J. Resour. Ecol. 2017 8(5) 526-537
DOI: 10.5814/j.issn.1674-764x.2017.05.010
www.jorae.cn

Assessment of Terrestrial Ecosystem Sensitivity and Vulnerability in Tibet

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Abstract: The Tibetan Plateau serves an important shelter function for the ecological security of Asia, and especially China. Here, we proposed and improved indicators and methods for assessing the ecological sensitivity and vulnerability of the terrestrial alpine Plateau ecosystems and assessed the freeze-thaw erosion, land desertification, water-caused soil loss, and land salinization sensitivity, together with ecological vulnerability, from the overall ecological sensitivity, ecological pressure, and elasticity aspects in Tibet. The results indicate that the terrestrial ecosystem of Tibet is quite sensitive to freeze-thaw erosion, land desertification and water-caused soil loss. Extremely and highly sensitive regions account for 9.62% and 83.69%, respectively, of the total area of the Tibet Autonomous Region. Extremely and highly vulnerable areas account for 0.09% and 52.61%, respectively, primarily distributed in the Himalayan and Gangdise mountain regions in west Tibet; the Nyainqentanglha, Tanggula, Hoh Xil, and Kunlun mountain regions; and the northwest and northern regions of the Changtang Plateau. The results will aid the development of customized protection schedules according to different ecological issues in each region.

Key words: freeze-thaw erosion; land desertification; water-caused soil loss; land salinization; ecological elasticity; ecological pressure

1 Introduction

The stability of the ecological environment is the foundation and precondition for the survival and development of humankind. Although the Chinese economy and society have experienced considerable development in recent years, the ecological environment is still worsening in the whole China and the ecological deficit will continue for a period of time in the future (Sun *et al.*, 2012b). Environmental issues remain serious, including soil erosion, land desertification, land salinization, sand storms, grassland degeneration, and wetland shrinkage, etc. Recently, the State Council issued an opinion about acceleration of the ecological civilization construction, which has built the basic framework and provided policy guarantees for ecological environmental protection work in China. One of the government's requirements is to assess the ecological sensitivity and vulnerability of land areas of China and further identify corresponding regions that must be under the strictest protection to guarantee ecological security in China.

Ecological sensitivity is the degree of ecosystem response to human activities and natural environmental change (Ouyang *et al.*, 2000). It can indicate to what extent ecological environmental issues are likely to occur in one particular region (Ouyang *et al.*, 2000). The ecological vulnerability of an ecosystem shows that it has weak ability to resist external disturbance, easily changing from one status to another, and is difficult to convert back to its original status (Qiao *et al.*,

Received: 2017-02-06 **Accepted:** 2017-08-01
Foundation: National Natural Science Foundation of China (41601458, 41771141); Natural Science Foundation of Jiangsu Province of China (BK 20170272)
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Citation: LI Yuanzheng, HAN Fengsen, ZHOU Hongxuan. 2017. Assessment of Terrestrial Ecosystem Sensitivity and Vulnerability in Tibet. *Journal of Resources and Ecology*, 8(5): 526–530.

2008). The resources and environment of a vulnerable ecosystem easily deteriorate towards to the trends of going against human utilization, thereby adversely affecting regional economic development (Tao *et al.*, 2006). Ecosystems that are more sensitive or vulnerable have a greater probability of experiencing ecological environment issues. Thus, more vulnerable ecosystems should receive greater attention for ecological protection and restoration. Although some researchers have studied the ecological sensitivity or vulnerability assessment of one type or various types of ecological issues in a nation, province, regional or watershed scale (Hornung *et al.*, 1995; Ouyang *et al.*, 2000; Shi and Liang, 2002; Liu *et al.*, 2003; Pan and Dong, 2006; Qiao *et al.*, 2008; Yan *et al.*, 2009; Pan *et al.*, 2012; Liu *et al.*, 2015), theories or case studies are rarely reported for terrestrial alpine and plateau ecosystems (Li *et al.*, 2005; Tao *et al.*, 2006; Zhang *et al.*, 2007; Yu and Lu, 2011), especially studies comprehensively focusing on ecological sensitivity and vulnerability assessments for the Tibet region. Moreover, some issues that exist in this field, including indicator selection, spatial discretization, and quantification of interactions and formulation of scientific grading standards for these indicators.

The Tibetan Plateau serves as an important shelter function for the ecological security of Asia, especially China (Zhong *et al.*, 2006; Sun *et al.*, 2012). The alpine climate ecosystem accounts for more than 90% of the area of Tibet (Zhong *et al.*, 2006), and it is characteristically sensitive and vulnerable. This region is within a narrow range of the ecological security threshold and low environmental population carrying capacity (Zhong *et al.*, 2006). The ecological environment is suffering unprecedented intense changes due to global warming and increase in anthropogenic activities, and therefore, various related issues are increasingly prominent (Zhong *et al.*, 2006; Sun *et al.*, 2012). According to the actual situation of ecological environment in Tibet we assessed the ecological sensitivity to freeze-thaw erosion, land desertification, water-caused soil loss, and land salinization of the Tibetan Plateau, together with its overall ecological vulnerability from three aspects based on the definition of vulnerability, including overall ecological sensitivity, ecological elasticity, and ecological pressure. This work is necessary and valuable for ecological protection in Tibet and will provide a reference for other regions with similar ecological environmental issues.

2 Data sources

MODIS data with 1 km resolution was provided by the International Scientific & Technical Data Mirror Site, Computer Network Information Centre, Chinese Academy of Sciences or the MODIS official website. These data included the average Normalized Vegetation Index data for August 2010, extracted by the TERRA satellite; land cover data for 2010, extracted by the combination of TERRA and AQUA satellites; and monthly average daytime land surface temperature (LST) data in January 2009 and night time daily LST data in July 2009, both extracted from the AQUA satellite data. Net primary productivity data for 2010 with 250-m resolution was provided by the Data Sharing Infrastructure of Urban and Regional Ecological Science. One-kilometer resolution digital elevation data and 1:1000 scale soil data in in the 1980s were provided by the Environmental and Ecological Science Data Center for West China. Daily climate data from 2008 to 2010 was provided by the China Meteorological Data Sharing Service System from 200 stations in Tibet and its four surrounding provinces. Society and economic data for 2010 was provided by the Data Sharing Infrastructure of Urban and Regional Ecological Science.

