil bulk density (BD), capillary porosity (CP), soil organic carbon (SOC), total nitrogen (TN), available nitrogen (AN), total potassium (TP), available potassium (AP), total phosphorus (TK) and available phosphorus (AK) of the alpine shrub meadow are shown at different degradation levels. Dot size indicates the magnitude of the absolute value of the correlation coefficient and the "*" symbol represents significant differences ($p < 0.05$) in the ecosystem service at different levels of degradation. The different colours indicate the magnitude of the correlation coefficient, from −1 to 1 (red to blue).

Table 2. A multiple linear regression model of water retention and environmental factors in an alpine shrub meadow (adjusted $R^2 = 0.240$).

Model	**Unstandardized Coefficients**		**Sig.**
	B	Standard error	
Constants	25.032	5.018	0.000
AK	−0.015	0.006	0.010
SOC	0.393	0.153	0.015

4. Discussion

4.1. Characteristics and Influencing Factors of the Ecosystem Services Relationship in the Alpine Shrub Meadow

Our research has found a trade-off relationship between forage supply and water retention in alpine shrub meadows, where the degree of trade-off increases with degradation. Related research has also demonstrated a trade-off between the provisioning and regulating services of grasslands in the context of grazing pressure and grassland degradation [20]. There is a trade-off between provisioning and most of the regulating services in Inner Mongolia grasslands as a result of increased grazing intensity [19,21]. In a healthy grassland ecosystem, the water retention and forage supply services should be mutually reinforcing and synergistic [44–46], whereas grassland degradation reverses the relationship, causing a conflict between the productive and ecological functions of grassland and severely compromising the sustainability of grassland use. Therefore, understanding the characteristics of the provisioning–regulating service relationships of grasslands is an important prerequisite for preventing and managing grassland degradation, balancing the long-term conflicts between grassland conservation and development, and building the sustainable use of grassland ecosystems.

By investigating the factors influencing water retention, we have indirectly sought to identify key factors that may influence ecosystem service relationships. It was shown that SOC indirectly affects the relationship between the two ecosystem services by influencing water retention services and that a reduction in SOC may further exacerbate the imbalance between forage supply and water retention services in alpine grasslands. Grassland degradation has generally led to a decline in SOC, with alpine grassland degradation on the Qinghai-Tibetan Plateau leading to a reduction in SOC stocks of up to 43% [47]. In addition, most studies have shown a positive correlation between soil organic carbon levels and soil moisture in grasslands [26,48,49].

4.2. Managing Ecosystem Services in Alpine Shrub Meadows

In this study, we have shown that the relationship between forage supply and water retention services can be expressed in the decay form of the exponential function and have shown that forage supply in alpine shrub meadows has a constraining effect on water retention, which effect increases with degradation. The strong constraining effect of forage supply on water retention may be due to grassland degradation. It can affect soil moisture by changing the soil's physical properties. For example, overgrazing and livestock trampling often accompany grassland degradation, increasing soil compaction and reducing soil porosity, resulting in a decrease in soil water-holding capacity. Grassland degradation can also increase soil erosion, leading to the loss of surface soil and organic matter, which can further reduce soil water retention capacity. The degradation-induced low vegetation cover not only increases the direct penetration of sunlight to the ground but also enhances soil evaporation (since more soil is exposed to the air) and reduces the vegetation's interception and buffering of rainfall. This, in turn, increases rainfall splash erosion on bare ground, further contributing to a decline in soil water retention capacity [50–53].

The constraint effect between ecosystem services provides us with a new way of understanding the relationship between grassland services. According to the characteristics of the constraint line, as the forage supply service increases, the rate of the decline in the water retention service accelerates, suggesting that there may be a threshold of change in the relationship between the two; i.e., forage supply service exceeding a certain value or range will cause a rapid decrease in the water retention service. Although no definite threshold was found in this paper due to the size of the sample plots, it can be seen from the constraint line that a forage supply service of between 400 and 450 g/m^2 is the turning point for the change in water retention services. This finding has important implications for the management of alpine grassland ecosystem services. Related studies have also used the constraint line to identify critical thresholds for ecosystem service management, for example, to explore critical thresholds between different ecosystem services and between different drivers and ecosystem services in the arid–semi-arid grasslands of eastern China [27,53]. Furthermore, as the points on the constraint line indicate the ideal configuration of the relationship between the two services, the points below the curve indicate that water retention services are more heavily influenced by other factors and that there is the potential to enhance this component in terms of optimizing ecosystem services.

