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A Topographic Perspective on the Propensity for Degradation of Plateau Swampy Meadows in Maduo County, West China

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Abstract: The swampy meadows atop the vast Qinghai–Tibet Plateau in West China fall into alpine, pediment, valley, floodplain, terrace, lacustrine, and riverine types according to their hydro-geomorphic properties. They have suffered degradation to various levels of severity due to climate change and external disturbance. In this paper, we studied the propensity of these types of swampy meadows to degrade from the topographic perspective. Evaluated against four degradation indicators of vegetation, hydrology, soil erosion, and pika (*Ochotona curzoniae*) damage, degradation severity at 106 swampy meadows representing all types of wetlands was graded to one of four levels, from which the field-based propensity to degrade (PtD) index value was derived. Judged against this index, terrace and alpine swampy meadows are the most prone to degradation while valley, lacustrine, and riverine swampy meadows are the least. The index value of a given swampy meadow type bears a close relationship (R^2 = 0.916) with its rate of change during 1990–2013, which confirms the validity of the proposed index in predicting the propensity of swampy meadows to change. The observed differential PtD of different types of swampy meadows is attributed primarily to elevation (R^2 = 0.746; p = 0.027) and, secondarily, to surface morphology (R^2 = 0.696; p = 0.039). Thus, the elevation at which a swampy meadow is situated is a more important factor to its PtD than its surface morphology. In particular, swampy meadows located at a higher elevation with a convex surface are much more prone to degradation than those at a lower elevation of a concave slope. Such findings can guide the proper management of different types of swampy meadows to achieve sustainable animal husbandry.

Keywords: swampy meadow type; degradation propensity; severity assessment; topographic influence; Qinghai–Tibet Plateau

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1. Introduction

Swampy meadows around the world provide several important eco-services, such as balancing regional ecology, conserving biodiversity, trapping pollutants, and being important habitats for the wildlife. As a consequence of global climate change, nutrient enrichment, salinization, and pollution with pesticides and heavy metals, swampy meadows around the world are facing a mounting risk of degradation, with millions of hectares lost over the last few decades [1,2]. Swampy meadow degradation is a highly complex phenomenon that has been defined in terms of hydrology, e.g., shrunk water areas and declined water regulation capacity [3], decreased vegetative cover and its interannual variability [4], changed plant community structure and species diversity [5], and soil properties [6]. In this paper, the degradation of swampy meadows on the Qinghai–Tibet Plateau is defined as the reduction in water reserves to such a level that their ecological functions are adversely impacted, including reduced water regulating capacity, reduced protection of the underlying soil, and reduced grazing value. Of these changes, the change in the

hydrological conditions of swampy meadows is considered the most fundamental, as other changes (e.g., change in grass species composition and even the advent of soil erosion) are secondary in that they are triggered by it. Therefore, the propensity of a swampy meadow to degrade is best studied through its hydrological state, especially its water/moisture level.

It is very important to study swampy meadow degradation and understand its causes because it can lead to grave consequences, such as dissolved carbon dynamics [7], reduced carbon uptake and increased global warming potential [8], reduced spawning grounds for fish, extinction of wild flora and fauna, and reduced capability of erosion control and sediment trapping [9]. Due to their environmental sensitivity and vulnerability, the swampy meadows atop the Qinghai–Tibet Plateau have been studied by a number of scientists. Wang et al. evaluated the changes in swampy meadow components, spatial pattern, and hydro-ecologic functions [10]. Niu et al. validated the gross primary production of the alpine swampy meadow on the Tibet Plateau from MODIS satellite data [11], while Yang et al. monitored grassland degradation with the assistance of a remote sensing-derived index in Shangri-La of China [12]. Wu et al. studied the associations between environmental factors in alpine marshy meadows and shifts in plant and soil C, N, and P concentrations and C:N:P stoichiometry [13]. Wu et al. examined the change in the microtopography of swampy meadows in Sanjiangyuan via inferring vegetation and soil properties [14]. Li et al. studied how the degradation of alpine marshy meadows affected ecosystem respiration and its components [15], while Lin et al. explored how the degradation succession of alpine marshy meadows impacted soil organic carbon and total nitrogen in the Yellow River source zone [16]. The potential risk of swampy meadow degradation in the Mt. Qomolangma National Nature Reserve was evaluated from annual mean temperature, settlements, and proximity to roads [17]. However, it still remains unknown why certain types of swampy meadows on the Qinghai–Plateau are more prone to degradation and degrade more seriously than others.

Dependent upon its type and geographic location, a swampy meadow can be degraded by different factors. The common causes of peatland and coastal wetland degradation and disappearance are attributed to land drainage and reclamation for agriculture [18]. The accelerated degradation of lacustrine swampy meadow was caused mainly by constructions in the concerned area and warmer temperature, while annual precipitation and evapotranspiration exerted little influence [19]. However, these causes are not applicable to the plateau setting where grassy wetlands occur mainly as swampy meadows. The causes of their degradation are identified as overgrazing, climate change, and external disturbances [20,21]. Regionally, they have caused widespread degradation and shrinkage of the swampy meadows on the Qinghai–Tibet Plateau to various levels [22].

At a finer local scale, both climate and external disturbance can be assumed to be uniform. Why one type of swampy meadow is more prone to degradation than another is dependent largely on its topography in the landscape. Topographic settings govern the distribution of solar energy and moisture on a slope and, hence, the propensity of swampy meadow to degrade. So far, topography has been considered in predicting sites of future coastal marsh loss [23] and in detecting swampy meadows using a topographic wetland index from multitemporal optical satellite data [24]. Chignell et al. recognized the importance of elevation to the nature of Afroalpine wetland of the Bale Mountains in Ethiopia [25]. Namely, wetlands located at over approximately 3800 m a.s.l. are likely to be ephemeral, and those at lower elevations tend to be perennial. Nungesser analyzed the temporal and spatial changes of a patterned peatland in relation to topography [26]. Nevertheless, nobody has examined the influence of topography on swampy meadow change and its propensity to degrade.