3 Indicators and methods

3.1 Assessment of ecological sensitivity

3.1.1 Assessment of freeze-thaw erosion sensitivity

Based on previous studies and data availability (Li *et al.*, 2005; Zhang *et al.*, 2007; Li *et al.*, 2011; Shi *et al.*, 2012), we used the following five main influence factors to assess freeze-thaw erosion sensitivity (Table 1): relief, annual maximum LST difference, annual precipitation, vegetation coverage, and annual minimum LST. Larger relief can result in more materials caused by freeze-thaw erosion and they can transport down farther due to the synthetic effect of precipitation and gravity. Large fluctuations in soil temperature result in a greater degree and depth of freezing and thawing (Zhu *et al.*, 1997; Zhang *et al.*, 2007). The maximum annual LST difference, defined as the difference between average day time LST in the warmest month and the night time LST in the coldest month, was used as an indicator of soil temperature fluctuation. Greater precipitation results in greater freeze-thaw erosion (Zhang *et al.*, 2007). Precipitation data were interpolated from three years of annual average data from 200 stations in Tibet and its four neighboring provinces using ordinary kriging. Lower vegetation coverage, calculated by the NDVI of a previous study (Han, 2012), results in greater freeze-thaw erosion (Zhang *et al.*, 2007). Table 1 presents the grading standard or method used for these indicators. The grading standards were formulated by referring to previous studies (Li *et al.*, 2005; Zhang *et al.*, 2007; Li *et al.*, 2011). Our study adapted the natural break method for indicators whose classification criteria were non-uniform or lacked sufficient scientific basis (Jenks, 1967; Li *et al.*, 2003; Martin *et al.*, 2003; Zhu *et al.*, 2007; Golian *et al.*, 2010; Köhl *et al.*, 2011). These indicators were divided into five classes by identifying breakpoints between classes that minimize the sum of the variance for each class. The indicators were set to 1, 3, 5, 7, and 9 after grading, corresponding to insensitivity, mild, moderate, high, and extreme sensitivity for freeze-thaw erosion, respectively. The sensitivity index was calculated by the weighted mean method, using graded indicators, and values for the annual average LST difference, annual average precipitation, relief, and vegetation coverage of 0.286, 0.198, 0.403, and 0.113, respectively (Li *et al.*, 2011). Then, the sensitivity index was assigned one of five degrees (Table 2). In addition, the freeze-thaw erosion will not occur in a region when the annual minimum LST is positive.

3.1.2 Assessment of land desertification sensitivity

Having considered the formation mechanism of land desertification and referring to previous studies (Pan and Dong, 2006; Helldén and Tottrup, 2008; Pan *et al.*, 2012; Becerril-Pina *et al.*, 2015; Liu *et al.*, 2015), we assessed land desertification sensitivity using four main factors: dryness, dust emission days in winter and spring, soil texture, and vegetation coverage. The aridity degree index, calculated using the previous classic method (Chen and Zhang, 1996; Liu *et al.*, 2015), reflects the incoming and outgoing situation of water sometime and somewhere, and represents the degree of dryness and wetness in a region. Dust emission days refer to the days with maximum wind speed greater than 6 m/s. The numbers of these days, both in winter and spring, could indicate the ability of wind to carry soil particles (Liu *et al.*, 2015). Soil texture indicates the difference in anti-erosion capability for soils with different grain-size composition (Liu *et al.*, 2015). In this study, gravelly soil was defined as soil with a gravel volume percentage of greater than 10%, referring to the soil texture classification standard of the Chinese soil survey and the rules published by the Ministry of Water Resources and Power in 1962. Non-gravelly soil was reclassified as sand, loam, or clay based on grain-size composition. Land desertification is more likely to occur in regions with less vegetation cover. Table 1 presents the grading standard or method for this issue (Chen and Zhang, 1996; Liu *et al.*, 2003; Pan and Dong, 2006; Pan *et al.*, 2012; Liu *et al.*, 2015). We multiplied these classified indicator layers and calculated the quarter power of the product to obtain the sensitivity index. Subsequently, the sensitivity index was assigned one of five degrees (Table 2).

3.1.3 Assessment of water-caused soil loss sensitivity

Having considered the formation mechanism and having referred to previous studies (Yoder and Lown, 1995; Wang *et al.*, 2001; Liu *et al.*, 2003; Pan and Dong, 2006; Pan and Feng, 2010; Pan *et al.*, 2012; Pradhan *et al.*, 2012; Pan and Wen, 2014; Liu *et al.*, 2015), we assessed water-caused soil loss sensitivity using four main factors: relief, vegetation coverage, rainfall erosivity and soil erodibility. The slope gradient and slope length were difficult to calculate on a

Table 1 Assessment indicators and their grading standards

Ecological environmental Issues	Indicators	Insensitivity	Mild Sensitivity	Moderate Sensitivity	High Sensitivity	Extreme Sensitivity
Freeze-thaw erosion	Relief (m)	0–20	20–50	50–100	100–300	>300
	Annual maximum LST difference (°C)	Natural break method				
	Annual precipitation(mm)	≤100	100–200	200–300	300–400	>400
	Vegetation coverage (%)	80–100	60–80	40–60	20–40	0–20
	Annual minimum LST (°C)	>0	≤0	≤0	≤0	≤0
Land desertification	Dryness	≤1.0	1.0–1.5	1.5-4.0	4.0–16.0	≥16.0
	Dust emission days in Winter and Spring	≤5	5–10	10-20	20–30	≥30
	Soil texture	Bedrock	Clay	Gravelly	Loamy	Sandy
	Vegetation coverage (%)	80–100	60–80	40–60	20–40	0–20
Water-caused soil loss	Relief (m)	0–20	20–50	50–100	100–300	>300
	Rainfall erosivity ($m*t*cm*hm^{-2}*h^{-1}*y^{-1}$)	≤25	25–100	100–400	400–600	>600
	Vegetation coverage (%)	80–100	60–80	40–60	20–40	0–20
	Soil erodibility	≤0.27	0.27–0.42	0.42–0.52	0.52–0.62	>0.62
Land salinization	Soil conductivity ($Ds*m^{-1}$)	Natural break method				

Table 2 Grading standards for ecological sensitivity, ecological elasticity, ecological pressure and ecological vulnerability