Ecosystem service management aims to mitigate conflicts and ensure that provisioning services are delivered without unduly compromising regulating services. From the perspective of drivers of service relationships, SOC may be an effective way to improve water retention services. Soil organic carbon (SOC) can affect soil moisture by altering the soil's physical properties, specifically soil bulk density and soil porosity. The mechanism involves the impact of SOC on soil bulk density and soil porosity, which ultimately influences soil moisture [48,54]. Previous studies also found a positive correlation between soil organic carbon and soil water retention in alpine ecosystems [26,48]. The decline in SOC in degraded grasslands can be caused by a reduction in the above- and below-ground biomass of the vegetation; therefore, ensuring a moderate grazing intensity in the first place and preventing the total loss of grassland productivity is an important condition for restoring water retention. In the case of severe degradation, the introduction of grazing exclusion to restore SOC and the water retention functions of grasslands remains an important approach.

This paper presents a comprehensive analysis of the correlation between forage supply and water retention services in degraded alpine shrub meadows, with a particular focus on exploring the constraints between the two. However, the analysis of the constraint relationship between the two services in this paper is limited by the sample size and sampling area. Thus, future studies should aim to expand the sampling range and include various vegetation types. Quantitative constraint models and key thresholds between provisioning and regulating services should also be established to provide more reliable recommendations for grassland management on the QTP.

5. Conclusions

This study highlights the trade-off relationship between forage supply and water retention services in degraded alpine shrub meadows on the northeastern Qinghai-Tibetan Plateau. The non-linear relationship between the two services indicates the constraining effect of water retention on the forage supply service; the turning point occurs when the forage supply reaches 400–450 g/m^2, resulting in a rapid decrease in water retention service. The relationship is influenced by various factors, with moderate and heavy degradation stages being crucial in the transition of service relationships. The decline in SOC, TN, and TK in the alpine shrub meadow was significant at different degradation levels and may indirectly affect the water retention service, which plays a vital role in the trade-off relationship. Therefore, to promote the sustainable development of alpine shrub meadows' ecological and production functions, it is essential to ensure moderate grazing intensity and adopt measures such as rotational grazing or closure to coordinate the ecosystem services relationships.

Author Contributions: Conceptualization, D.Q.; data curation, D.Q., B.F. and Y.L.; formal analysis, D.Q.; funding acquisition, D.Q.; investigation, Y.L. and M.S.; methodology, D.Q. and Q.L.; project administration, D.Q.; resources, Q.L. and X.G.; supervision, Q.L. and X.G.; validation, D.Q. and M.S.; visualization, D.Q.; writing—original draft, D.Q.; writing—review and editing, Q.L. and X.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 32001241, the Doctoral Startup Fund of Chongqing Normal University, grant No.23XLB004 and the Natural Science Foundation of Qinghai, grant number 2020-ZJ-938Q.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the first author on reasonable request.

Acknowledgments: We would like to thank the editor and reviewers for their valuable comments.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Millennium Ecosystem Assessment. *Ecosystems and Human Well-Being: Synthesis: A Report of the Millennium Ecosystem Assessment*; Island: Washington, DC, USA, 2005.
2. Haines-Young, R.; Potschin, M. *Proposal for a Common International Classification of Ecosystem Goods and Services (CICES) for Integrated Environmental and Economic Accounting*; Department of Economic and Social Affairs, Statistics Division, United Nations: New York, NY, USA, 2010.