Of particular note, in the plateau setting topography plays an especially decisive role in affecting surface water distribution (e.g., melting of permafrost, evaporation of moisture, and water flow) and, hence, potential degradation of swampy meadows on the Qinghai–Tibet Plateau. How topography affects a swampy meadow's propensity to degrade (PtD) has not been explored yet. This study aimed to bridge this knowledge gap

by ascertaining why different types of swampy meadows atop the Qinghai–Tibet Plateau have been degraded to various levels of severity, even though they have undergone the same environmental change over the last few decades. The specific objectives were: (1) to devise an index for realistically assessing the PtD by swampy meadow type based on field data; (2) to determine how the PtD varies among different types of swampy meadow; and (3) to assess the relative influence of elevation and surface morphology on the PtD of swampy meadows in Maduo County on the Qinghai–Tibet Plateau. The knowledge about the topographic influence on the PtD of different types of swampy meadows can guide their proper grazing to achieve sustainable animal husbandry.

2. Study Area

Situated in southern Qinghai Province, Maduo County (33°50′ N–96°50′ E to 35°40′ N–99°20′ E) has a dimension of 228 km by 207 km, covering an area of 25,253 km^2 (Figure 1). It has a frigid alpine continental climate, with the annual temperature averaging only 1.2 °C. This perennially low temperature regime causes the growing season to be limited to June–September. Most of the county lies between 4500 and 5000 m a.s.l., at which there is no distinct seasonality. Distributed atop the tall mountains are snow and glaciers. Natural vegetation at lower elevations comprises mostly alpine meadows, with grasslands making up 87.5% of the entire county, including marshy and swampy meadows [22].

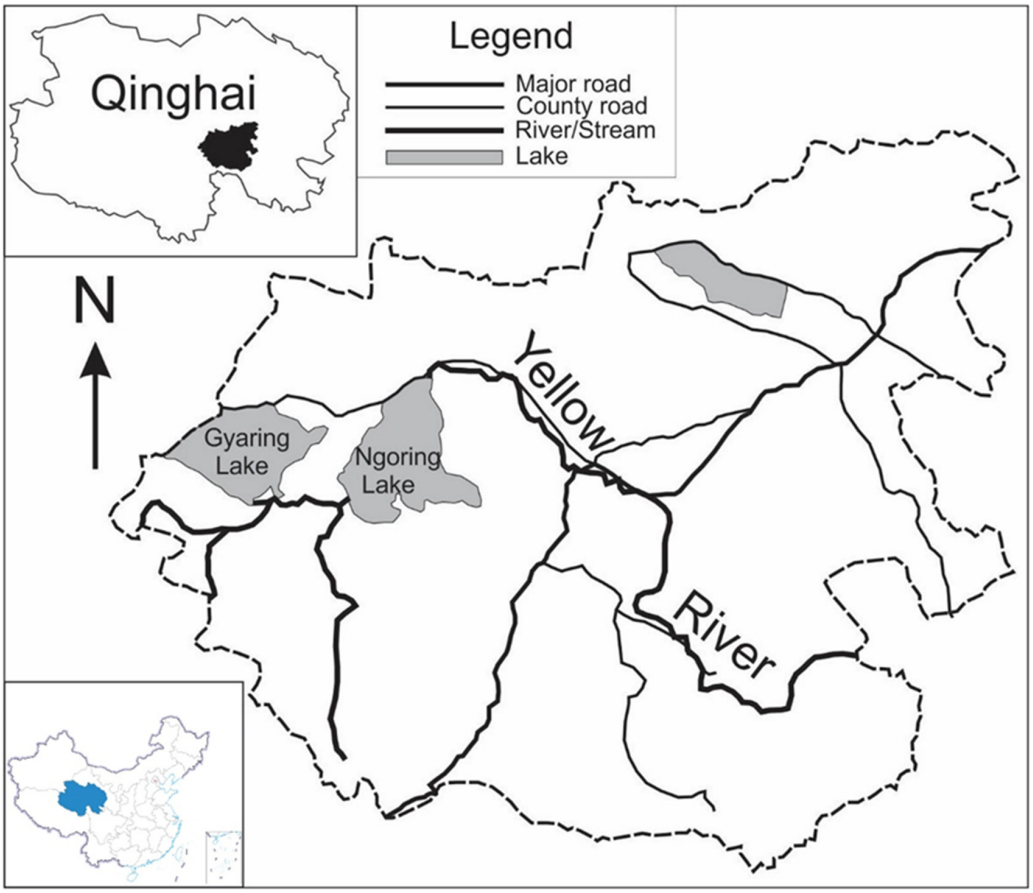


Figure 1. Location of the study area in Qinghai Province, West China.

Maduo receives an annual rainfall of only 303.9 mm per annum, a fraction of the annual evaporation of 1260 mm. Despite this huge deficit, it is bountiful in water resources owing to the injection of water via numerous rivers. In addition, thousands of freshwater lakes are distributed throughout the County at a combined area of 1674 km^2. Associated with the rivers, lakes, and glaciers are swampy meadows of various sizes and types. These swampy meadows are inherently fragile and vulnerable to degradation due to the harsh

environment (e.g., strong solar radiation and winds, low precipitation). Swampy meadows have declined in the past, even though they have showed signs of recovery over recent years [10]. This county was selected for study because it encompasses a variety of swampy meadows. The high elevation of the county makes them extremely sensitive to topography and external disturbance. More importantly, the swampy meadows of this area have been widely degraded to various levels as a consequence of overgrazing and climate change [27]. If not properly managed, meadow degradation will worsen with more swampy meadows eventually lost to become ordinary meadows.

