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ECOLOGICAL VULNERABILITY EVALUATION OF NYINGCHI CITY BASED ON LANDSCAPE PATTERN

WENBO LI[1,2], JIANGPING FANG[2]*, ZHEN XING[1,2], WENYUAN HAO[1] AND WENTAO ZHAO[1]

Research Institute of Tibet Plateau Ecology, Tibet Agriculture & Animal Husbandry College, Nyingchi, Tibet 860000, China

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Abstract

The construction of an ecological vulnerability evaluation model for Nyingchi city, based on the landscape pattern indices was envisaged. Subsequently, the ArcGis tool was used in combination with the natural breaks, range method and principal component analysis (PCA) in SPSS software to carry out a comprehensive quantitative analysis and evaluation of ecological vulnerability for various types of ecosystems in Nyingchi City and for different towns under its administration. The results showed that (1) when ranked in a descending order of the landscape pattern indices, the following order was observed: PLADJ > LPI > DIVISION > COHESION > TI > CI > LSI > MNFD; (2) when ranked in a descending order of the ecological vulnerability of different types of ecosystems, the order was: grassland (0.188101246) > water bodies (0.155774109) > forest land (0.127443959) > unused land (0.104511001) > farmland (0.023126395) > construction land (0.006232102); (3) in regard to the distribution of ecological vulnerability, the areas with grade V and IV ecological vulnerability were mainly found in the northwest, southwest and the north of the Nyingchi City. It was found that the terrain, landscape pattern and human interferences were the major factors leading to the spatial differentiation.

Introduction

Landscape pattern refers to the features associated with the physical distribution or configuration of patches of varying sizes and shapes within a landscape (Zhang *et al*. 2015). It is a result of the various influences acting on the ecosystem, which has a further impact on the ecosystem process and function (Peng *et al*. 2015). Ecological vulnerability is a measure of the sensitivity of the landscape pattern to an external disturbance; it is also an attribute associated with the undesired alteration of landscape structure, function, and properties due to the lack of adaptability (Sun *et al*. 2014). Nowadays, the issue of ecological vulnerability has been aggravated due to the increased human activities and global warming, which in turn affects significantly the human life, production and development (Zhang *et al*. 2016). The issues of ecological vulnerability, human settlement environment and eco-environmental bearing capacity have become increasingly pronounced, given the far-reaching impact of human activities. Regional ecological vulnerability evaluation is not only important for the eco-environment itself, but also lays the basis for the eco-environmental protection, land management, reasonable resources utilization and regional sustainable development (Meng *et al*. 2010). Domestic researchers have carried out extensive studies on the ecological vulnerability (Ma *et al*. 2015, Mansur *et al*. 2016, Yu 2016, Pang *et al*. 2018). A more comprehensive approach has been adopted towards the study of natural ecosystem and socio-economic system, as is widely practiced in the fields of economy, engineering, and geology. For ecological vulnerability evaluation, an evaluation indicator system

Author for correspondence: <xzfjp@21cn.com>. [1]Department of Resources and Environment, Tibet Agricultural and Animal Husbandry College, Nyingchi, 860000, China. [2]United Key Laboratories of Ecological Security, Tibet Autonomous, Nyingchi, 860000, China.

is usually established by combining the natural, social, economic, and environmental factors. Along with the development in ARCGIS technology, domestic researchers have applied various methods using the ARCGIS when approaching this topic, such as PSR model (Yu *et al*. 2014), AHP (Zhao *et al*. 2016), PCA (Wu *et al*. 2014), artificial neural network, comprehensive evaluation method and fuzzy comprehensive evaluation method (Pan *et al*. 2012). In recent years, as the domestic researches on ecological vulnerability are furthering, the concept of vulnerability of the coupled human-environment system that combines various features has emerged (Yu *et al*. 2017). Feng *et al.* used the landscape pattern indices and constructed an evaluation indicator system in three dimensions, *viz.*, ecosystem stress, sensitivity, and resilience, for characterizing the spatial differentiation of ecological vulnerability of the Yuyang district (Feng *et al*. 2016). Zhang *et al.* constructed the landscape vulnerability index model based on the landscape indices. They divided the plain region of the Ebinur lake basin into 5 vulnerability grades, *viz.* very low, low, intermediate, high and very high. By addressing the ecological vulnerability of highly urbanized regions (Zhang *et al*. 2016), Hong *et al.* established the evaluation indicator system which consisted of 12 indicators categorized under 9 factors, including, ecological sensitivity, stress and resilience. This system was then used to evaluate the ecological vulnerability of the urban areas (Hong *et al*. 2016). Since different methods have different advantages and defects, the applicability of an ecological vulnerability evaluation method for Nyingchi city based on the landscape pattern indices was envisaged.