Value	Ecological Sensitivity Degree	Ecological Elasticity Degree	Ecological Pressure Degree	Ecological Vulnerability Degree
≤2.0	Insensitivity	Extreme elasticity	Non-pressure	Non-vulnerability
2.0–4.0	Mild sensitivity	High elasticity	Mild pressure	Mild fragility
4.0–6.0	Moderate sensitivity	Moderate elasticity	Moderate pressure	Moderate fragility
6.0–8.0	High sensitivity	Mild elasticity	High pressure	High fragility
>8.0	Extreme sensitivity	Inelasticity	Extreme pressure	Extreme vulnerability

large scale. Relief is commonly used to reflect the terrain factor (Wang *et al.*, 2001). Water-caused soil loss is more likely to occur in the region with less vegetation coverage. Rainfall erosivity was firstly calculated using the Wischmeire method by considering precipitation in each month and the whole year (Wischmei.Wh and Mannerin.Jv, 1969; Huang, 2012). We then used the linear regression method to convert its units to commonly used ones in China based on the above calculated and previously published rainfall erosivity in primary observation stations in China (Wang and Jiao, 1996). Soil erodibility was calculated as reported in a previous study by comprehensively considering the content of sand, silt, and clay grain, as well as organic carbon (Yu *et al.*, 2014). Table 1 presents the grading standard or method for this issue (Wang *et al.*, 2001; Liu *et al.*, 2003; Pan and Dong, 2006; Pan *et al.*, 2012; Liu *et al.*, 2015). Subsequently, the sensitivity index was calculated by the weighted mean method, using the grading layers of these indicators. Weights for relief, rainfall erosivity, vegetation coverage, and soil erodibility were set as 0.35, 0.25, 0.25 and 0.15, respectively, as noted in the previous study (Pan and Dong, 2006). Then, the sensitivity index was assigned one of five degrees (Table 2).

3.1.4 Assessment of land salinization sensitivity

Electrical conductivity measurements are a popular and reliable tool for land salinization monitoring and assessment. Salt content of a soil can be estimated from electrical conductivity of the soil (Marion and Babcock, 1976; Rhoades *et al.*, 1999; Corwin and Lesch, 2003). To include all grades of these salinization soils, we divided the soils of China into five grades based on electrical conductivity using the natural break method, and then extracted the grading result by the Tibet border.

3.1.5 Assessment of overall ecological sensitivity

Ecological sensitivity was defined as the maximum value of the abovementioned four sensitivity assessment layers.

3.2 Assessment of ecological vulnerability

3.2.1 Assessment of ecological pressure

Ecological pressure is caused by human social and economic activities associated with survival and development. Resource pressure was assessed by the net primary productivity (NPP) per standard sheep. This indicator considered only NPP that could be empirically utilized by pasture, mainly distributed in various grasslands, sparse brushwood, permanent wetland, barren, or sparsely vegetated land cover. Poor economic condition results in greater pressure for economic development. We used the gross domestic product (GDP) per capita to reflect this aspect. Population density indicates the degree of human disturbance to the natural environment. For counties next to national boundaries, we calculated the abovementioned indexes exclusively for the region actually controlled by China, and set the values to the corresponding counties. These three indicators were all graded by the natural break method. Subsequently, the ecological pressure index was calculated by the weighted mean method, using the grading layer of these indicators. The weights were empirically set as 0.50, 0.30, and 0.20, for the NPP per standard sheep, GDP per capita, and population density indicators, respectively (Qiao *et al.*, 2008). Then, the ecological pressure index was graded to five degrees (Table 2).

3.2.2 Assessment of ecological elasticity

Ecological elasticity refers to self-adjusting and self-recovery characteristics of the ecological system when internal and external disturbance or pressure does not exceed a defined elastic threshold (Qiao *et al.*, 2008). Ecological elasticity was evaluated using three major indicators: vegetation potential productivity, vegetation coverage, and soil organic carbon content. Vegetation potential productivities were calculated for all climate stations using the Thornthwaite Memorial model, based on temperature and precipitation data (Lieth and Box, 1972), which were interpolated with 1 km resolution by ordinary kriging. The vegetation coverage was divided into five grades, including 0%–20%, 20%–40%, 40%– 60%, 60%–80%, 80%–100%, corresponding to inelasticity, mild, moderate, high and extreme elasticity, respectively. The grades for the other two indicators were separated by the natural break method. In order to include all grades of these indicators, we divided soil organic carbon content for all of China and the vegetation potential productivities for Tibet and its four surrounding provinces into five grades and then extracted data by the Tibetan border. Subsequently, the ecological elasticity index was calculated by the weighted mean method, using these grading layer of these indicators. Based on the method of scoring by experts, weights were empirically set to 0.45, 0.35, and 0.20, for vegetation potential productivity, vegetation cover, and soil organic carbon content indicators, respectively. Then, the ecological elasticity index was graded to five degrees, as presented in Table 2.

3.2.3 Assessment of ecological vulnerability

The ecological vulnerability index was evaluated by the weighted mean method, considering overall ecological sensitivity, ecological elasticity, and the ecological pressure, whose weights were empirically set as 0.50, 0.25, and 0.25, respectively (Qiao *et al.*, 2008). The ecological vulnerability was graded according to five degrees (Table 2).

4 Results

4.1 Assessment of ecological sensitivity

4.1.1 Assessment of freeze-thaw erosion sensitivity

Relief was extremely large and extremely sensitive for the freeze-thaw erosion issue in Tibet, except for the Changtang Plateau region, where the relief was quite large and highly sensitive (Fig. 1a). In general, the LST difference and its sensitivity increased progressively from southeast to northwest (Fig. 1b), whereas the annual precipitation was opposite (Fig. 1c). Vegetation decreased while its sensitivity increased from southeast to northwest (Fig. 1d). The minimum LST was negative in the vast majority of Tibet except for the southeast region (Fig. 1e).

The extreme sensitivity region for freeze-thaw erosion, with an area of 57 856 km^2, accounting for 4.87% of the total area of the Tibet (Table 3), was centralized in the Himalayas and Gangdise mountain regions in west Tibet (Fig. 1f), The high sensitivity region, with an area of 935 070 km^2, was widely distributed and accounted for 78.71% of the area of Tibet. The moderate sensitivity region was mainly distributed in the north region. The mild sensitivity region in Tibet, which accounted for 3.67% of the area of Tibet, was mainly in the southeast region.

4.1.2 Assessment of land desertification sensitivity

The dust emission wind factor associated with land desertification issue was extremely sensitive in all of Tibet. In general, dryness and its sensitivity increased progressively from southeast to northwest (Fig. 2a). Most soil had moderate sensitivity in Tibet, and the remaining soil was mainly of the extreme sensitivity type, and centralized in the northwest region (Fig. 2b). The vegetation factor was the same as that mentioned above.

The extreme sensitivity region for the land desertification was centralized in the northwest side of Tibet (Fig. 2c), in an area of 53 502 km^2, which accounted for 4.50% of the total area of Tibet (Table 3). The adjacent area was a widely distributed, high sensitivity region that covered a vast majority of the northwest part, with an area of 616 562 km^2, accounting for 51.90% of the area of Tibet. The moderate and mild sensitivity region was mainly distributed in the southeast. No area of insensitivity existed.