3. Grading of Swampy Meadow Degradation Severity

3.1. Swampy Meadow Types

Inland swampy meadows have been classified as alpine, lacustrine, riverine, and swampy based on wetland hydrology, plants, and soil [28]. Since the swampy meadows on the Qinghai–Tibet Plateau have drastically differing internal structures, such a broad classification is not conducive to revealing how they can be properly restored in case of degradation. In particular, no consideration is given to their geomorphic uniqueness. This deficiency has been overcome with the hydro-geomorphic classification in which these swampy meadows are categorized into valley, terrace, floodplain, piedmont, alpine, lacustrine, and riverine [29]. Alpine swampy meadows are small, irregularly shaped marshy meadows distributed in the middle and lower slopes on a tall mountainside. Confined to the bottom of a valley, valley swampy meadows are flanked by mountains or mountainous ranges on both sides, or partially encircled by them if they join. Piedmont swampy meadows are located at the foot of a mountain (range) that has a gentler slope than the mountain slope. Very extensive in area, they usually lie parallel to the mountain (range) in an elongated shape. Floodplain swampy meadows are distributed on a floodplain of a river between the terrace and the channel. Terrace swampy meadows are situated on the higher river terrace due to tectonic activities or channel incision. Spatially, they are further away from the channel than floodplain swampy meadows. Both floodplain and terrace swampy meadows are hydrologically replenished by the river water during flooding. Lacustrine swampy meadows refer to the narrow band of the land–water interface of lakes, within which grassy plants are distributed. Thus, the deeper water devoid of grasses is excluded from consideration. Riverine swampy meadows are those small grassy wetlands located amid inactive or stagnant channels or in the riverbank.

3.2. Selection of Degradation Indicators

Selection of the most appropriate degradation indicators is a prerequisite to constructing a reliable and reasonable grading scheme of degradation severity. Yu and Zhou developed a wetland degradation geoindicatior system involving cause indicators, state indicators, and result indicators [30]. The state and result indicators are identified as land degradation, reduced water reserve, and vegetation degradation [31]. Although vegetative cover and aboveground biomass are significantly lower in degraded swampy meadows than at intact sites [6], biomass is not a reliable indicator due to the varying proportion of surface water area in a swampy meadow. In contrast, the composition of the plant community and the emergence of indicator species are useful clues for assessing swampy meadow degradation [6]. For example, *Kobresia tibetica* is dominant in intact swampy meadows, but is replaced by *Pedicularis* at the advanced stage of degradation. The advent of a completely new plant community comprising mostly pioneer species and alien species is a sure sign of peatland degradation [32].

Denudated ground area and vegetation cover can be used to predict meadow condition and associated ecological thresholds [33]. The percentage of vegetative cover and soil moisture are more reliable indicators than pika burrow density, even though neither is perfect [34]. Based on these findings, four indicators (vegetation, hydrology, soil erosion, and pika damage) were selected for grading the degradation severity of swampy meadows (Table 1). As the most sensitive indicator, vegetation encompasses two subvariables of

cover (%) and species composition. A low cover indicates a high severity of degradation. The presence of *Kobresia tibetica* signifies a sound state. The advent of drought-tolerant species that have replaced it suggests severe degradation. Similarly, hydrology also encompasses two subvariables of water reserve and soil moisture. An abundant water reserve is indicative of a healthy state while a dry surface with a moisture content of 25–40% signifies that the swampy meadow is under stress (Table 1). In case of reduced water reserve, the soil moisture at 10 cm below the surface is also used. Soil conditions are indicative of the bioproductivity of degraded swampy meadows and their potential for recovery. The more damage is done to the sod layer, the more likely the underlying soil will be eroded, and the more vulnerable the remaining vegetation will be to erosion, all diminishing the chance of vegetation regeneration and growth, a sign of severe degradation. As a kind of external disturbance to the swampy meadows, pikas (*Ochotona curzoniae*) are an active agent in exacerbating swampy meadow degradation [27]. Pika damage accelerates degradation from the slight to the advanced stage quickly [35]. Since it is difficult to accurately census pika population, the density of active pika burrows was used as a proxy for this indicator.

Table 1. Indicators of plateau swampy meadow degradation and criteria for grading degradation severity of swampy meadows in the study area.

Severity Level	Vegetation		Hydrology		Soil Erosion	Pest Damage (Pika Burrows/9 m^2)
	Cover (%)	Indicator Species *	Water Reserve	Moisture Content at 10 cm		
Reference	>90	*K. tibetica*	Ponds & pools	>50%	Absent	<1
Slight	>80	*K. pygmaea*, *K humilis*	Small pools	>40%	Sod layer damaged	2–3
Moderate	≥50	*Poaannua*, *Stipacapillata*	Wet surface	≥25%	Piles of loosened soil	4–5
Severe	<50	*Pedicularis*	Dry surface	<25%	>50 sod layer gone	≥5

*: The exact indicator species vary with wetland type. These are based mostly on swampy meadows.