Materials and Methods

Nyingchi city is located in the downstream of Yarlung Tsangpo River in the southeastern Tibet (longitude 9209′ ~ 9847′ east, latitude 2652′ ~ 300′ north). The administrative regions under the Nyingchi city include Bayi, Milin, Gongbo'gyamda, Motuo town, Bomi, Chayu and Lang town, which collectively cover an area of 117 thousand km^2.By 2017, the total population of the Nyingchi city had reached 228.2 thousand. The average altitude of the Nyingchi city is 3100 m, and the annual average precipitation is around 650 mm. Nyingchi city is rich in forest resources and exemplifies a distinctive landscape feature and ecological vulnerability. This region is considered highly critical for safeguarding the ecological safety and equilibrium not only for Tibet, but also for the entire Qinghai-Tibet Plateau. Therefore, the Nyingchi city is worthy of further investigation in terms of its ecological vulnerability. In this study, the vulnerability evaluation indicator system was constructed for the Nyingchi city considering three aspects, *viz.* ecological stress, sensitivity, and resilience. Weights were assigned to the indicators by using the range method and PCA in SPSS, and the ecological vulnerability was calculated using the relevant indicators. ArcGis tool and natural breaks were applied to analyze the ecological vulnerability of the social-economic-natural complex ecosystem in the study area.

DEM data of the Nyingchi city with 30 m resolution and the TM remote sensing images captured the year 2017 were used, and they were calibrated using the GCS-WGS-1984 coordinate system. The TM remote sensing images were interpreted based on a field survey. Landscape types were classified according to the "Classification and Coding of Current Land Use Condition" (GB/T21010-2017). Based on the actual conditions in the Nyingchi city, 6 land use types were considered, *viz.*, farmland, forest land, grassland, water bodies, construction land and unused land. Data processing was conducted as follows: (1) ENVI5.3 software was used for the fusion and correction of the images, followed by regular cut with the shp data to obtain the study area. (2) Maximum likelihood classifier in ENVI5.3 was used for supervised classification to obtain the data of land use types. After validation for precision, the classification results were assessed, and the precision and reliability of classification were determined. (3) Fragstats 4.0 software was used to calculate the landscape pattern indices, and MS Excel was used to analyze them (4) Weights were assigned to each indicator by using the range method and PCA. The vulnerability of landscape pattern of the Nyingchi city was calculated from the ecological vulnerability evaluation model.

Landscape pattern indices are the quantitative metrics of composition features, spatial layout and dynamic changes of the landscape. Based on the actual conditions of the Nyingchi city, the mean patch fractal dimension (MNFD), percentage of like adjacencies (PLADJ) and landscape shape index (LSI) were chosen as the ecological stress indicators; the connectivity index (Ci), landscape division index (DIVISION), and topographic index (TI) were chosen as ecological sensitivity indicators; and the patch cohesion index (COHESION) and largest patch index (LPI) were chosen as ecological resilience indicators. Each landscape pattern index was calculated.

As mentioned above, MNFD, PLADJ and LSI were chosen as the metrics of ecological stress. The formula and meaning of each index are shown below:

(1) MNFD was calculated from the relationship of perimeter *vs.* area, which reflects the complexity degree of landscape shape and spatial stability of landscape. MNFD can be obtained from Eq. (1).

$$MNFD = \frac{2 In(0.25\, p_{ij})}{In(a_{ij})} \quad (1)$$

where, MNFD is the mean patch fractal dimension, the value range is (1,2). The closer the value of MNFD reaches to 1,the straighter the perimeter of the patch is; when MNFD approaches 2,it means the patch perimeter is circuitous. This index reflects the influence of human activities on landscape pattern to a certain degree. Generally speaking, MNFD is higher if the natural landscape is less interfered by human activities, and the value is lower if the opposite is true.

(2) PLADJ is given by Eq. (2).

$$PLADJ = \frac{g_{ij}}{\sum_{K=1}^{m} g_{ik}} \times 100 \quad (2)$$

where, PLADJ is the percentage of like adjacencies; gij is the number of nodes between the patch type i and patch type i as calculated based on the double method; gik is the number of nodes between the patch type i and patch type k as calculated based on the double method. When a specific patch type is maximally discretized and there are no pairwise adjacencies, PLADL = 0; when the weight of adjacent nodes increases, PLADJ increases constantly.