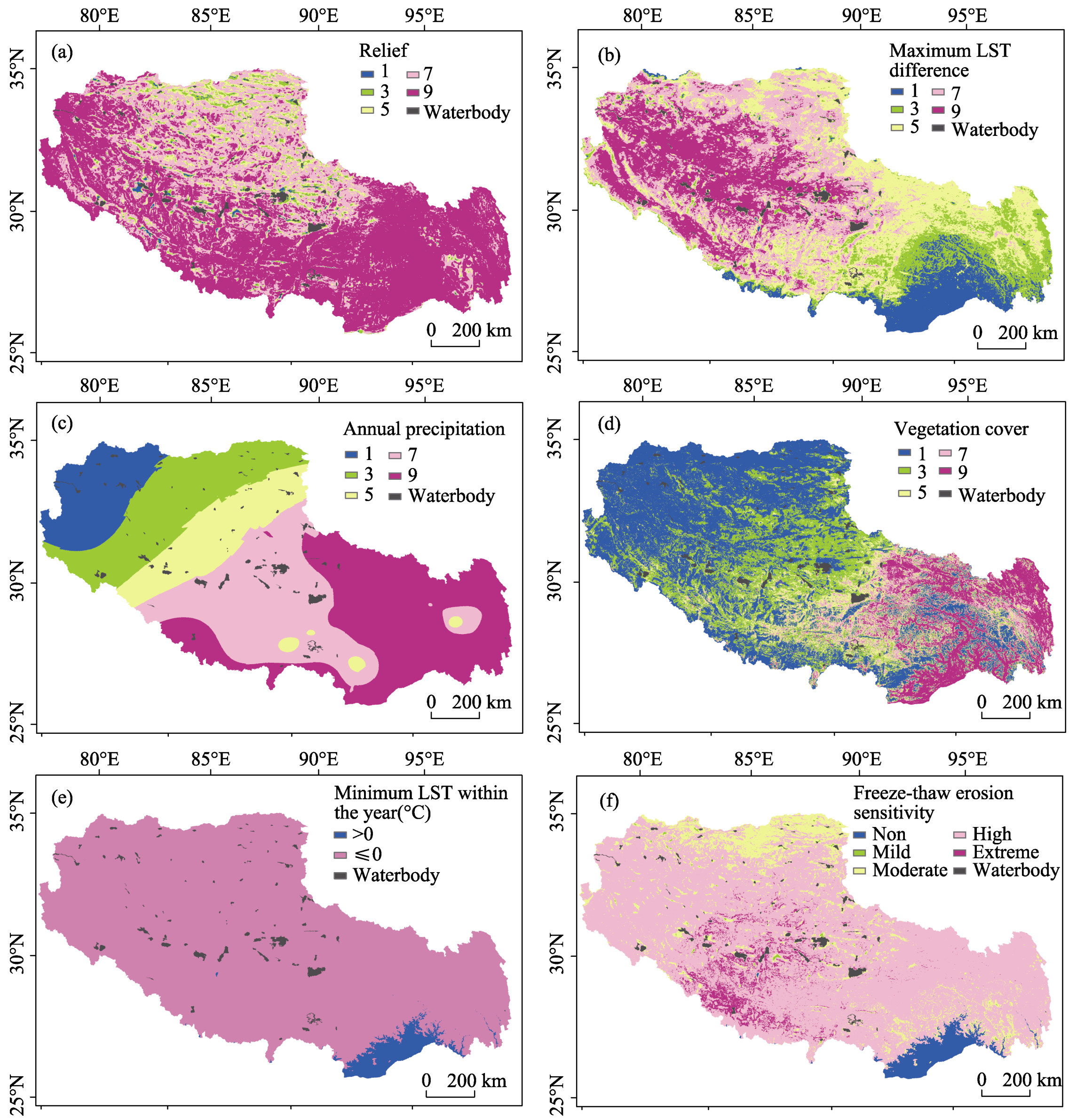

Fig.1 Sensitivity distribution of freeze-thaw erosion and influential factors in Tibet. The indicators were set to 1, 3, 5, 7, or 9, corresponding to insensitivity, or mild, moderate, high, or extreme sensitivity for freeze-thaw erosion, respectively.

Table 3 Area statistics for ecological sensitivity, ecological elasticity, ecological pressure and ecological vulnerability in various degrees. PCT means the proportion of total area of Tibet.

Ecological environmental issues	Indexes	Non	Mild	Moderate	High	Extreme
Freeze-thaw erosion sensitivity	Area(km^2)	43 575	3 231	148 246	935 070	57 856
	PCT(%)	3.67	0.27	12.48	78.71	4.87
Land desertification sensitivity	Area(km^2)	0	312 301	205 613	616 562	53 502
	PCT(%)	0.00	26.29	17.31	51.90	4.50
Water-caused soil loss sensitivity	Area(km^2)	168	35 727	717 247	434 836	0
	PCT(%)	0.01	3.01	60.38	36.60	0.00
Land salinization sensitivity	Area(km^2)	1 168 387	5 019	4 211	6 971	3 390
	PCT(%)	98.35	0.42	0.35	0.59	0.29
Ecological sensitivity	Area(km^2)	0	1 668	77 852	994 219	114 239
	PCT(%)	0.00	0.14	6.55	83.69	9.62
Ecological pressure	Area(km^2)	28 139	585 454	444 699	116 977	12 709
	PCT(%)	2.37	49.28	37.43	9.85	1.07
Ecological elasticity	Area(km^2)	278 496	513 922	300 675	94 857	28
	PCT(%)	23.44	43.26	25.31	7.98	0.00
Ecological vulnerability	Area(km^2)	0	31 488	530 515	624 944	1 031
	PCT(%)	0.00	2.65	44.66	52.61	0.09

4.1.3 Assessment of water-caused soil loss sensitivity

Relief and vegetation coverage factors were the same as mentioned above. The rainfall erosivity factor mainly had mild and moderate sensitivity (Fig. 3a). The soil erodibility factor was mildly sensitive for water-caused soil loss in Tibet, except for insensitivity in some of the northwest and north regions (Fig. 3b). No extreme sensitivity region existed. Much of the high sensitivity region for water-caused soil loss was centralized in the mountainous regions in the northwest and west of Tibet (Fig. 3c). Some of the high sensitivity region included some mountain regions in eastern Tibet, encompassing an area of 434 836 km^2 and accounting for 36.60% of the total area of Tibet (Table 3). The moderate sensitivity region was widely distributed, accounting for 60.38% of the area of Tibet. The mild sensitivity region was centralized in the local region of northern Tibet between the Tanggula and Nyainqentanglha mountains and accounted for 3.01% of the area of Tibet. Only a small region of mild sensitivity existed.

4.1.4 Assessment of land salinization sensitivity

The insensitivity region for land salinization was the most widely distributed region (Fig. 4), accounting for 98.35% of the total area of the Tibet (Table 3). The areas for other degree sensitivity types were minimal and mainly distributed in the great lakes basin region in the Changtang Plateau.