3.3. Grading of Degradation Severity

After the indicators of swampy meadow degradation have been selected, criteria must be established to grade degradation severity that is enumerated at four levels of intact, slight, moderate, and severe (Table 1). Intact refers to the original, ideal, pristine state of swampy meadows with few signs of external disturbance (Figure 2A). It can serve as the reference state, against which the degradation severity of the same type of swampy meadow is judged. Intact swampy meadows are healthy with abundant forage (mostly *Kobresia tibetica*) for productive grazing. Occasionally, there may be one pika burrow present, but it is mostly innocuous as the soil surrounding it is still not affected. Slight degradation means an 80–90% cover of mostly *Kobresia pygmaea* and *K. humilis* vegetation. Surface water is also reduced to small pools with a corresponding drop in soil moisture (Figure 2B). Some of the original soil has been exposed by pika whose burrows are numbered 2–3 per 9 m^2. By the moderate stage of degradation, surface vegetation cover is reduced further to about 50% (Figure 2C). Although the swampy meadow surface is still wet, the moisture content at 10 cm below the surface drops to just above 25%. By this stage, pika burrow density has risen to 4–5 per 9 m^2. Pika have caused noticeable damage to the soil and partially destroyed the top crust. At the severe stage, <50% of the original vegetation remains, with the remaining vegetation either disappeared or replaced by exotic, unpalatable species of grass, such as *Pedicularis* (Figure 2D). The meadow surface is rather dry with a moisture content <25%. The original turf has been mostly eroded, resulting in a low soil fertility. In extreme cases, only pebbles and sands are left behind, within which pika burrows total more than 5 per 9 m^2.

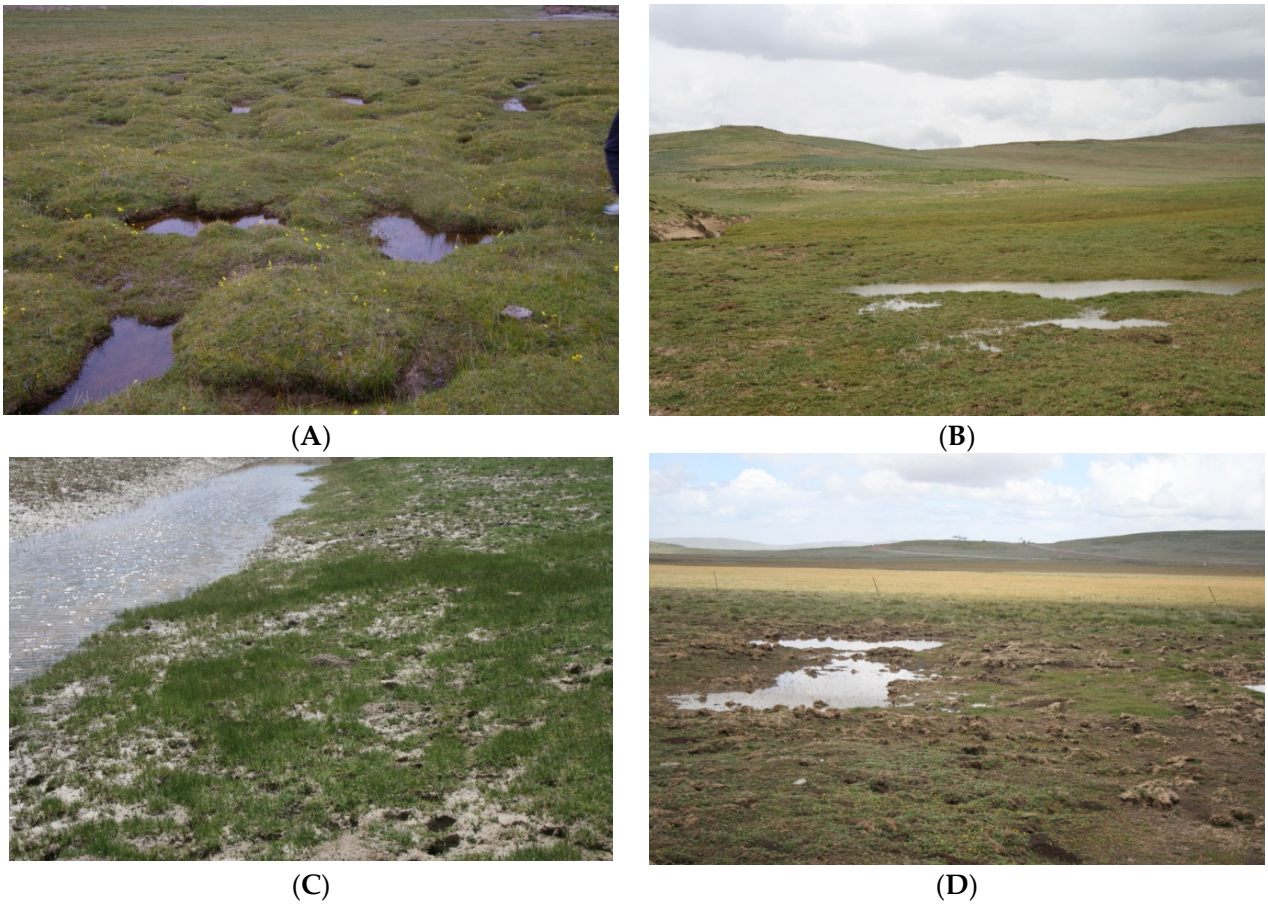


Figure 2. Typical severity levels of swampy meadow degradation in the study area. The original state (**A**) can be used as the reference state against which the severity level of degradation is judged (Table 1). (**A**) Intact; (**B**) Slight degradation; (**C**) Moderate degradation; (**D**) Severe degradation.

4. Data and Analysis

4.1. Data Collection

Field work was carried out in late August of 2011. Swampy meadows distributed in a diverse range of elevations were sampled, subject to site accessibility. In total, samples were collected at 106 randomly selected sites encompassing all seven types of swampy meadows. Sample size is proportional to swampy meadow prevalence. Namely, the more predominant types of swampy meadows are better represented in the samples (e.g., having a larger sample size) than the rare ones. At each site, the swampy meadow type was identified first. Afterwards, a sample plot of 3 m by 3 m in size was randomly laid out on the ground. Together with surface water area, vegetative cover within it was estimated visually to an accuracy of 5% by three experts independently, and the average of the three estimates was used as the final result. The grass species and their richness were recorded. After the number of pika burrows was counted, the soil condition (e.g., portion of denudated patches and the remaining sod layer) was assessed, and the slope gradient measured. The surface morphology was identified as one of three forms (linear, concave, and convex), with the general morphologic setting (e.g., curvature) noted. At each site, soil moisture was measured at 10 cm below the surface using the Delta-T ML2x ThetaProbe sensor to an accuracy of ±1%. The measurement was replicated thrice at three spots within each plot, and the mean was used as the final reading. Finally, the location of each site was logged with a Garmin GPS_{map} 60 CS_x receiver in the stationary mode. Owing to the absence of any obstruction (e.g., no trees and no buildings nearby), horizontal positions were logged at the best accuracy of <10 m, and the vertical height had a much lower accuracy (GPS readings were not differentially corrected, only averaged).

