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A Study on Spatiotemporal Changes of Ecological Vulnerability in Yunnan Province Based on Interpretation of Remote Sensing Images

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Abstract: The inherent ecological environment of mountainous regions is highly fragile, and the degree of sustainable development is low. There has not yet been a multi-phase ecological vulnerability evaluation (EVE) study based on remote sensing (RS) and GIS for mountainous provinces, for which there is an urgent need to establish a system that is appropriate, practicable and easily operated and applied. In this study, an integrated "RS and GIS + multi-phase land use/cover change (LUCC) + practically quantitative theory and methods of EVE" approach was adopted for analysis based on the interpretation results of five phases of the land use/land cover (LULC) RS images of Yunnan, with 129 counties being considered as the evaluation units. The organic combination of quantitative multi-index comprehensive evaluation (QMCE) and qualitative comprehensive analysis (QCA) methods was adopted to perform quantitative calculations of a system of county-level evaluation indicators which includes "innate" natural ecological vulnerability (INEV), land use ecological vulnerability (LUEV) and land cover ecological vulnerability (LCEV); the degree of ecological vulnerability (DEV) was assessed for the 129 counties within the province during the five study phases (1980, 1990, 2000, 2010 and 2020). The spatiotemporal variation characteristics and laws of DEV from 1980 to 2020 in the whole province and 129 counties were revealed, aiming to provide a basis for meeting the SDGs for mountainous provinces. The results are as follows: (1) Overall, INEV is high because of the high mountains and steep slopes, and the entire province is classified as "highly vulnerable" on average. In terms of counties, more than 79.07% are classified as "moderately vulnerable", "highly vulnerable" and "very highly vulnerable". (2) The degree of LUEV and LCEV caused by acquired human socioeconomic activities was higher in 1980. However, after a series of ecological measures in the past 40 years, the values of D_{EVLU} and D_{EVLC} in the whole province and counties in 2020 have decreased to different degrees. Accordingly, the degree of overall ecological vulnerability of Yunnan province and counties decreased significantly from 1980 to 2020. The basic law of change is that the number of counties with high DEV decreases significantly, while the number of counties with low DEV increases significantly. (3) The regional difference in the DEV of Yunnan province is large. In general, the degree of ecological vulnerability is lower in the southern, southwestern, western and central areas of Yunnan and higher in the northwest high mountain canyon, northeast mountain areas and east and southeast karst areas. (4) Overall, the DEV in Yunnan province is currently still high. There is an urgent need to enhance the construction of ecological civilization across the whole province and take effective measures to protect the ecological environment according to local conditions, so as to steadily reduce the DEV.

Keywords: remote sensing image interpretation; multi-phase ecological vulnerability evaluation; spatiotemporal change; the vanguard of ecological civilization construction; mountainous province

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Citation: Yang, Z.; Yang, S.; Yang, R.; Wu, Q. A Study on Spatiotemporal Changes of Ecological Vulnerability in Yunnan Province Based on Interpretation of Remote Sensing Images. *Diversity* **2023**, *15*, 963. https://doi.org/10.3390/d15090963

Academic Editors: James Magidi, Tsitsi Bangira and Matlhogonolo Kelepile

Received: 29 July 2023
Revised: 23 August 2023
Accepted: 25 August 2023
Published: 26 August 2023