(3) The regularity of patch shape is closely related to human interferences. LSI is given by Eq. (3).

$$LSI = \frac{e_i}{\min e_i} \quad (3)$$

where, LSI is the landscape shape index, whose value range is LSI ≧ 1; e_i is the total length or perimeter of the edges of landscape type i; and $\min e_i$ is the minimum possible value of e_i; when the value is 1, a higher value of LSI indicates a higher complexity of landscape types and greater dissociation between the patches.

The equations for deriving Ci, DIVISION and TI are given below:

(1) Calculation method of Ci is shown in Equation (4).

$$C_i = \frac{N}{A} \quad (4)$$

where, N is the total number of patches in the study area; A is the total landscape area, referring to the process by which the landscape types become more complex due to natural or human interferences. This index reflects the complexity of landscape spatial structure and the degree of interference to this landscape spatial structure due to human activities.

(2) Calculation method of DIVISION is given by Eq. (5).

$$DIVISION = \left[1 - \sum_{j=1}^{n} (\frac{a_{ij}}{A})2\right] \quad (5)$$

where, DIVISION is the landscape division index; A is the entire landscape area; aij is the area of patch ij. The larger the value, the greater the dissection and fragmentation of the landscape and the more frequent the succession between different landscape types will be. The value range of DIVISION is 0 - 1. If its value approaches 0, it means the landscape is made up of a single large patch; and the higher the value, the smaller the patch size and the more fragmented the landscape will be.

(3) TI

TI is an important factor influencing ecosystem vulnerability. As a result of environmental damage due to human interference, the terrain slope increases and the landscape sensitivity increases as well, which further leads to greater landscape erosion and degradation. According to the "Standards for Classification and Gradation of Soil Erosion" (SL190-2007) published by the Ministry of Water Resources and the topographic features of the Nyingchi City, six slope grades were set up, *viz.* 0°~5°, 5°~8°, 8°~15°, 15°~30°, 30°~60° and 60~90°, to which the value of 0.05, 0.1, 0.3, 0.5, 0.7 and 0.9 was assigned, respectively. The higher the TI, the higher the ecological sensitivity will be. TI is given by Eq. (6).

$$TI = \sum_{i=1}^{6} A_{ij} w_j / A_i \quad (6)$$

where, Aij is the area of landscape type i of the j^{-th} slope grade; Wj is the weight of the j^{-th} slope grade; Ai is the total area of landscape type i.

(1) COHESION can be obtained from Eq. (7).

$$COHESION = \left[1 - \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} Pij}{\sum_{n}^{m}\sum_{j=1}^{n} Pij\sqrt{aij}}\right]\left[1 - \frac{1}{\sqrt{A}}\right]^{-1} \times 100 \quad (7)$$

where, COHESION is the patch cohesion index; Pij is the perimeter of patch ij with the number of surface meshes as the unit; A is the total mesh number of the landscape. The larger the COHESION, the better the natural connectivity of the patches and the lower the local ecological vulnerability will be.

(2) LPI is given by Eq. (8).

$$LPI = a_{i\max} / A \quad (8)$$

where, a_{imax} is the largest patch area of landscape type i; A is the total landscape area. The higher the index, the stronger the resistance of the landscape type to external interference. That is, the ecological resilience is higher under the same level of stress.

(1) In order to make the data of different dimensions comparable, the data was first normalized, using Eq. (9).

Vulnerability of the positive relationship indicator:

$$P_i = \frac{x_i - x_{i\min}}{x_{i\max} - x_{i\min}} \ (i=1,2......6) \quad (9)$$

Vulnerability of the negative relationship indicator:

$$P_i = 1 - \frac{x_i - x_{i\min}}{x_{i\max} - x_{i\min}} \quad (i=1,2.....6) \qquad (10)$$

where, i is the i^{-th} indicator; P_i is the vulnerability of the i^{-th} indicator; X_i is the value of the i^{-th} indicator; X_{imax} is the maximum value of the i^{-th} indicator; X_{imin} is the minimum value of the i^{-th} indicator. After normalization, the meanings of all indicators are as follows: a closer the value to 1 indicates high vulnerability; a closer value to 0, indicates a lower vulnerability. Four out of 8 indicators considered in the present study were found to be positive relationship indicators, namely, LSI, Ci, TI and LPI, while the remaining indicators were negative relationship indicators.

(2) PCA was performed using the SPSS 20.0 software on the normalized ecological vulnerability indicators. The first three components with the cumulative contribution rate above 85% were extracted as the principal components. As shown in Table 1, the first three components contained 95.601% of the original variable information, and so they could be treated as principal components. In other words, the information contained in these three principal components could largely reflect the ecological vulnerability of the Nyingchi city.

Table 1. Characteristic values and contribution rates of principal components reflecting ecological vulnerability.