3. Squires, V.R.; Dengler, J.; Hua, L.; Feng, H. *Grasslands of the World: Diversity, Management and Conservation*; CRC Press: Boca Raton, FL, USA, 2017.
4. O'Mara, F.P. The role of grasslands in food security and climate change. *Ann. Bot.* **2012**, *110*, 1263–1270. [CrossRef] [PubMed]
5. Bardgett, R.D.; Bullock, J.M.; Lavorel, S.; Manning, P.; Schaffner, U.; Ostle, N.; Chomel, M.; Durigan, G.; LFry, E.; Johnson, D.; et al. Combatting global grassland degradation. *Nat. Rev. Earth Environ.* **2021**, *2*, 720–735. [CrossRef]
6. Gang, C.C.; Zhou, W.; Chen, Y.Z.; Wang, Z.Q.; Sun, Z.G.; Li, J.L.; Qi, J.G.; Odeh, I. Quantitative assessment of the contributions of climate change and human activities on global grassland degradation. *Environ. Earth Sci.* **2014**, *72*, 4273–4282. [CrossRef]
7. Gibbs, H.K.; Salmon, J.M. Mapping the world's degraded lands. *Appl. Geogr.* **2015**, *57*, 12–21. [CrossRef]
8. Lark, T.J.; Spawn, S.A.; Bougie, M.; Gibbs, H.K. Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nat. Commun.* **2020**, *11*, 4295. [CrossRef]
9. Bayer, W. Building resilience of human-natural systems of pastoralism in the developing world: Interdisciplinary perspectives. *Rangel. J.* **2017**, *39*, 401–403. [CrossRef]
10. Bengtsson, J.; Bullock, J.M.; Egoh, B.; Everson, C.; Everson, T.; O'Connor, T.; O'Farrell, P.J.; Smith, H.G.; Lindborg, R. Grasslands-more important for ecosystem services than you might think. *Ecosphere* **2019**, *10*, 20. [CrossRef]
11. Rodríguez, J.; Beard Jr, T.D.; Bennett, E.; Cumming, G.; Cork, S.; Agard, J.; Dobson, A.; Peterson, G. Trade-offs across space, time, and ecosystem services. *Ecol. Soc.* **2006**, *11*, 1–14. [CrossRef]
12. Bennett, E.M.; Peterson, G.D.; Gordon, L.J. Understanding relationships among multiple ecosystem services. *Ecol. Lett.* **2009**, *12*, 1394–1404. [CrossRef]
13. Zhang, Y.; Lu, X.; Liu, B.; Wu, D.; Fu, G.; Zhao, Y.; Sun, P. Spatial relationships between ecosystem services and socioecological drivers across a large-scale region: A case study in the Yellow River Basin. *Sci. Total Environ.* **2020**, *766*, 142480. [CrossRef]
14. Pan, Y.; Wu, J.X.; Xu, Z.R. Analysis of the tradeoffs between provisioning and regulating services from the perspective of varied share of net primary production in an alpine grassland ecosystem. *Ecol. Complex.* **2014**, *17*, 79–86. [CrossRef]
15. Petz, K.; Alkemade, R.; Bakkenes, M.; Schulp, C.J.E.; van der Velde, M.; Leemans, R. Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models. *Glob. Environ. Chang.* **2014**, *29*, 223–234. [CrossRef]
16. Khosravi Mashizi, A.; Heshmati, G.A.; Salman Mahini, A.R.; Escobedo, F.J. Exploring management objectives and ecosystem service trade-offs in a semi-arid rangeland basin in southeast Iran. *Ecol. Indic.* **2019**, *98*, 794–803. [CrossRef]
17. Onatibia, G.R.; Aguiar, M.R.; Semmartin, M. Are there any trade-offs between forage provision and the ecosystem service of C and N storage in arid rangelands? *Ecol. Eng.* **2015**, *77*, 26–32. [CrossRef]