1. Introduction

The study of vulnerability has become a focal topic and a meaningful analysis tool in the field of sustainable science and global environmental changes in recent years [1]. Sustainable development goals (SDGs) mean common development among countries worldwide today, which includes both the sustainability of the ecological environment and the sustainability of economic and social development. Among them, the sustainability of the ecological environment is the foundation of the sustainability of economic and social development. In terms of the SDGs, vulnerability (especially the vulnerability of the ecological environment) is often an obstacle or in opposition to achieving sustainability (especially with regard to economic and social development). To enhance regional sustainable development capabilities, it is necessary to find ways to reduce vulnerability. The concept of “vulnerability” originated from research on natural calamities and impoverishment [2,3]. In 1981, Timmerman expanded this study to the field of geography [4]. It has then generally been applied in various disciplines: ecology, economics, sociology, etc. In particular, research on ecological environment vulnerability (EEV) and its quantitative evaluation has become a significant direction for research on the SDGs [5,6]. Most of the existing empirical evaluation studies on ecological vulnerability focus on specific ecological areas, such as karst areas [7,8], northern agricultural and pastoral interlaced zones [9,10], coastal zones [11–13], river basins [14,15], reservoir areas [16] and high cold areas [17]. In general, for mountainous areas, while some scholars have conducted empirical analyses [18], the depth and breadth of research in this area are still significantly insufficient. From a global perspective, mountainous areas account for approximately 30% of the earth; from China’s perspective, it is a mountainous country, with mountainous areas accounting for over two-thirds [19]. Mountainous areas are a unique natural-human synthesis with specific slopes and altitudes [20], and their extremely obvious feature is the EEV system. The innate fragility of mountainous systems leads to the instability of the ecosystems and the hardships in resource development and determines that once mountainous ecosystems are destroyed, they lack the ability to restore to their original state, thereby restricting the use of mountainous resources and the progress of mountainous economy and society. In terms of general mountainous regions, rural residents are constrained by poor natural resources and ecological, economic and social conditions, which might result in irrational human activities and rough development, further leading to the destruction of the ecological environment. Moreover, the continual occurrence of natural calamities and a decrease in income levels could increase the social–economic–ecological vulnerability. This has led to a vicious cycle of mountainous vulnerability $\rightarrow$ irrational exploitation $\rightarrow$ ecological damage $\rightarrow$ socioeconomic regression $\rightarrow$ mountainous vulnerability, causing the entire mountainous ecological, economic and social system to exhibit enormous fragility. For example, considering Yunnan province, located on the southwestern border of China, the mountainous area accounts for 94%. The ecological environment is highly vulnerable [21], and the economy remains correspondingly weak. Among the 129 counties (cities, districts) in Yunnan, 88 are classified as nationally impoverished, making Yunnan the representative mountainous province with the highest number of impoverished counties among all the provinces in China. Therefore, in-depth research on the ecological vulnerability of mountainous regions has important practical significance.

The core content of ecological vulnerability research is ecological vulnerability evaluation (EVE), which refers to the quantitative, qualitative or integrated study and identification of the degree of vulnerability in regional ecosystems or ecological environments. The aim of the study is to investigate the causes, mechanisms and change rules underlying ecosystem or regional ecological environment fragility, so that reasonable resource utilization methods and measures for ecological protection and restoration can be proposed toward ensuring the regional coordinated advancement of resources, environment, society and economy. In terms of the system of indicators and data sources of EVE, the progress and literature can be generally classified into four categories. The first is “existing statistical data and survey + quantitative measurement of EEV in the current situation or a certain year". For example, Liu Yi et al. (2010) conducted a natural disaster vulnerability evaluation of 31 provinces in China using DEA [22]. Lu Yaling et al. (2010) analyzed the autocorrelation of EVE and spatial aspects for the Bohai Rim Region [23], and Liu Gang (2013) conducted a disaster risk vulnerability evaluation of communities [24]. The second category is "the quantitative measurement of eco-environmental vulnerability for several years based on existing surveys and statistical data". For example, Li Yonghua et al. (2015) carried out a study on the spatiotemporal distinction of ecological vulnerability in Chaoyang County, Liaoning, China, from 2003 to 2012 [25]. Nguyen (2016) conducted a study on the eco-environment vulnerability in Hue province, Vietnam, for the years 1989, 2003 and 2014 [26], and Liu Yujie et al. (2016) evaluated water resource vulnerability [27]. The third category is "existing statistical data and survey + quantitative evaluation of vulnerability level of composite systems over several years". For example, Petrosillo et al. (2006) conducted a quantitative modeling study on the vulnerability of composite systems based on tourism activities [28]. Li Bo (2012) conducted a spatiotemporal analysis of the vulnerability of the human–sea resource and environment system [29]. Chen Jia et al. (2016) carried out a study on the vulnerability of the social ecosystem in Yulin City, Shaanxi, China, from 2000 to 2011 [30], and Wen Xiaojin et al. (2016) conducted a socioecological vulnerability evaluation of mountainous cities from 1997 to 2013 [31]. The fourth category is "RS image interpretation + quantitative measurement of ecological vulnerability in a certain year or some years". For example, Zhang et al. (2007) studied the eco-environment vulnerability of Fuzhou [32]. Xu Qingyong et al. (2013) comprehensively evaluated the eco-environment vulnerability of the Pearl River Delta from 2004 to 2008 [33]. Hu Baoqing et al. (2014) comprehensively evaluated the eco-environment vulnerability of Guangxi karst areas based on GIS [8]. Sahoo et al. (2016) evaluated the vulnerability of eco-environment [34]. Wang Xuemei et al. (2016) conducted EVE of the Weigan River Basin [35]. França et al. (2022) studied the ecological vulnerability of Brazil [36]. From the perspective of the EVE index system, many researchers have conducted studies from various focuses and aspects, generally selecting various specific evaluation indicators from four framework systems and models: the Sensitivity–Resilience–Pressure (SRP) conceptual model [19], Natural Ecology–Human Socioeconomy [8], Pressure–State–Response (PSR) [37,38] and Vulnerability Scoping Diagram (VSD) [39,40]. The core of the evaluation process is to determine the evaluation method. Currently, the primary approaches used include the comprehensive index method (CIM) [8,41–43], the analytic hierarchy process (AHP) [33,44] and the cluster analysis method [8,33]. Recently, EVE based on GIS and RS has generally been applied [8,32–36,45,46]. This is because, through RS image interpretation and GIS technology, information on LULC can be objectively obtained, which results in higher accuracy of the data on eco-environment vulnerability. In the existing research literature, there is currently no comprehensive EVE for certain consecutive years based on RS and GIS for mountainous provinces. Correspondingly, an appropriate, practicable, easily operated and applied regional EVE system for mountainous regions has not been established, which is not beneficial for carrying out the SDGs of mountainous areas.