Component	Initial characteristic value			Extraction sums of squared loadings		
	Total	Variance (%)	Cumulative (%)	Sum	Variance (%)	Cumulative (%)
1	4.147	51.838	51.838	4.147	51.838	51.838
2	2.225	27.815	79.653	2.225	27.815	79.653
3	1.276	15.949	95.601	1.276	15.949	95.601

Source of the Table: Tibet Bureau of Statistics 2017.

(3) From Table 2, the following order was observed: PLADJ > LPI > DIVISION > COHESION > TI > SPLIT > LSI > PLADJ exhibited the highest weight of 0.3184, while the weight of FRAC_MNFD was the smallest, being 0.0141.

Table 2. Weights of ecological vulnerability indicators.

Index	COHESION	PLADJ	TI	Ci	LPI	LSI	DIVISION	MNFD
Weight	0.1257	0.3184	0.0631	0.0628	0.1866	0.0514	0.1780	0.0141

Source of the Table: Tibet Bureau of Statistics 2017.

The synthetic ecological vulnerability index is a relative value intended to measure the spatial differentiation within the study area. It can be calculated from Eq. (11), where EVD is the ecological vulnerability of the i^{-th} evaluation unit; Pij is the j^{-th} indicator of the i^{-th} unit; Wj is the weight of the j^{-th} indicator. A larger the value of the index indicates a greater ecological vulnerability; and *vice versa* and its range is 0 - 1 (Table 3).

$$EVD_i = \sum_{j=1}^{8} P_{ij} D_{ij} \qquad (11)$$

Table 3. Ecological vulnerability evaluation of landscape types of Nyingchi city.

Landscape type	MNFD	PLADJ	LSI	Ci	Division	TI	Cohesion	LPI
Farmland	0.000000	0.019916	0.044452	0.062074	0.000000	0.050724	0.082594	0.000068
Forest land	0.059834	0.318353	0.062000	0.062846	0.186579	0.051379	0.178031	0.014065
Grassland	0.080776	0.247613	0.013987	0.062845	0.002617	0.051378	0.173486	0.001839
Water bodies	0.125651	0.166196	0.000000	0.062638	0.000000	0.051155	0.130216	0.000065
Construction land	0.102715	0.000000	0.063095	0.000000	0.000000	0.000000	0.000000	0.000000
Unused land	0.049862	0.292246	0.051738	0.062846	0.010469	0.051378	0.176371	0.003124

Source of the Table: Tibet Bureau of Statistics 2017.

The relevant formula was corrected based on the existing studies. The regional vulnerability index (RVI) was then estimated according to the vulnerability indices of different landscape types and the weights assigned to each landscape type based on its area. The ecological vulnerability is given by Equation (12).

$$RVI = \sum \frac{A_i}{A} EVD \quad (12)$$

where, RVI is the regional vulnerability index of each town; Ai is the area of each landscape type in each town and the total area of the corresponding landscape type in that town; EVD is the vulnerability of the evaluation unit (Table 4).

Results and Discussion

A quantitative study was performed on the composition features and dynamic changes of the landscape based on the landscape pattern indices. Among various indices, different landscape types could be ranked in a descending order of FRAC_MNFD as follows: water bodies > construction land > grassland > forest land > unused land > farmland. This indicated that the farmland had the least circuitous perimeter. If ranked in a descending order of PLADJ, the order was: forest land > unused land > grassland > water bodies > farmland > construction land. If ranked in a descending order of LSI, the order was: water bodies > grassland > farmland > unused land > forest land > construction land, indicating that the water bodies had the largest degree of dissociation. This, however, has a significant correlation to the main rivers of the Yarlung, Tsangpo and Niyang river within the study area. The construction land had the lowest degree of dissociation. If ranked in a descending order of C_i, the order was: construction land > farmland > water bodies > grassland > unused land > forest land. Since the U-shaped and V-shaped canyons were extensively found in the Nyingchi city, the traditional human habitats showed a scattered distribution. On the landscape scale, this leads to higher fragmentation. The value of DIVISION was 1 for farmland, water bodies and construction land, indicating that these landscape types were more fragmented in distribution. As to TI, areas with slope grade of 30°~60° and 60~90° accounted for 37.3 and 42.3%, respectively. Thus, terrain is a major influence factor of ecological vulnerability of the study area. If ranked in a descending order of COHESION, the order was: forest land > unused land > grassland > water bodies > farmland > construction land. This indicated that the forest land had the highest natural connectivity and lower vulnerability. If

Table 4. Ecological vulnerability estimates of each town under the administration of Nyingchi city.