4.1.5 Assessment of overall ecological sensitivity

The total region of extreme sensitivity had an area of 114 239 km^2, accounting for 9.62% of the total area of Tibet (Table 3), mainly included the Himalayas and Gangdise mountain regions in west Tibet and northwest side of Tibet (Fig. 5). The high sensitivity region was widely distributed, with an area of 994 219 km^2, and accounting for 83.69% of the area of Tibet. The moderate sensitivity region was centralized in southeastern Tibet, accounting for 6.55% of the total area of Tibet. The mild sensitivity region in Tibet was small, and no insensitive region existed.

4.2 Assessment of ecological vulnerability

4.2.1 Assessment of ecological pressure

Resource pressure was relatively large in areas of Tibet with denser population and moderate natural conditions (Fig. 6a). The distribution rule of economic pressure was relatively complex (Fig. 6b). In general, there is less economic pressure in regions containing an administration center or boundary trade port, development of mineral or hydropower resources, tourism resources, airports, or good natural conditions. Given the limited population, extreme economic pressure did not tend to occur in the region with the worst natural conditions, but was noted in regions with relatively denser population and moderate natural conditions. Population pressure was relatively higher in the wide river valley region of Yarlung Zangbo, Nyang Qu, Lhasa, Yarlung river and so on in west Tibet, and it was relatively lower in northwest and southeast Tibet (Fig. 6c).

The extreme ecological pressure region was centralized in some local counties between the Himalayas and Gangdise mountain regions in southwest Tibet (Fig. 6d), accounting for an area of 12 709 km^2 and 1.07% of the total area of Tibet (Table 3). The high pressure region was mainly widely distributed between the Himalayas, and the Gangdise-Nyainqentanglha mountains, with an area of 116 977 km^2 that accounted for 9.85% of the area of Tibet. The moderate sensitivity region was mainly distributed in the north region of Tibet. A minimal mild sensitivity region was noted in

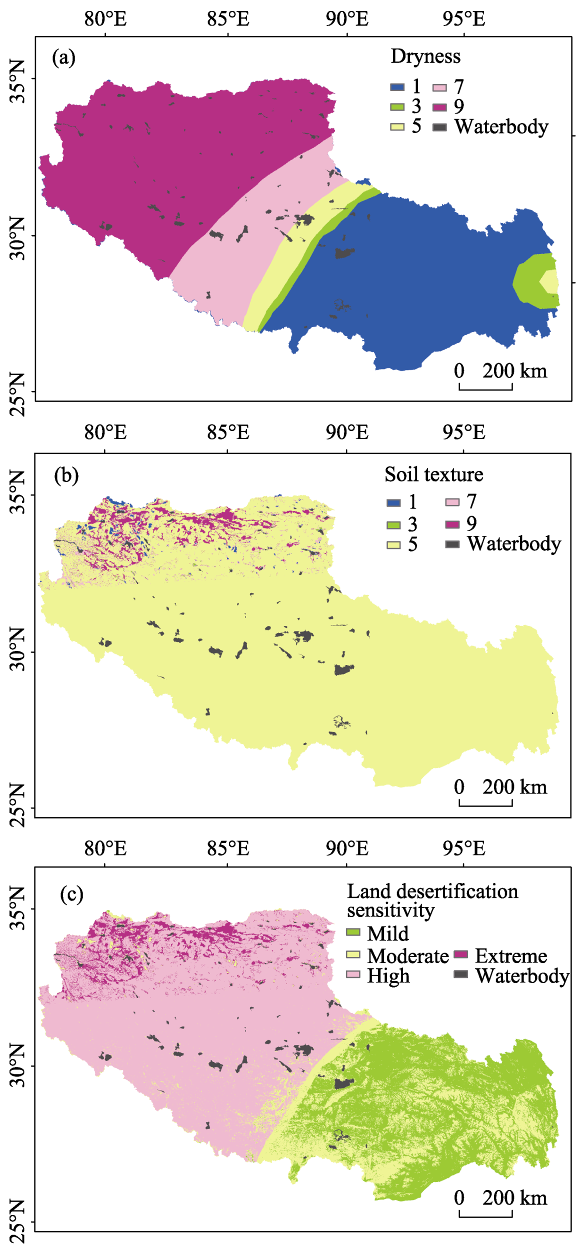

Fig.2 Sensitivity distribution of the land desertification and its major influential factors in Tibet. The indicators were set to 1, 3, 5, 7, or 9, corresponding to insensitivity, or mild, moderate, high, or extreme sensitivity for land desertification, respectively.

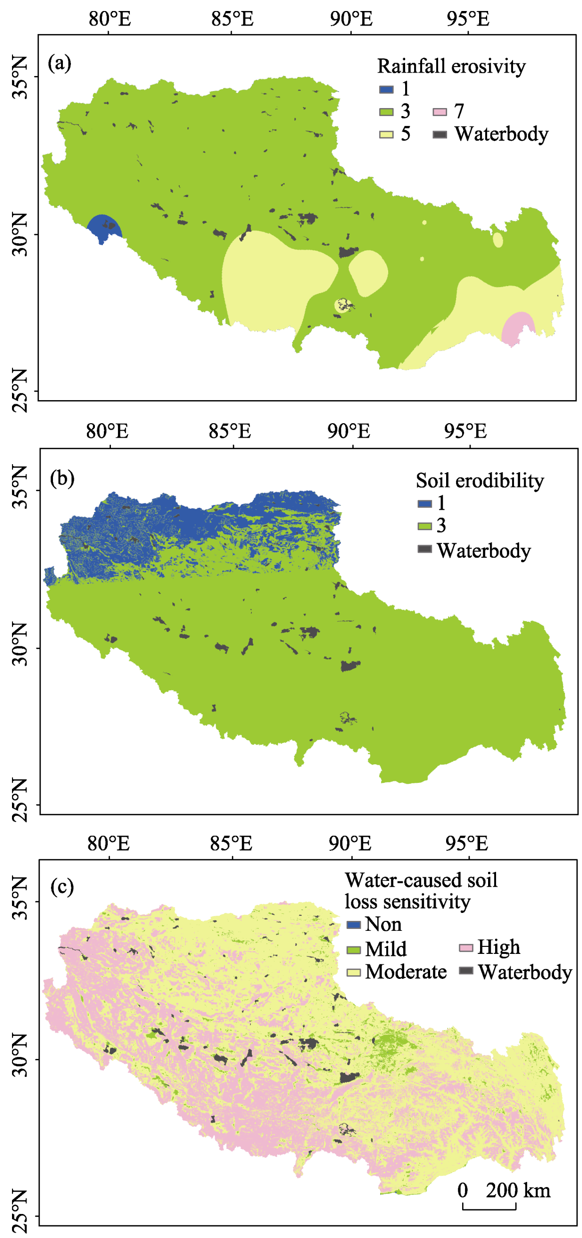

Fig.3 Sensitivity distribution of water-caused soil loss and its major influential factors in Tibet. The indicators were set to 1, 3, 5, or 7, corresponding to insensitivity, or mild, moderate, or high sensitivity for water-caused soil loss, respectively.