18. Wu, J.X.; Zhao, Y.; Yu, C.Q.; Luo, L.M.; Pan, Y. Land management influences trade-offs and the total supply of ecosystem services in alpine grassland in Tibet, China. *J. Environ. Manag.* **2017**, *193*, 70–78. [CrossRef] [PubMed]
19. Fan, F.; Liang, C.Z.; Tang, Y.K.; Harker-Schuch, I.; Porter, J.R. Effects and relationships of grazing intensity on multiple ecosystem services in the Inner Mongolian steppe. *Sci. Total Environ.* **2019**, *675*, 642–650. [CrossRef]
20. Xu, Y.D.; Dong, S.K.; Gao, X.X.; Yang, M.Y.; Li, S.; Shen, H.; Xiao, J.N.; Han, Y.H.; Zhang, J.; Li, Y.; et al. Trade-offs and cost-benefit of ecosystem services of revegetated degraded alpine meadows over time on the Qinghai-Tibetan Plateau. *Agric. Ecosyst. Environ.* **2019**, *279*, 130–138. [CrossRef]
21. Li, M.; Li, X.; Liu, S.; Li, X.; Lyu, X.; Dang, D.; Dou, H. Ecosystem services under different grazing intensities in typical grasslands in Inner Mongolia and their relationships. *Glob. Ecol. Conserv.* **2021**, *26*, e01526. [CrossRef]
22. Dong, S.K.; Sherman, R. Enhancing the resilience of coupled human and natural systems of alpine rangelands on the Qinghai-Tibetan Plateau. *Rangel. J.* **2015**, *37*, i-iii. [CrossRef]
23. Cao, J.; Adamowski, J.F.; Deo, R.C.; Xu, X.; Gong, Y.; Feng, Q. Grassland Degradation on the Qinghai-Tibetan Plateau: Reevaluation of Causative Factors. *Rangel. Ecol. Manag.* **2019**, *72*, 988–995. [CrossRef]
24. Yashiro, Y.; Shizu, Y.; Hirota, M.; Shimono, A.; Ohtsuka, T. The role of shrub (Potentilla fruticosa) on ecosystem CO2 fluxes in an alpine shrub meadow. *J. Plant Ecol.* **2010**, *3*, 89–97. [CrossRef]
25. Li, H.Q.; Zhang, F.W.; Li, Y.N.; Wang, J.B.; Zhang, L.M.; Zhao, L.; Cao, G.M.; Zhao, X.Q.; Du, M.Y. Seasonal and inter-annual variations in CO2 fluxes over 10 years in an alpine shrubland on the Qinghai-Tibetan Plateau, China. *Agric. For. Meteorol.* **2016**, *228*, 95–103. [CrossRef]
26. Dai, L.; Guo, X.; Ke, X.; Du, Y.; Zhang, F.; Cao, G. The variation in soil water retention of alpine shrub meadow under different degrees of degradation on northeastern Qinghai-Tibetan plateau. *Plant Soil.* **2020**, *458*, 231–244. [CrossRef]
27. Li, S.; Li, X.; Dou, H.; Dang, D.; Gong, J. Integrating constraint effects among ecosystem services and drivers on seasonal scales into management practices. *Ecol. Indic.* **2021**, *125*, 107425. [CrossRef]
28. Horning, M. Constraint lines and performance envelopes in behavioral physiology: The case of the aerobic dive limit. *Front Physiol.* **2012**, *3*, 381. [CrossRef] [PubMed]
29. Mills, A.J.; Fey, M.V.; Grongroft, A.; Petersen, A.; Medinski, T.V. Unravelling the effects of soil properties on water infiltration: Segmented quantile regression on a large data set from arid south-west Africa. *Aust. J. Soil Res.* **2006**, *44*, 783–797. [CrossRef]
30. Jiang, C.; Wang, X.C.; Zhang, H.Y.; Labzovskii, L.; Wang, J.; Liu, T. Re-orienting ecological restoration in degraded drylands for a more sustainable soil-water relationship: Non-linear boundary of limited water resources in combating soil loss. *J. Arid Environ.* **2019**, *167*, 87–100. [CrossRef]