County name	Town name	Farmland vulnerability	Forest land vulnerability	Grassland vulnerability	Water bodies vulnerability	Construction land vulnerability	Unused land vulnerability
Bayip	Gengzhang Menba ethnic township	0.023760433	0.106216237	0.204634515	0.159757708	0.005812982	0.097076123
	Baiba town	0.016762381	0.124090898	0.184185748	0.170032124	0.003611204	0.120886327
	Bayi town	0.02952842	0.107998547	0.181818139	0.156724651	0.007511773	0.102145286
	Linzhi town	0.037847793	0.12683395	0.201891603	0.133748685	0.009368397	0.065732442
	Bujiu township	0.030159843	0.119422984	0.191719043	0.130441717	0.012548917	0.094038623
	Mirui township	0.034795832	0.141165568	0.291789402	0.060759088	0.011148978	0.051889721
	Lulang town	0.027058971	0.121937438	0.171720227	0.194385827	0.001504941	0.085694623
	Pai town	0.03195841	0.140560763	0.207588906	0.126106784	0.004860468	0.093949302
Mainling	Milin town	0.031593623	0.095914029	0.209751519	0.154163321	0.007019206	0.080318716
	Zhaxiraodeng township	0.021489012	0.133927572	0.175859577	0.165028984	0.006221931	0.105514512
	Nanyi Luoba ethnictownship	0.029283121	0.117812823	0.155994049	0.228111255	0.000993438	0.058330926
	Lilong township	0.015515241	0.141087113	0.172577635	0.185511178	0.004313477	0.101173875
	Wolong town	0.008488624	0.138943338	0.197751689	0.119498546	0.006272893	0.171693996
	Qiangna township	0.025793802	0.120556315	0.250392217	0.122394744	0.008352345	0.068524204
	Danniangtownship	0.021116044	0.110272542	0.260103342	0.11617265	0.010804364	0.075883096
Bomê	Zhamu town	0.030376097	0.10090534	0.183518387	0.177040402	0.004588811	0.089148036
	Gu township	0.03234869	0.107874878	0.192203819	0.170120505	0.004047572	0.080371922
	Qingduo town	0.010174439	0.117445915	0.199811939	0.182695003	0.004738551	0.105126982
	Yuxu township	0.007592522	0.120166859	0.19512887	0.200861992	0.001909218	0.103428152
	Yigong township	0.015044649	0.054027857	0.194255132	0.21347639	0.003246013	0.111789153
	Bagai township	0.00415591	0.103637706	0.171562368	0.233839091	0.000778335	0.112758952
	Duoji township	0.007309485	0.115669912	0.18331932	0.190711008	0.003378541	0.127579868
	Songzong town	0.017351674	0.09681212	0.202893142	0.175015361	0.006140058	0.101994203
	Kangyu township	0.000779839	0.149909571	0.182500442	0.138543236	0.009274506	0.163535456
	Yupu township	0.005199882	0.115379686	0.204765517	0.160495529	0.006396177	0.136524059

(Contd.)

County name	Town name	Farmland vulnerability	Forest land vulnerability	Grassland vulnerability	Water bodies vulnerability	Construction land vulnerability	Unused land vulnerability
Nang	Lang town	0.010872313	0.181139044	0.248693886	0.054175744	0.015760593	0.122825244
	Zhongda town	0.023697351	0.318719616	0.204226072	0.059812309	0.008670247	0.056872659
	Dongga town	0.003241443	0.170065201	0.229784248	0.088480947	0.011045277	0.14758015
	Laduo township	0.006252992	0.198089984	0.201849895	0.108537009	0.013426221	0.113107667
	Dengmu township	0.003948511	0.198126881	0.148884728	0.118188686	0.008944687	0.183831316
	Jindong township	0.005544244	0.17119654	0.196503366	0.157736713	0.005546785	0.110100847
Gongbo'g yamda	Gongbujiangda town	0.021275431	0.118415616	0.186932595	0.122232184	0.005942151	0.162432066
	Jiangda township	0.001609776	0.119567484	0.219706658	0.150278206	0.002238307	0.157411907
	Zhongsha township	0.004770198	0.109869476	0.213281457	0.15619671	0.001827117	0.157266702
	Jinda town	0.000742027	0.124203747	0.182646243	0.160595755	0.000871289	0.189359885
	Jiaxing township	1.88396E-05	0.137463827	0.182031007	0.153739853	0.003214827	0.181123638
	Niangpu township	5.32265E-05	0.216695189	0.148243524	0.161127666	0.000173607	0.162107747
	Zhula township	0.000661927	0.145398658	0.182003116	0.185542685	0.001318858	0.140049411
	Bahe town	0.018600228	0.126496211	0.203548091	0.165218072	0.003875067	0.098009211
	Cuogao town	0.003042936	0.112163841	0.140340031	0.171618067	0.001070067	0.22353149
	Motuo town	0.07900257	0.098449031	0.180836739	0.133389625	0.004323648	0.021270693
Mêdog	Deixing township	0.067335232	0.07834789	0.159319216	0.177723537	0.002065109	0.043086754
	Beibeng township	0.076267226	0.096578072	0.167388036	0.14759596	0.002771292	0.032844804
	Gedang township	0.024711221	0.127651585	0.170347871	0.211751321	0.000771169	0.069707489
	Damu Luoba ethnic township	0.0608899	0.0977797	0.169015104	0.165189315	0.001335294	0.054597592
	Bangxin township	0.051070863	0.093672474	0.148636846	0.197200887	0.000700302	0.067444879
	Jiaresa township	0.066162142	0.08152645	0.191767391	0.150898214	0.000644982	0.049083785
	Gandeng township	0.059044709	0.087707228	0.154143624	0.143700339	0.013923291	0.058445192
Zayü	Zhuwagen town	0.006300401	0.076838497	0.124043805	0.148985897	0.046095141	0.099063515
	Gula township	0.007867864	0.157308318	0.106976748	0.163061158	0.016827685	0.158306943
	Chawalong township	0.031697559	0.128224787	0.194701503	0.125098706	0.011179663	0.092765658
	(Xia)chayu town	0.038318042	0.133562611	0.198769318	0.198302539	0.002165001	0.009114312
	(Shang)chayu town	0.053680023	0.125641872	0.132832169	0.20060997	0.001221538	0.047270777
	Guyu township	0.006661396	0.12250398	0.202277473	0.169178006	0.003741214	0.12987315