Therefore, for this study, Yunnan province, the southwest frontier mountainous province, was selected as the empirical study region to conduct comprehensive EVE of mountainous provinces based on RS and GIS for numerous consecutive years. The reason why Yunnan province was chosen as the study area is not only because its mountainous area accounts for 94%, but also because it is located at the headstream or upstream region of six world-famous rivers, namely, the Yangtze River, Pearl River, Lancang River, Red River, Nu River and Irrawaddy River. Its location is extremely significant, and it is an ecological security barrier. Furthermore, Yunnan plays an indispensable and imperative role in ensuring the ecological security of these six major rivers and has significance as an international ecological security barrier. Strengthening ecological environment protection and striving to become the VECC are major strategic tasks of direct concern to both the whole country and Yunnan province. In January 2015, President Xi visited Yunnan and proposed the strategic position of striving to become the VECC for Yunnan. In January

2020, President Xi visited Yunnan again and demanded that Yunnan strive to continuously make new progress in building the VECC. For many years, Yunnan province has firmly established the concepts of "protecting the eco-environment is protecting productivity, improving the eco-environment is developing productivity", placing eco-civilization construction in a prominent position in the overall work and always adhering to the policy of "ecological priority and green development". As a result of work toward realizing the VECC in Yunnan province, there have been many unprecedented achievements [47]. So, does Yunnan's VECC work alleviate and reduce the inherent ecological vulnerability and enhance the potential for sustainable development? What exactly is the effect? There is an urgent need to conduct accurate scientific evaluation.