4.2. Data Analysis

The collected data were analyzed to grade the degradation severity at each site into one of the four levels (Table 1). In order to compare the PtD of different types of swampy meadows objectively, the observed number of swampy meadows at each severity level was converted to a numerical weight (e.g., s_4 = severe, s_3 = moderate, s_2 = slight, s_1 = intact). PtD_j of swampy meadow type j(j = 1, 2,.., 7) in a given year was calculated from the summed product of weighted severity of degraded sites (s_i) and their quantity, divided by the total number of sampling sites N_j, namely:

$$PtD_j = \Sigma(s_i \times n_i)/N_j \quad (1)$$

where n_i refers to the number of sites at a given severity i (i = 1, 2, 3, 4); s_i is the weight assigned to the severity (e.g., s_4 = 4, s_3 = 3, s_2 = 2, s_1 = 1) (Table 2).

Table 2. The observed number of sampled swampy meadows (n_i) that have been degraded to various severity levels (s_i), the calculated PtD score by swampy meadow type, its mean elevation, and the numerical value assigned to surface morphology of the seven types of swampy meadow for the purpose of regression analysis.

Swampy Meadow Type	Severity of Degradation (s_i)				Sum (N)	PtD Score	Elevation (m)	Morphology	Tendency to Degrade
	Intact (1)	Slight (2)	Moderate (3)	Severe (4)					
Terrace *			2	3	5	3.60	4248	0.2	
Alpine		2	3	2	7	3.00	4310	0.05	Vulnerable
Piedmont	10	8	2	7	27	2.22	4269	0.3	
Floodplain	6	3	4	2	15	2.13	4243	0	Stable
Valley	7	1			8	1.13	4252	−0.5	
Lacustrine	23	5	1	1	30	1.33	4230	−0.2	Resilient
Riverine	12	2			14	1.14	4221	−0.3	

*: Since terrace swampy meadows have been degraded to the moderate level and beyond, they are virtually ordinary meadows and, hence, excluded from further analysis.

The proposed PtD_j index was validated against the rate of swampy meadow change during 1990–2013 via regression analysis. It was determined from overlay analysis of swampy meadow distribution maps visually interpreted from multitemporal Landsat satellite images in a geographic information system (for more information, refer to [22]). After the elevation of the same type of swampy meadow samples was averaged, the influence of elevation and surface morphology on PtD was statistically analyzed through regression analysis individually. Prior to the analysis, each type of linear, concave, and convex surfaces was assigned a weight proportional to its ability to retain water within the swampy meadow. Namely, a positive value was assigned to a convex surface (e.g., piedmont swampy meadow) as it causes water/moisture to diverge from the swampy meadow, reducing its water reserve and increasing its propensity to degrade. Conversely, a negative value was assigned to a concave surface because it facilitates convergence of water/moisture to the swampy meadow. The exact value was proportional to surface curvature (Table 2). A more concave morphology (e.g., valley) receives a higher weight. A weight of 0 was assigned to linear or flat surfaces that neither encourage nor discourage the accumulation of water within the swampy meadow, such as floodplain swampy meadows (Table 2).

5. Results

5.1. Propensity for Degradation by Swampy Meadow Type

Of all the samples, lacustrine swampy meadows are the most represented (30), followed by piedmont (27), while terrace (5), alpine (7), and valley (8) are less represented due to their subordinance in the landscape (Table 2). A swampy meadow type is construed to be more prone to degradation if it has a higher proportion of more severely degraded sample sites and vice versa. The calculated PtD score (Table 2) ranges from 1.13 for valley swampy meadows to 3.60 for terrace swampy meadows. Valley, lacustrine, and riverine

swampy meadows are the least prone to degradation with a PtD value < 1.5 (Table 2). They are considered resilient. Except for lacustrine swampy meadows, they have not been degraded beyond the moderate level. Lacustrine swampy meadows have been degraded to all three levels, even though those moderately and severely degraded ones are truly rare, accounting for only 6.7% of the total. The degradation was caused and exacerbated by the frequent trampling of livestock along lakeshores, as deducted from their hoof prints on the ground. Such differential PtD is attributed to water reserve. Both riverine and lacustrine swampy meadows have a large water reserve that enables them to withstand short-term environmental fluctuations without showing obvious signs of degradation. Moreover, the lakeshores and riverbanks are not prone to pika attacks because pika burrows can be easily inundated during rains or flooding. Valley swampy meadows are not so prone to degradation because of their relative abundance of water. The high moisture content of the ground makes them immune to pika attacks.

Piedmont and floodplain swampy meadows are considered stable as they have a PtD value between 2 and 3. Both have experienced degradation at all severity levels (Table 2), with moderately and severely degraded swampy meadows comprising roughly one third of the total sites. Their moderate vulnerability is attributed to their low water reserve and limited chances of hydrologic replenishment. Although floodplain swampy meadows have a higher water reserve, they are not rehydrated frequently. Apart from the direct recharge by rainwater, their primary source of replenishment is river water during infrequent flooding. In contrast, piedmont swampy meadows are constantly replenished via surface and subsurface inflows from upland. However, there is also a high rate of outflow.