Tibet (3.67% of the area of Tibet) mainly in the southeast region. The mild and non-pressure regions were centralized in northwest and southeast Tibet. The remaining area had moderate pressure.

4.2.2 Assessment of ecological elasticity

In general, vegetation potential productivity and its ecological elasticity decreased from southeast to northwest of Tibet (Fig. 7a). From the soil organic carbon aspect, the ecosystem mainly exhibited mild elasticity (Fig. 7b). The vegetation coverage factor was the same as previously mentioned.

Ecological elasticity generally decreased from southeast to northwest of Tibet (Fig. 7c). The non-elasticity region was 278 469 km^2, accounting for 23.44% of the total area of Tibet (Table 3). The mild elasticity region was 513 922 km^2 and amounted for 43.26% of the area of Tibet. No extreme elasticity region existed.

4.2.3 Assessment of ecological vulnerability

The extreme vulnerability region was centralized in the local region between the Himalayas and Gangdise mountain regIons in southwest Tibet (Fig. 8), with an area of 1 031 km^2, accounting for 0.09% of the total area of Tibet (Table 3). The high vulnerability region was widely distributed in mountainous regions in west Tibet; the Nyainqentanglha,

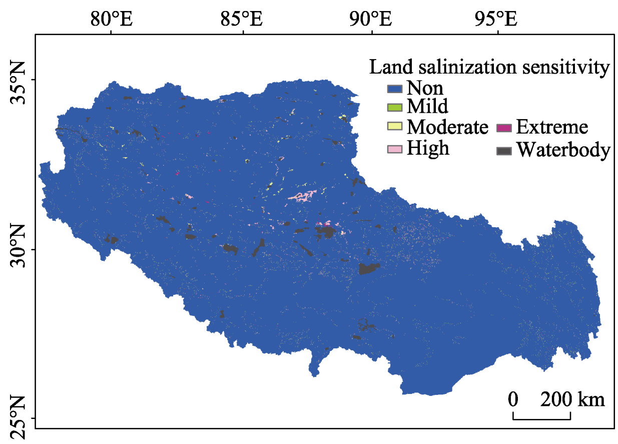

Fig.4 Distribution of the land salinization sensitivity in Tibet

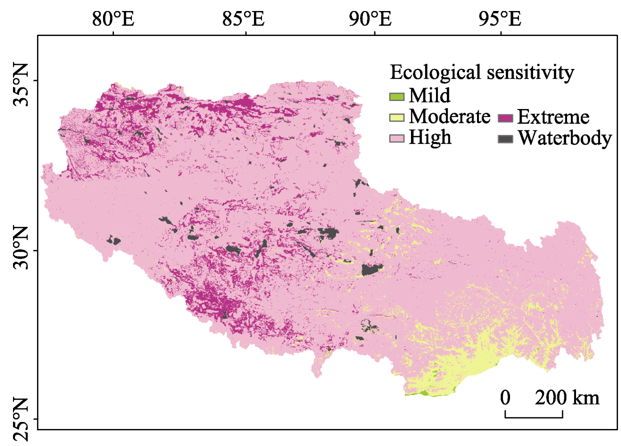

Fig.5 Distribution of the overall ecological sensitivity in Tibet

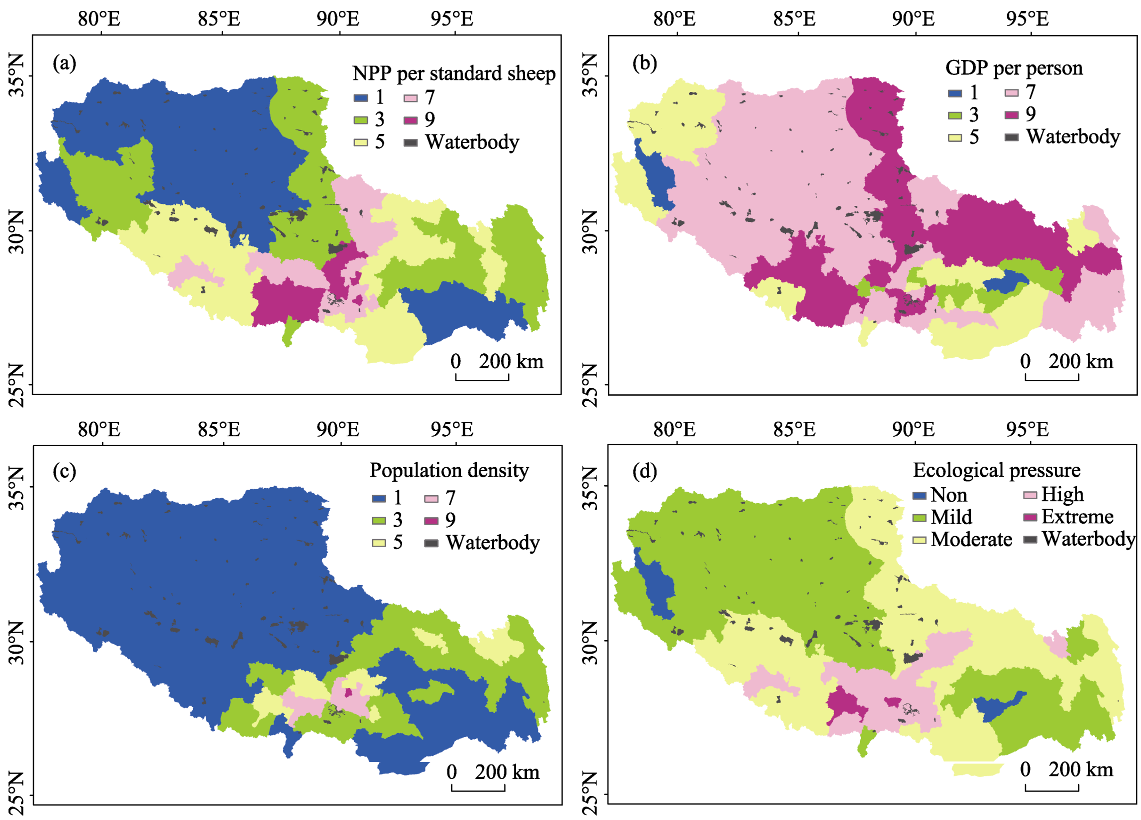

Fig.6 Distribution of the ecological pressure and major influential factors in Tibet. The indicators were set to 1, 3, 5, 7, or 9, corresponding to non-pressure, mild, moderate, high, or extreme pressure, respectively.