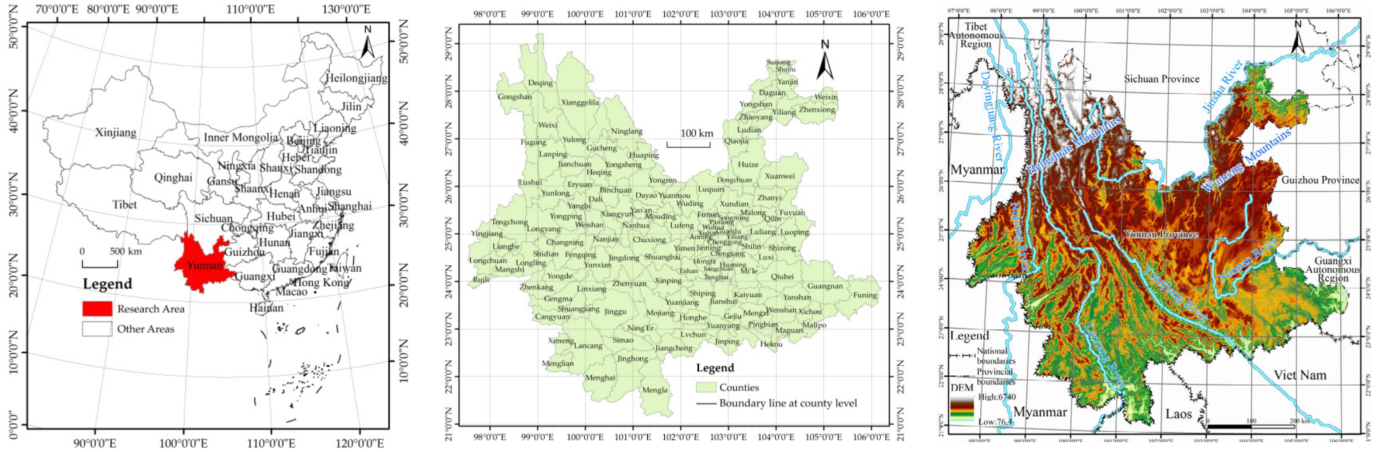
Compared with existing study achievements, the primary characteristic and contribution of this paper consist in an approach, involving a comprehensive combination of "RS and GIS + LUCC with multi phases + practically quantitative theory and methods of EVE" based on the features of mountainous provinces and results of RS images interpretation of LULC from Yunnan province over five periods (i.e., 1980, 1990, 2000, 2010 and 2020). According to the research needs and data availability, this paper establishes a comprehensive evaluation indicator system, a grading system for various levels of DEV, and quantitative classification standards for EVE in the mountainous provinces. Furthermore, it promotes qualitative and quantitative integrated analysis methods for EVE in mountainous regions. At the same time, specific evaluation practices were carried out using county-level regions as evaluation units to quantitatively measure the ecological vulnerability level (EVL) in Yunnan province. The ecological vulnerability levels of 129 counties from 1980 to 2020 were determined, and based on these, the spatiotemporal evaluation of EVL for the whole province and 129 counties over the past 40 years was conducted, aiming to offer a reference for alleviating the DEV and boosting regional sustainable development strategic planning and management in mountainous provinces. In theory, this study not only promotes the progression and advancement of EVE research but also provides fundamental ideas and approaches for boosting regional actions toward achieving the SDGs, which is theoretically helpful for further enrichment and innovative development of the ecological vulnerability system. In actuality, methods are also established for qualitative and quantitative integrated analysis of DEV and its dynamic change trend in mountainous areas.

2. Materials and Methods

2.1. Overview of the Study Area

Yunnan is located in the southwestern border area of China (21°8′32″ N–29°15′8″ N and 97°31′39″ E–106°11′47″ E). It is one of the provinces with the most neighboring countries and the longest border in China. So far, it has 16 prefecture-level cities under its jurisdiction, and there are 129 county-level administrative units [48] (Figure 1).

Yunnan is a representative mountainous province mainly composed of mountains amounting to 94% being mountainous area [49]. The terrain of the whole province is characterized by being high in the northwest and low in the southeast (Figure 1). The average elevation is about 2000 m, and the difference in elevation between the highest point and the lowest point is 6663.6 m. The basic characteristics of Yunnan's landform are mainly mountainous areas and large terrain slopes. In Yunnan province, more than three-quarters of the land has a ≥15° slope, and nearly two-thirds of the land has a ≥25° slope [50], indicative of the steep terrain of Yunnan. The terrain characteristics dominated by mountainous areas cause the "innate" ecological environment to be exceedingly vulnerable, and cultivated land resources remain restricted. The long-term unreasonable exploitation and use of mountainous land resources can easily result in the incompatibility of humans and land in the mountainous regions, causing soil erosion and environment deterioration and further leading to serious disasters. Currently, major eco-environmental issues such as rocky desertification in the province are still severe, with a trend of frequent and prone occurrences of geological disasters, such as drought, floods, wind and hail, low-temperature freezing, landslides and mudslides [51].