Terrace and alpine swampy meadows are the most vulnerable and prone to degradation with a PtD value ≥ 3 (Table 2). Terrace swampy meadows are the most degraded due to their remoteness from the water flow from upslopes. Their high ground from the river channel means that they have a limited chance of being replenished by river water even during flooding. Although saturated with moisture, alpine swampy meadows are still prone to degradation for three reasons despite the fact they are the least subject to grazing due to their high elevation. First, their small extent and a highly limited water reserve make them sensitive to climate fluctuation. A minor drought can trigger degradation. Once their moisture level drops below a certain threshold, alpine swampy meadows become the ideal candidate for pika attacks. Second, they are located at the steepest terrain among all types of swampy meadows. Any effects caused by external disturbances are magnified disproportionately here and can trigger severe degradation easily. Third, located at the highest elevation among all the types of swampy meadows (Table 2), they have the smallest moisture/water contributing area.

5.2. Validation of the Propensity to Degrade Index

The observed PtD of the six types of swampy meadows (terrace swampy meadows were excluded from further study because they did not experience any change, e.g., no change from swampy meadow to ordinary meadow) is correlated closely with their annual rate of change during 1990–2013 (Figure 3) that had been detected from satellite images [22]. The regression relationship between the two can be represented as:

$$\text{Annual rate of change} = 12.31 - 9.009\text{PtD} \ (R^2 = 0.916) \quad (2)$$

The negative coefficient of 9.009 means that those swampy meadows having a larger PtD will be lost at a higher rate than those with a lower PtD. This close relationship indicates that the derived PtD is credible as it can show the propensity of a swampy meadow to degrade. Namely, those swampy meadows more prone to degradation disappeared at a faster pace than those having a lower PtD value during 1990–2013. Conversely, those more resilient ones actually gained more. For instance, alpine swampy meadows having the (second) highest PtD score of 3 suffered the highest rate of loss at 16 km^2 per annum (Figure 3). Having the lowest PtD score of 1.13, valley swampy meadows expanded by 3.3 km^2 annually. They are only one of the two types of swampy meadows whose area

increased during 1990–2013. Given their high mean elevation of 4252 m, their area should have shrunk instead of expanded. The explanation is the climate-enhanced melting of glaciers and possibly permafrost that causes more water to converge on the valley floor. The warmed climate in this region over the last two decades [22] accelerated snow melting and permafrost thawing, both of which facilitated the expansion of valley swampy meadows.

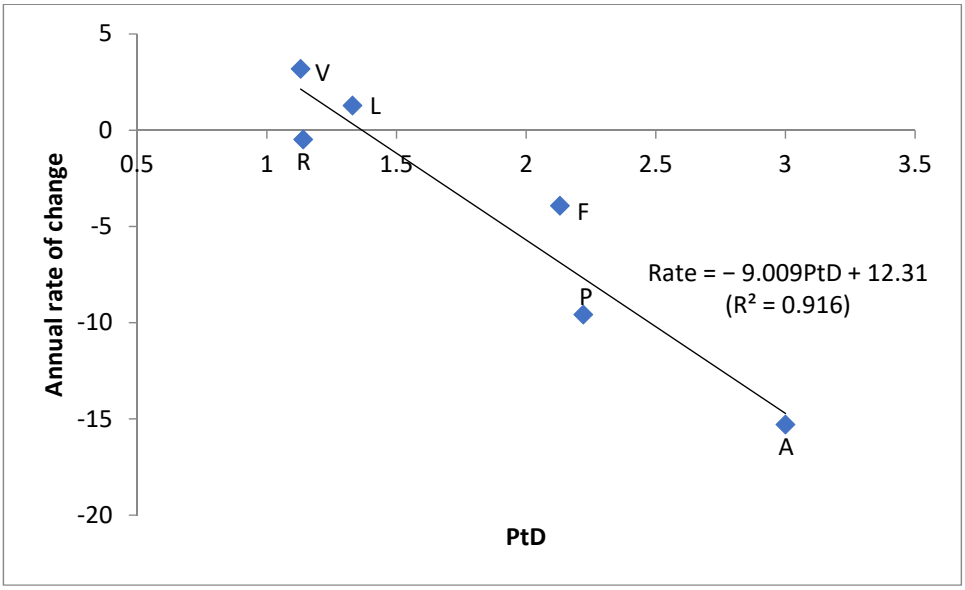


Figure 3. Regression relationship between the annual rate [(Area$_{2013}$–Area$_{1990}$)/(2013–1990), unit: km^2 per annum] of swampy meadow change during 1990–2013 derived from satellite images [22] and the derived propensity for degradation. A-alpine; F-floodplain; L-lacustrine; P-piedmont, R-riverine; V-valley (the same in Figures 4 and 5).

The high R^2 value (0.916) of Equation (2) validates that the derived PtD is able to reveal the propensity of swampy meadows to change reliably. It can be used to predict future changes based on the past environmental settings. In addition, the degradation indicators and the severity grading criteria in Table 1 used to derive the PtD score are appropriate and reasonable. They should be applicable to other areas with a similar setting.