Tanggula, Hoh Xil, and Kunlun mountain regions; and the northwest and north regions of Changtang Plateau, with an area of 624 944 km^2 and accounted for 52.61% of the area of Tibet. The remaining areas of Tibet were a moderate vulnerability region, except some regions in southeast Tibet, accounting for 2.65%.

5 Discussion

Limited by the complexity of ecological environmental issues, data source availability, and other factors, existing indicators could not account or correctly account for some critical ecological factors. To the best of our knowledge, a method of quantitatively determining loss due to freeze-thaw erosion has not been reported in the scientific literature, although some authors have used typical indicators to assess this issue (Li *et al.*, 2005; Zhang *et al.*, 2007; Li *et al.*, 2011; Shi *et al.*, 2012). In these studies, lithology has not been considered. Soil temperature change has usually been indicated using annual air temperature differences calculated by longitude, latitude and altitude data based on observed records in stations, and slope aspect (Zhang *et al.*, 2007; Li *et al.*, 2011; Shi *et al.*, 2012). We used annual LST difference

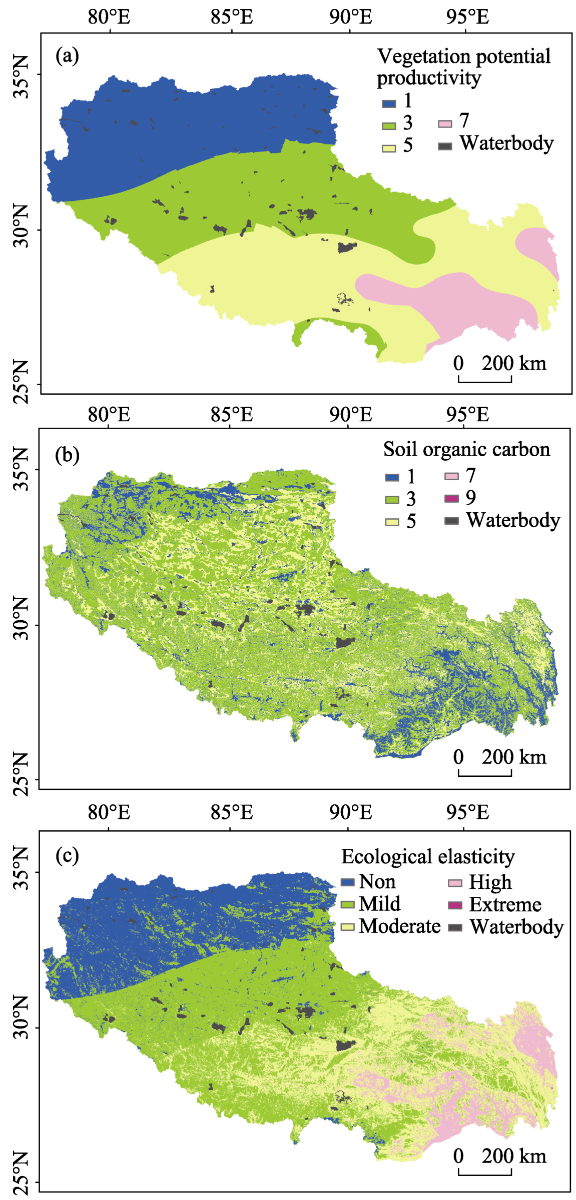

Fig.7 Distribution of ecological elasticity and influential factors in Tibet. The indicators were set to 1, 3, 5, 7, or 9, corresponding to inelasticity, mild, moderate, high, or extreme elasticity, respectively.

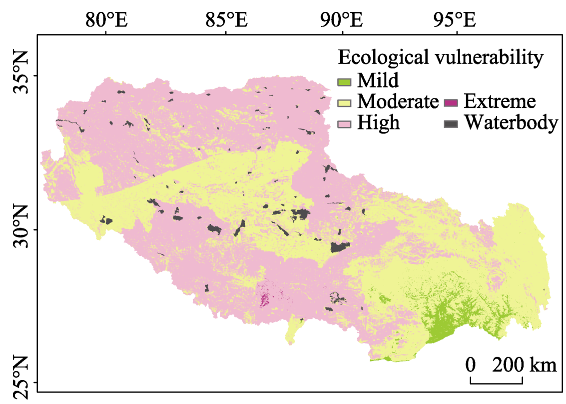

Fig.8 Distribution of ecological vulnerability in Tibet

derived from satellite data to more accurately approximate soil temperature change than the air temperature difference (Zhang *et al.*, 2007; Li *et al.*, 2011; Shi *et al.*, 2012). The LST data of MODIS has been validated with high accuracy in many cases and widely accepted and used, although uncertainties or issues remain, especially for areas of complex terrain or vegetation due to the known anisotropy issue (Clinton and Gong, 2013). Meanwhile, obvious bias exists for calculated air temperature, especially in regions with high heterogeneity. For assessment of water-caused soil loss sensitivity, we calculated soil erodibility rather than simply using soil texture (Wang *et al.*, 2001; Liu *et al.*, 2003; Pan and Dong, 2006; Pan *et al.*, 2012; Liu *et al.*, 2015). Previous studies generally used the degree of mineralization or depth to ground water to assess land salinization sensitivity (Liu *et al.*, 2003; Pan and Dong, 2006; Ma and Yi, 2011; Mamatsawut *et al.*, 2012; Pan *et al.*, 2012; Liu *et al.*, 2015). However, it was generally difficult to identify a sufficient amount of site-specific data. Landform types or slope data have often been adapted to reflect the groundwater level (Liu *et al.*, 2003; Pan and Dong, 2006; Wiebe *et al.*, 2007; Ma and Yi, 2011; Mamatsawut *et al.*, 2012). Irrigation and drainage data were also typically neglected. Having considered the ecological environmental characteristic in the pastoral area, we proposed exploitable NPP per standard sheep to indicate resource pressure, which can not only consider grassland area like the previous study (Tao *et al.*, 2006), but also the grass quality for a standard sheep. Different utilization rates of the NPP for different land cover types were not considered. It was our opinion that peasant income per capita indicates economic pressure better than the GDP per capita. In addition, it is difficult to realize spatial discretization for social and economic indicators. Such indicators could not precisely align with individual land parcels. Social and economic indicators are generally collected based on administration cells at the country level. Additionally, spatial heterogeneity often exists for social and economic conditions in an internal administrative unit, especially within large areas or areas of severely changed natural conditions.