(**a**) (**b**) (**c**)

Figure 1. Geographical location and DEM map of the research region: (**a**) location of the province, (**b**) distribution of all counties and (**c**) DEM map of the province.

The special geographical location and natural environment make Yunnan province a barrier to ecological security. The country is focused on preserving the ecological environment in Yunnan, and there are positive expectations that Yunnan will strive to become the VECC. This is not only a major strategic task undertaken by Yunnan but also represents the foundation for sustainable development in the province. It is necessary to implement an ecologically friendly development approach according to local conditions and take a win–win path toward protection and development.

2.2. RS Data Acquisition and Interpretation

Data for the five phases of the RS image (i.e., 1980, 1990, 2000, 2010 and 2020) used in this paper were obtained from the website of the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (CAS) (URL: "https://www.resdc.cn/" and accessed on 23 August 2022). Images with winter cloud cover of less than 10% were selected for interpretation (Table 1). The entire interpretation work is based on a unified land use classification system and it was combined with RS interpretation symbols in the ArcGIS software environment to interpret the LULC types from 5 phases of RS images through human–machine interaction, thus obtaining a vector database for the 5 phases of LULC (Figure 2).

Table 1. Detailed information on the RS images of the five different phases.

Year	RS Image Date	RS Image Data	Spatial Resolution
1980	Dec. 1979–Feb. 1982	Landsat TM	
1990	Dec. 1989–Feb. 1992	Landsat TM	
2000	Dec. 1999–Feb. 2000	Landsat TM/ETM	30 m × 30 m
2010	Dec. 2009–Feb. 2010	Landsat TM	
2020	Jan. 2020–Feb. 2020	Landsat-8	

Referring to Xu Xinliang et al. [52] and Liu Jiyuan et al. [53–56], and considering the real conditions and research needs of Yunnan, five-phase LULC classification systems in Yunnan were determined to comprise 6 first-level land use types and 12 second-level land use types. Figure 2 provides a detailed description of the entire process of RS image interpretation to acquire the five-phase LULC map of Yunnan. Finally, a vector database of LULC was generated, and ArcGIS was used to compile the five-phase LULC map (Figure 3), and values for the classifications of LULC area were calculated (Table 2).

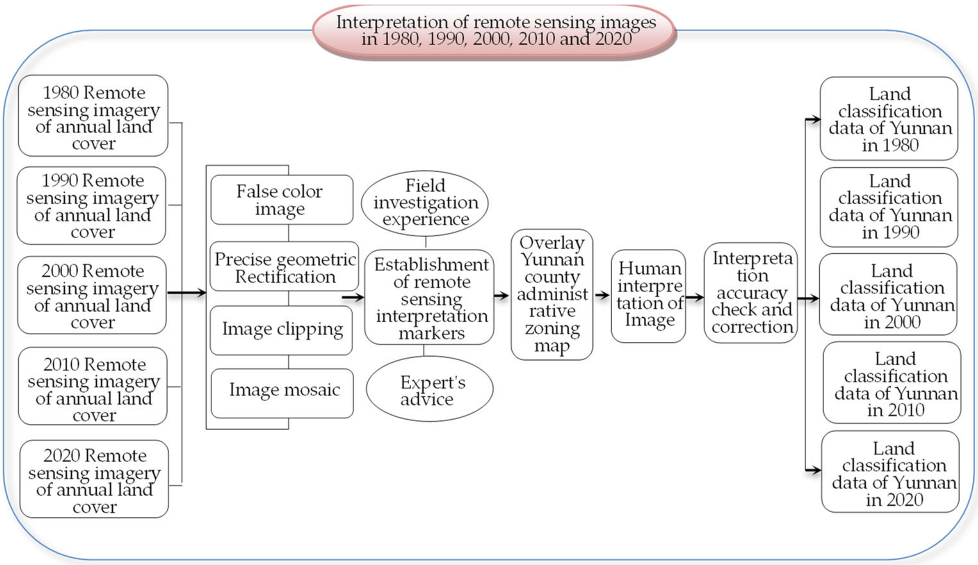


Figure 2. RS image interpretation of land cover in Yunnan province in 1980, 1990, 2000, 2010 and 2020.