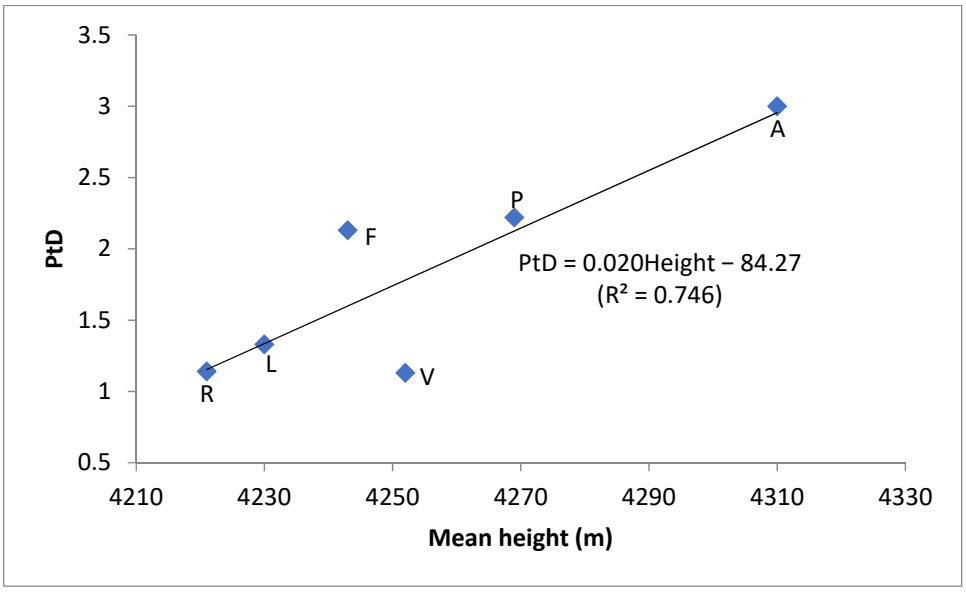
5.3. Influence of Topographic Variables on Degradation Propensity

The influence of topographic variables on the propensity of a swampy meadow type to degrade verbally described above was quantitatively analyzed, and the results are presented in this section. As shown in Figure 4a, the propensity of a given type of swampy meadow to degrade is related positively to its mean height (R^2 = 0.746, p = 0.027):

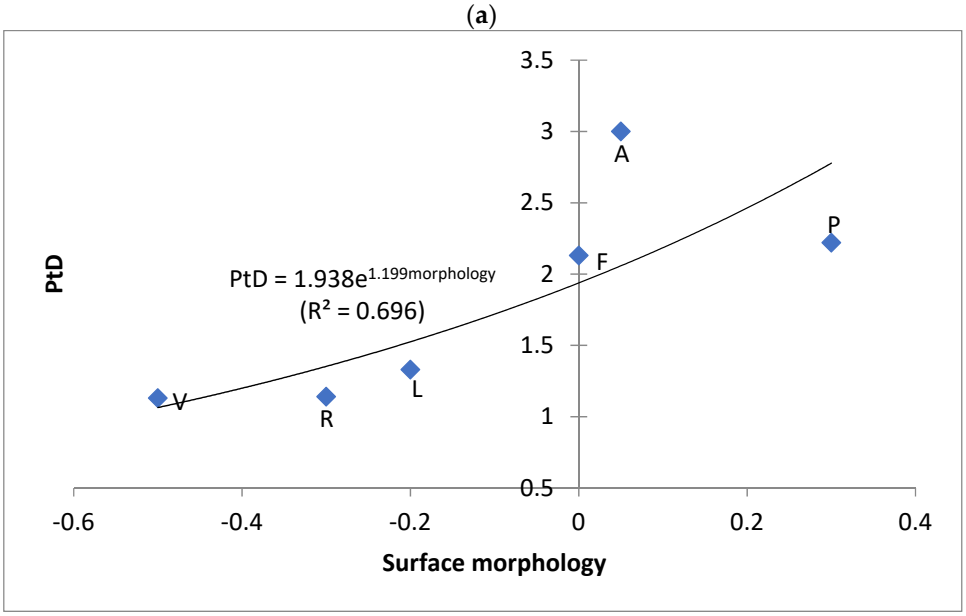
$$PtD_H = 0.0202Height - 84.273\ (R^2 = 0.746;\ p = 0.027) \quad (3)$$

The relationship between height and PtD is perfect for alpine, piedmont, lacustrine, and riverine swampy meadows (Figure 4a). As elevation rises, their PtD also rises linearly. The lowest propensity occurs in lacustrine and riverine swampy meadows whose elevation is lower than 4230 m a.s.l., while alpine swampy meadows are the most prone to change because of their highest elevation (≥4269 m a.s.l.) among all the swampy meadow types. This importance of elevation to PtD is consistent with the finding that changes in elevation will reduce habitat quality within the salt marshes in the San Francisco Estuary [36]. Nevertheless, the regression model is marred by two anomalies, the unusually low PtD of valley swampy meadows, and the slightly above the propensity trend of floodplain swampy meadows. Given their rather high elevation (4252 m a.s.l.), valley swampy meadows should receive a higher PtD score than their elevation suggests of 1.13 while floodplain swampy meadows' PtD should be lower than the current PtD value of 2.13 due to their lower

elevation (4243 m a.s.l.). These anomalies can be explained by the surface morphology to be discussed below.



(**a**)



(**b**)

Figure 4. Regression relationship between propensity to degrade (PtD) and topographic features for six types of swampy meadows. (**a**) Mean height (m) above sea level; (**b**) surface morphology.