The interactive effect among various indicators was complex. The contribution rates of the various indicators were different, and thus, the assessment results would be quite different if the indicator weights were assigned different values. Previously, weights were typically established the same for land desertification, water-caused soil loss, and land salinization assessment, resulting in some errors (Wang *et al.*, 2001; Liu *et al.*, 2003; Pan and Dong, 2006; Wiebe *et al.*, 2007; Yan *et al.*, 2009; Ma and Yi, 2011; Pan *et al.*, 2012; Liu *et al.*, 2015). Based on experience and the outcomes of previous studies, we assigned different values to indicators for the freeze-thaw erosion and water-caused soil loss sensitivity (Pan and Dong, 2006; Li *et al.*, 2011), ecological pressure, elasticity, and vulnerability assessment. The limited effect of these indicators cannot be disregarded. For example, freeze-thaw erosion cannot occur if the annual minimum LST value is positive. The best solution is to adopt the model that is based on the ecological process and has clear ecological meaning, such as the Revised Universal Soil Loss Equation, or use an indicator that can indicate the ecological environmental issue situation. For instance, we adopted soil electric conductivity to assess the land salinization, due to this metric can directly and effectively reflect the water-salt movement final result. Although soil properties have changed minimally for quite some time, and the available soil data are relatively old, this issue will be solved with the recently appealed third national soil survey of China.

The grading standard should additionally be based on economic meaning of each indicator. If the grading standards are scientifically based on field experiment studies, the ecosystem assessment results for the larger region will be valid and credible when geospatial information technology is employed. These standards were different for some indicators, such as the relief factor (Wang *et al.*, 2001; Liu *et al.*, 2003; Li *et al.*, 2005; Pan and Dong, 2006) and annual precipitation (Li *et al.*, 2005; Li *et al.*, 2011), which could lead to different assessment results. Although the grading standards were uniform for some indicators, it did not indicate that no issues existed. For instance, vegetation coverage is not simply linearly correlated with these ecological issues, and the applicable grading standards should be different for different issues. The present standard was to some degree too simple and crude. The natural break method was typically adopted for indicators without any grading standards. This method was suitable for only the variables fitting a normal distribution. However, numerous data cannot fit this condition, even after various transformations. The Head/Tail Breaks method was also not suitable for use because a precondition of its use is that data are heavily right skewed (Jiang, 2013). Grading standards are based only on statistics do not have specific ecological meaning, even if the original or the transformed data were fitted to either normal or heavy-tailed distribution. Another popular method was as follows. All indicators were first normalized to [0,1]. Transformation values were subtracted by 1, if the factors were negatively correlated with the assessment issue. Finally, all indicators were set to different weights to calculate a final assessment score (Tao *et al.*, 2006; Qiao *et al.*, 2008; Yu and Lu, 2011). Essentially, this system provides relative grading. Some ecological indicators do not span all grades, especially for regions with limited area or homogeneous natural conditions. Absolute grading is more valid than a grading standard.

The method of maximum value and weighting are two commonly used methods to synthesize various types of ecological sensitivity (Yan *et al.*, 2009). The previous method uses the maximum value of various ecological sensitivity values as the overall sensitivity. It can reflect the serious degree of the most primary issue of ecological environment. Moreover, humans do not need to assign weight values for each type of ecological sensitivity and subjectivity is avoided. However, when using this method other ecological environmental issue are neglected. The method of weighting usually calculates weighted averages of all ecological environmental sensitivity. It can consider all ecological environmental issues. Nevertheless, three main defects existed. First, humans need to assign weight values for each type of ecological sensitivity that can bring in a certain humans' subjectivity. Second, the weight values are usually set based on the serious degree of various ecological environment in a region. Therefore, these weight values may variate in different sub regions when the study area is too large. Third, the concern extent for the most serious ecological issue can be weakened. The main goal to assess the ecosystem is to find the most serious issue and furtherly make corresponding protecting measures. Based on the analysis mentioned above, here we chose the method of maximum value to synthesize various types of ecological sensitivity.

The global change effect is more obvious for sensitive and vulnerable ecosystems in Tibet. However, this factor has not been considered given its extreme complexity.

6 Conclusions

Based on previous studies and the actual conditions in Tibet, we proposed and improved assessment indicators and methods for assessing of ecological sensitivity and vulnerability of terrestrial alpine and plateau ecosystems. We assessed freeze-thaw erosion, land desertification, water-caused soil loss, and land salinization sensitivity, together with overall ecological vulnerability with respect to overall ecological sensitivity, ecological pressure and elasticity aspects.

The areas of extreme ecological sensitivity mainly included the freeze-thaw erosion regions, centralized in the Himalayas and Gangdise mountain regions in west Tibet, and the land desertification regions that are mainly located in northwest Tibet. These areas account for 9.62% of the total area of Tibet. Except for the land salinization issue, the high sensitivity regions were widely distributed for other three issues, accounting for 83.69% of Tibet. The remaining regions which account for 6.55% of the area of Tibet and are mainly located mainly in northeast Tibet, were determined to be moderately sensitive.

The extremely vulnerable region, which accounts for 0.09% of the total area of Tibet, is centrally distributed in the region between the Himalayas and Gangdise mountain regions in southwest Tibet. The highly vulnerable region, which accounts for 52.61% of the area of Tibet, was widely distributed in the mountainous regions of west Tibet; the Nyainqentanglha, Tanggula, Hoh Xil, and Kunlun mountain regions; and the northwest and north region of Changtang Plateau.

Spatial distribution assessments are necessary and helpful for proposing customized protection schedules, based on limiting factors in each region. Many issues remain that require the assessment of ecological sensitivity and vulnerability, such as indicator selection, spatial discretization for social or economic indicators, and quantification of the interaction and scientific grading standards formulation for these indicators.

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西藏陆地生态系统敏感性和脆弱性评估

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摘　要：青藏高原的生态平衡对中国乃至亚洲的生态安全具有极为重要的作用。本文提出和改进了针对高山高原陆地生态系统生态敏感性和脆弱性评估的指标和方法；评价了西藏自治区的冻融侵蚀、土地沙化、水土流失和土地盐渍化的敏感性；并从综合生态敏感性、生态压力和生态弹力三个方面评价了其生态脆弱性。结果显示，西藏陆地生态系统对冻融侵蚀、土地沙化和水土流失问题非常敏感。极度和高度敏感区分别占西藏自治区总面积的9.62%和83.69%。极度和高度脆弱区分别占0.09%和52.61%，主要分布在西藏西部的喜马拉雅和冈底斯山山区，念青唐古拉、唐古拉、可可西里和昆仑山区，及羌塘高原西北部和北部地区。这些结果有助于根据各区域存在的生态问题提出具有针对性的保护方案。

关键词：冻融侵蚀；土地沙化；水土流失；土地盐渍；生态弹力；生态压力