Source of the Table: Tibet Bureau of Statistics, 2017.

ranked in a descending order of LPI, the order was: forest land > unused land > grassland > farmland > water bodies > construction land. LPI was the highest for the forest land, indicating the highest resistance to external interference.

Based on the proposed method and equations, the vulnerability of different landscape types was estimated in terms of the landscaper pattern indices. As shown in Tables 3 and 4, the synthetic ranking of different landscape types in the study area was as follows: grassland > water bodies > forest land > unused land > farmland > construction land. Thus, the grassland was the most vulnerable, with low landscape stability and high susceptibility to external interference.

The grassland area was 254.68×10^4 hm^2 and accounted for 22.2% of the total landscape area. The grassland was mainly found along the mountain bodies and was subject to the influence of terrain segmentation and geological and meteorological disasters. Thus, grassland had a large bearing on the overall ecosystem stability. Water bodies are an important landscape type in the Nyingchi city, and the main rivers of the Yarlung, Tsangpo and Niyang river account the majority of the area of this landscape type. The area of water bodies was 105.93×10^4 hm^2, accounting for 9.232% of the total landscape area. The grassland and water bodies had the highest PLADJ of all landscape types, indicating that the weights assigned to the adjacent nodes of the two patch types were higher.

The area of farmland was 9.65×10^4 hm^2, accounting for 0.84% of the total landscape area. Of different landscape indices of farmland, COHESION was the largest, indicating better natural connectivity of this patch type and thereby a lower ecological vulnerability. MNFD and DIVISION were zero for farmland, indicating almost straight perimeter of the farmland patches and low fragmentation degree between the patches. As shown above, farmland was little interfered by human activities, and thus had a small impact on the overall landscape vulnerability.

The area of forest land was $525.73 \times 10^4 hm^2$, accounting for 45.82% of the total landscape area. Forest land was the largest landscape type in the Nyingchi city. Among various landscape indices, PLADJ was the highest for the forest land, indicating that the weights assigned to the adjacent nodes between the patches of this type were overlapping and higher. LPI of the forest land 0.014065 was the smallest, indicating the weakest resistance to external interference and the lowest ecological resilience.

The area of construction land was 3.61×10^4 hm^2, accounting for 0.31% of the total landscape area. Among different landscape indices, MNFD of 0.102715 and LSI of 0.063095 were the largest for the construction land, while all other indices were zero. The reason is probably that the study area exhibited a low urbanization scale and a small population size, which caused little interferences to the ecosystem. Thus, the construction land had a low ecological vulnerability.

The area of unused land was 247.73×10^4 hm^2, accounting for 21.59% - 7 of the total landscape area. PLADJ was the highest landscape index for the unused land, with a value of 0.292246, while LPI was the smallest landscape index with a value of 0.003124. Thus, for the unused land, the weights assigned to the adjacent nodes between the patches of this type were overlapping and higher. A smaller LPI indicated weaker resistance to external interference. The above findings suggest that the protection should be enhanced for the unused land, which can improve its utilization efficiency and ecological resilience.