If PtD is nonlinearly estimated from the weighted surface morphology, 69.6% of its variations can be accounted for by surface morphology (Equation (4)). This proportion is 5.0% lower than that of height. Hence, elevation is a more reliable predictor of a swampy meadow's PtD than surface morphology. The same conclusion can be drawn from the larger p value (0.039 versus 0.027). As shown in Figure 4b, riverine, lacustrine, and valley swampy meadows located in a concave topography all possess a low degree of PtD, which is explained by the accumulation of melted snow and glacier water converging inside them. In contrast, alpine and piedmont swampy meadows deviate from the general trend widely owing to their indistinct morphology or unusually high elevation.

$$\mathrm{PtD_M} = 1.938e^{1.199\mathrm{Morphology}} + 2.0484\ (R^2 = 0.696,\ p = 0.039) \quad (4)$$

6. Discussion

6.1. PtD and Topography

The established relationship between PtD and topography can be traced to water/moisture movement and water balance on a slope and in the catchment. Both are inherently affected by elevation in that water/moisture always flows from a higher ground to a lower one. A higher elevation is synonymous with a smaller catchment size and, hence, lower chances of rehydration. Admittedly, a swampy meadow at a higher elevation is grazed less intensively than its counterpart at a lower elevation, the reduced biomass exerts only a secondary impact on water reserve through evaporation in comparison with temperature. A lower elevation corresponds to a warmer temperature regime that enhances evaporation. Thus, elevation exerts the most direct influence on moisture availability and distribution at the local (e.g., watershed) scale and is, thus, the primary influential controller of PtD of plateau swampy meadows. Dissimilar to elevation that affects all types of swampy meadows indiscriminately, morphology dictates the local movement of water and moisture on a slope for only certain types of swampy meadow selectively.

6.2. Reference State of Degradation

Since intact swampy meadows can serve as the reference state of degradation, naturally, the PtD of a given type of swampy meadow can also be judged from the ratio of the number of degraded swampy meadows to the total number of observed swampy meadows. The portion of degraded swampy meadows out of the total samples (%) is treated as the dependent variable in another regression analysis (Figure 5). This variable achieved a high R^2 value of 0.735 (p = 0.029). This value is rather similar to, but slightly lower than, the 0.746 achieved by PtD. In the scatterplot, the position of the six types of swampy meadows in relation to the general trend is identical to that in Figure 4a. Therefore, the percentage of degraded sites is also a reliable indicator of the tendency of a swampy meadow to degrade, even though it is not as accurate as the PtD. The exact way of expressing degradation severity (e.g., enumerated in two versus four levels) does not alter the influence of elevation on a swampy meadow's PtD.

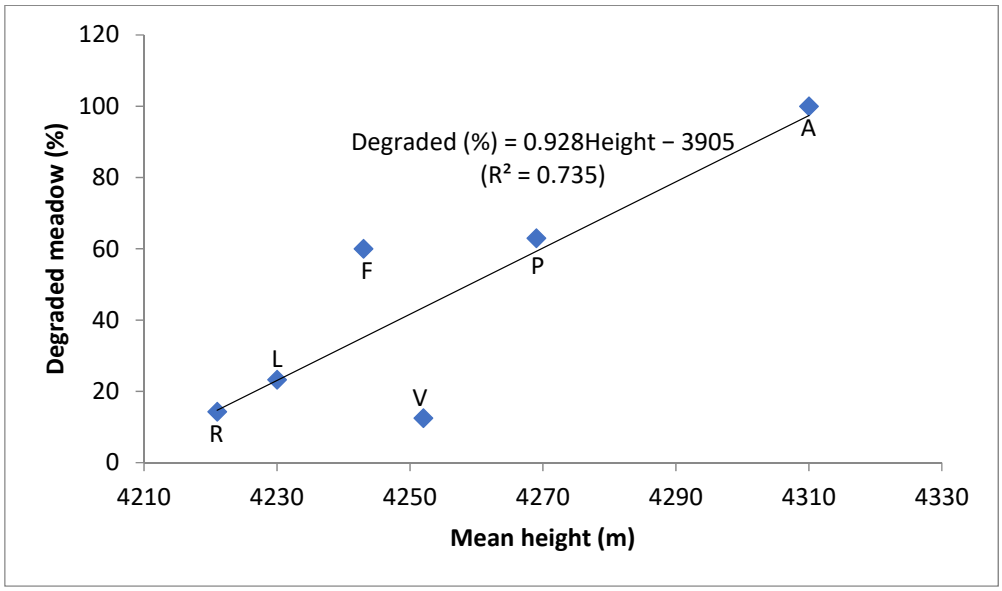


Figure 5. Regression relationship between the ratio of degraded swampy meadow sites to the total sampled sites (%) with their mean height among the six types of swampy meadow.

Due to the lack of the reference state, the 106 samples cannot be analyzed individually in a way similar to Equations (2) and (3). In fact, such regression relationship between topography and PtD may not exist at the individual swampy meadow level because the properties of one type of swampy meadows may overlap with those of another owing to

the spatial variation in their topographic features. The relationship becomes more apparent and definite after swampy meadows are grouped by their hydro-geomorphic properties. This grouping is conducive to revealing the topographic influence on the PtD of swampy meadows by type.

7. Conclusions

Derived from swampy meadow degradation severity based on the consideration of vegetation, hydrology, soil erosion, and pika damage, the proposed PtD index of plateau swampy meadows can predict their tendency of change by swampy meadow type in the study area reliably. This conclusion is backed by the close correlation of the calculated PtD score with the 1990–2013 annual rate of swampy meadow change detected from satellite images (R^2 = 0.916). The swampy meadows with a higher PtD index value shrank more while those with a lower PtD actually expanded. Of the seven types of swampy meadows, terrace and alpine swampy meadows are vulnerable to degradation judging by their highest PtD value. Both piedmont and floodplain swampy meadows are stable with a moderate PtD value. By comparison, valley, riverine, and lacustrine swampy meadows are resilient in having the lowest value. Such differential PtD is explained mostly by topography. The PtD of a given type of swampy meadow is related inversely to its mean elevation (R^2 = 0.746, p = 0.027). Elevation is a more effective predictor of the PtD of a swampy meadow type than surface morphology that explains only 69.6% of the variation in PtD (p = 0.039), 5% lower than elevation (p = 0.027). The level of degradation severity enumeration exerts little influence on the relationship between the mean elevation of a swampy meadow and its PtD. The findings of this study have practical value for proper meadow resource management in that those swampy meadows with a higher PtD value should be grazed less intensively to prevent them from degrading and to achieve sustainable animal husbandry.

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