31. Qiao, J.; Yu, D.; Cao, Q.; Hao, R. Identifying the relationships and drivers of agro-ecosystem services using a constraint line approach in the agro-pastoral transitional zone of China. *Ecol. Indic.* **2019**, *106*, 105439. [CrossRef]
32. Dade, M.C.; Mitchell, M.G.E.; McAlpine, C.A.; Rhodes, J.R. Assessing ecosystem service trade-offs and synergies: The need for a more mechanistic approach. *Ambio* **2019**, *48*, 1116–1128. [CrossRef]
33. Obiang Ndong, G.; Therond, O.; Cousin, I. Analysis of relationships between ecosystem services: A generic classification and review of the literature. *Ecosyst. Serv.* **2020**, *43*, 101120. [CrossRef]
34. Cao, G.; Du, Y.; Liang, D.; Wang, Q.; Wang, C. Character of passive-active degradation process and its mechanism in alpine kobresia meadow. *J. Mt. Sci. Engl.* **2007**, *25*, 641–648.
35. Dai, L.; Guo, X.; Ke, X.; Du, Y.; Zhang, F.; Li, Y.; Li, Q.; Lin, L.; Cao, G.; Peng, C.; et al. The response of Potentilla fruticosa communities to degradation succession in Qinghai-Tibet plateau. *Ecol. Environ. Sci.* **2019**, *28*, 732–740. [CrossRef]
36. Zhang, F.; Zeng, C.; Zhang, Q.; Yao, T. Securing water quality of the Asian Water Tower. *Nat. Rev. Earth Environ.* **2022**, *3*, 611–612. [CrossRef]
37. Jiao, F.; Wen, Z.M.; An, S.S. Changes in soil properties across a chronosequence of vegetation restoration on the Loess Plateau of China. *Catena* **2011**, *86*, 110–116. [CrossRef]
38. Cui, Z.; Liu, Y.; Huang, Z.; He, H.H.; Wu, G.L. Potential of artificial grasslands in crop rotation for improving farmland soil quality. *Land Degrad. Dev.* **2019**, *30*, 2187–2196. [CrossRef]
39. Cao, G.; Zhang, F. *China Ecosystem Positioning Observation and Research Dataset: Grassland and Desert Ecosystem Volume, Qinghai Haibei Station*; China Agriculture Press: Beijing, China, 2021.
40. Xie, H.T.; Yang, X.M.; Drury, C.F.; Yang, J.Y.; Zhang, X.D. Predicting soil organic carbon and total nitrogen using mid- and near-infrared spectra for Brookston clay loam soil in Southwestern Ontario, Canada. *Can. J. Soil Sci.* **2011**, *91*, 53–63. [CrossRef]
41. Fu, B.J.; Liu, S.L.; Chen, L.D.; Lu, Y.H.; Qiu, J. Soil quality regime in relation to land cover and slope position across a highly modified slope landscape. *Ecol. Res.* **2004**, *19*, 111–118. [CrossRef]
42. Nelson, D.W.; Sommers, L.E. Total Carbon, Organic Carbon, and Organic Matter. *Methods Soil Anal.* **1996**, *5*, 961–1010.
43. Bradford, J.B.; D'Amato, A.W. Recognizing trade-offs in multi-objective land management. *Front. Ecol. Environ.* **2012**, *10*, 210–216. [CrossRef]
44. Deng, L.; Wang, K.B.; Li, J.P.; Zhao, G.W.; Shangguan, Z. Effect of soil moisture and atmospheric humidity on both plant productivity and diversity of native grasslands across the Loess Plateau, China. *Ecol. Eng.* **2016**, *94*, 525–531. [CrossRef]
45. Hao, H.M.; Lu, R.; Liu, Y.; Fang, N.F.; Wu, G.L.; Shi, Z.H. Effects of shrub patch size succession on plant diversity and soil water content in the water-wind erosion crisscross region on the Loess Plateau. *Catena* **2016**, *144*, 177–183. [CrossRef]
46. Yang, Y.; Dou, Y.X.; An, S.S.; Zhu, Z.L. Abiotic and biotic factors modulate plant biomass and root/shoot (R/S) ratios in grassland on the Loess Plateau, China. *Sci. Total Environ.* **2018**, *636*, 621–631. [CrossRef] [PubMed]
47. Breidenbach, A.; Schleuss, P.M.; Liu, S.B.; Schneider, D.; Dippold, M.A.; de la Haye, T.; Miehe, G.; Heitkamp, F.; Seeber, E.; Mason-Jones, K.; et al. Microbial functional changes mark irreversible course of Tibetan grassland degradation. *Nat. Commun.* **2022**, *13*, 2681. [CrossRef] [PubMed]
48. Yang, F.; Zhang, G.-L.; Yang, J.-L.; Li, D.-C.; Zhao, Y.-G.; Liu, F.; Yang, R.-M.; Yang, F. Organic matter controls of soil water retention in an alpine grassland and its significance for hydrological processes. *J. Hydrol.* **2014**, *519*, 3086–3093. [CrossRef]
49. Kerr, D.D.; Ochsner, T.E. Soil organic carbon more strongly related to soil moisture than soil temperature in temperate grasslands. *Soil Sci. Soc. Am. J.* **2020**, *84*, 587–596. [CrossRef]
50. Chen, W.; Wolf, B.; Zheng, X.; Yao, Z.; Butterbach-Bahl, K.; Brüggemann, N.; Liu, C.; Han, S.; Han, X. Annual methane uptake by temperate semiarid steppes as regulated by stocking rates, aboveground plant biomass and topsoil air permeability. *Global Chang. Biol.* **2011**, *17*, 2803–2816. [CrossRef]
51. Tian, D.; Niu, S.; Pan, Q.; Ren, T.; Chen, S.; Bai, Y.; Han, X. Nonlinear responses of ecosystem carbon fluxes and water-use efficiency to nitrogen addition in Inner Mongolia grassland. *Funct. Ecol.* **2016**, *30*, 490–499. [CrossRef]
52. You, Q.; Xue, X.; Peng, F.; Dong, S.; Gao, Y. Surface water and heat exchange comparison between alpine meadow and bare land in a permafrost region of the Tibetan Plateau. *Agric. For. Meteorol.* **2017**, *232*, 48–65. [CrossRef]
53. Hao, R.F.; Yu, D.Y.; Wu, J.G. Relationship between paired ecosystem services in the grassland and agro-pastoral transitional zone of China using the constraint line method. *Agric. Ecosyst. Environ.* **2017**, *240*, 171–181. [CrossRef]
54. Geroy, I.J.; Gribb, M.M.; Marshall, H.P.; Chandler, D.G.; Benner, S.G.; McNamara, J.P. Aspect influences on soil water retention and storage. *Hydrol. Process.* **2011**, *25*, 3836–3842. [CrossRef]