In the spatial analysis module of Arc GIS, natural breaks was used to divide the ecological vulnerability of each landscape type into 5 grades, A higher grade indicated more vulnerability of the landscape type. The spatial differentiation showed: (1) The evaluation value of grassland was in the range of 0.106977 - 0.291789, the area of grade V vulnerability was 168519 hm^2,accounting for1.65%; the area of grade IV vulnerability was 3306987 hm^2, accounting for 32.3%. Town of Lang, Qiangna, Mirui and Danniang were the regions with severe vulnerability of the grassland.

(2) The evaluation value of the water bodies was in the range of 0.054176 - 0.233839; the area of grade V vulnerability was 3065260 hm^2,accounting for 30%; the area of grade IV vulnerability was 1763200 hm^2, accounting for 17.2%. Town of Yigon, Bagai, Bangxin, Lulang, NeyulLhopa, Yuren, Gedang, Shangchayu and Xiachayu were regions with severe vulnerability of the water bodies. (3) The evaluation value of the forest land was in the range of 0.054028 - 0.318720; the area of grade V vulnerability was 310990hm^2, accounting for 3%; the area of grade IV vulnerability was 2095405 hm^2, accounting for 20.5%. Town of Niangpu, Dengmu, Laduo and Zhongda were regions with severe vulnerability of the forest land. (4) The evaluation value of unused land was in the range of 0.009114 - 0.223531; the area of grade V vulnerability was 1588561 hm^2, accounting for15.5%; the area of grade IV vulnerability was 1162620 hm^2, accounting for 11.4%. Jiaxing Town, Jinda, Dengmu, Gongbujiangda, Woluo, Jiangda, Cuogao, Zhongsa, Gula and Kangyu were regions with severe vulnerability of unused land. (5) The evaluation value of farmland was in the range of 0.00019 - 0.79003; the area of grade V vulnerability was 2204849 hm^2, accounting for 21.6%; the area of grade IV vulnerability was 2712766 hm^2, accounting for 26.5%. Town of Beibeng, Motuo, Dexing, Gandeng, Jialasa, Bangxin, Dambyn Lhoba and Shangchayu were regions with severe vulnerability of farmland. (6) The evaluation value of the construction land was in the range of 0.000174 - 0.046095; the area of grade V vulnerability was 567093 hm^2, accounting for 5.54%; the area of grade IV vulnerability was 925667 hm^2, accounting for 9.1%. Zhuwagen town was the region with severe vulnerability of construction land.

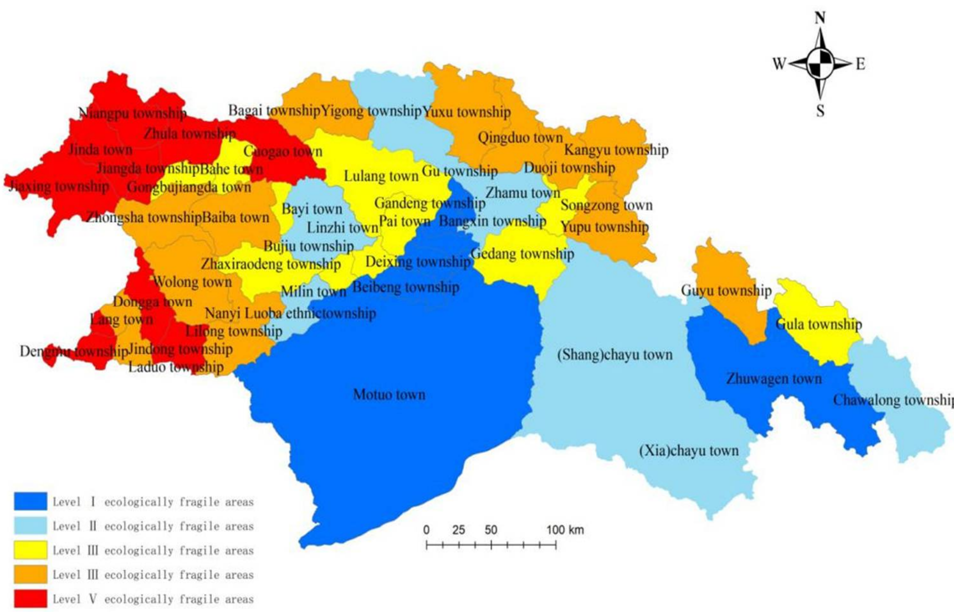

Fig. 1. Spatial differentiation of ecological vulnerability of each town under the administration of Nyingchi city, 2017.

In order to better reveal the spatial differentiation of ecological vulnerability, a synthetic ranking of 54 towns under the administration of the Nyingchi city was produced. The evaluation values of these towns fell within the range of 0.501327 - 0.688401. Under the GIS platform, the ecological vulnerability of 54 towns was divided into 5 grades using natural breaks, as shown in Fig. 1.

That the regions of different grades of ecological vulnerability exhibited an alternate distribution in space (Fig. 1). Roughly speaking, the ecological vulnerability decreased from west to east and from north to south. As to spatial distribution, regions of grade V and IV were mainly found in the northwestern, southwestern and northern parts of the Nyingchi city. Regions of grade V were concentrated in the Gongbujiangda County and Lang County. It can be seen that the area of grade II vulnerability was the largest, accounting for 29.06%, followed by grade IV vulnerability, which accounted for 22.81%. This was followed by the grade III, I and V vulnerability, which accounted for 21.83, 13.89 and 12.41%, respectively.

Ecological vulnerability is a relative concept. In this study, the ecological vulnerability of the Nyingchi City was evaluated and compared using the landscape pattern indices and from three aspects, *viz.* ecological stress, sensitivity, and resilience. The following conclusions may be made from the present study.

(1) The largest evaluation value of the ecological vulnerability in the Nyingchi city was 0.688401. When compared with the ecosystems of other cities, the Nyingchi city apparently falls within the category of sustainable development considering the ecological vulnerability. In recent years, the local government has stepped up the efforts in eco-environmental protection, and Nyingchi city generally has a good eco-environment throughout the year. A synthetic ranking of 54 towns under the administration of the Nyingchi city was generated. The results showed that the Nyingchi city faced potential or low level of ecological vulnerability. The area belonging to this category accounted for 43%, and those with mild, moderate and severe vulnerability accounted for 21.8, 22.81 and 12.4%, respectively. The above results demonstrate that Nyingchi city has a bright prospect of sustainable development.

(2) Of various landscape types, the area of grassland with grade IV - V vulnerability accounted for 34%, with regions of moderate to severe vulnerability accounting for 1.6%; the area of water bodies with grade IV - V vulnerability accounted for 47.2%, with regions of moderate to severe vulnerability accounting for 30%; the area of forest land with grade IV-V vulnerability accounted for 23.5%, with regions of severe vulnerability accounting for 3%; the area of farmland with grade IV - V vulnerability accounted for 48.1%, with regions of severe vulnerability accounting for 21.6%; the area of unused land with IV-V vulnerability accounted for 26.9%, with regions of severe vulnerability accounting for 15.5%; the area of construction land with IV-V vulnerability accounted for 21.6%, with regions of severe vulnerability accounting for 9.1%. If ranked in a descending order of area with grade V vulnerability (severe vulnerability), the order was: water bodies > farmland > unused land > construction land > forest land > grassland.

(3) By applying the ArcGis superposition analysis and natural breaks method, the synthetic ranking of different landscape types in 54 towns under the administration of Nyingchi was generated as follows: grassland (0.188101246) > water bodies (0.155774109) > forest land (0.127443959) > unused land (0.104511001) > farmland (0.023126395) > construction land (0.006232102). Of the six landscape types, grassland and forest land were most vulnerable, while the construction land was the least vulnerable. The above findings point to the importance of the scientific planning, especially of the grassland and forest land. Of the 54 towns evaluated, regions with grade V vulnerability were mainly found in the Gongbujiangda County and Lang County. This was closely related to the special ecological and geographical environment of the regional landscape. These two counties are important ecological corridors in the middle and lower reaches of the Yarlung Zangbo River Basin. The human interferences to the ecosystems in these two towns should be minimized in the future, so as to improve the ecological vulnerability and enhance the regional sustainable development capacity.

(4) The vulnerable habitat of the plateau region represents a complex system. Building a quantitative ecological vulnerability evaluation model is conducive to reveal the spatial distribution pattern of ecological vulnerability of cities and rural areas in plateaus. Starting from a smaller scale and a controllable unit, a quantitative evaluation was performed for the *status quo* of the ecological vulnerability of this region in the light of the landscape pattern methodology. Here, 54 towns under the administration of the Nyingchi city were studied in terms of ecological vulnerability. The present research findings provide a scientific support for the local ecological planning and ecological protection of this typical alpine tourist city. In the future, besides a better understanding of the natural factors, social, economic and ecological civilization factors should also be incorporated into relevant studies. It is expected that the present findings will shed some light on the decision making for the local sustainable development, so as to facilitate sustainable development of the drainage basin. This method is also applicable to the ecological vulnerability evaluation of the smaller landscape units on the prefecture, county and town levels.

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