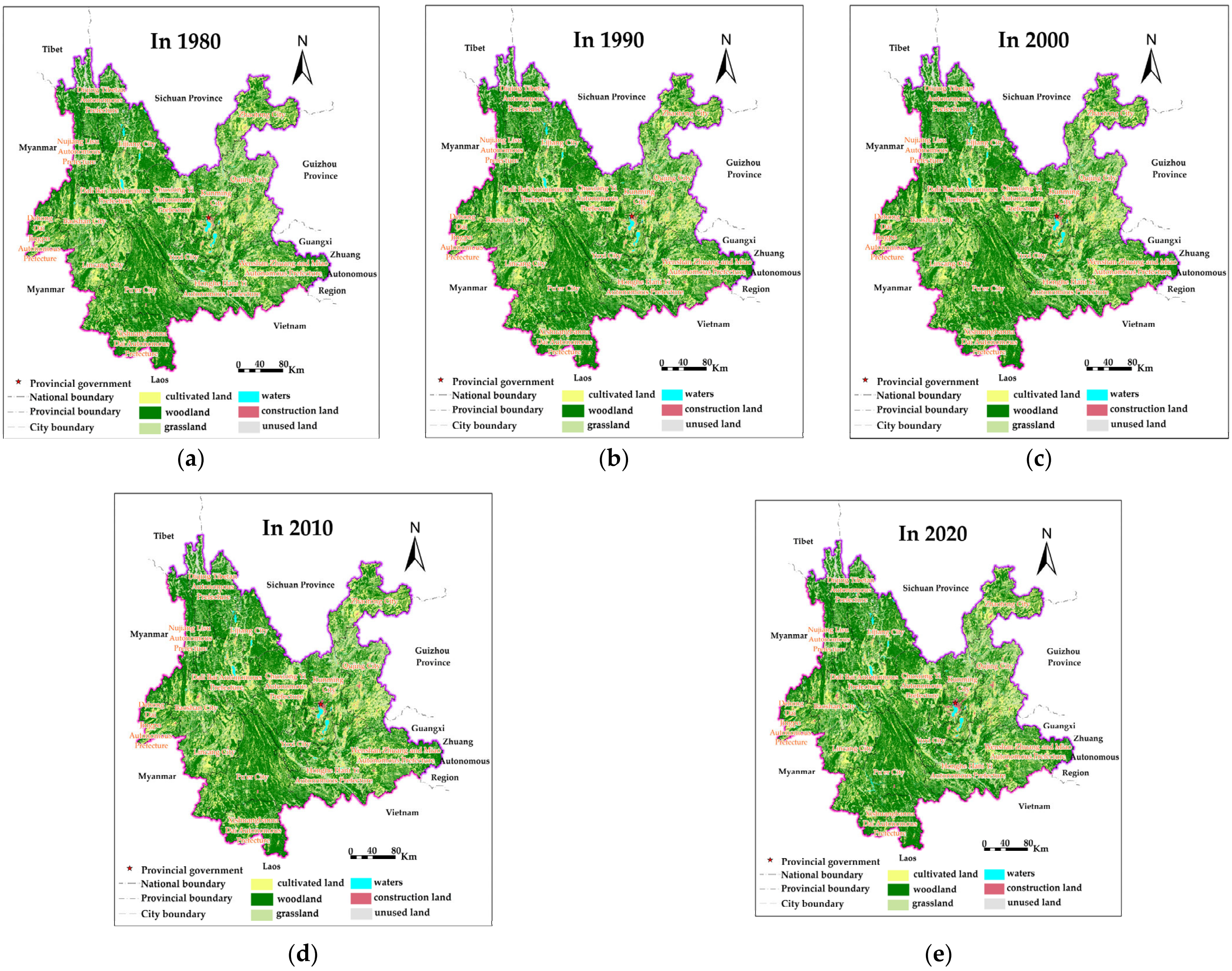


Figure 3. LULC map of Yunnan province in (**a**) 1980, (**b**) 1990, (**c**) 2000, (**d**) 2010 and (**e**) 2020.

Table 2. The classified area of land use/land cover in Yunnan province in 1980, 1990, 2000, 2010 and 2020.

First-Level Land Use Types		Second-Level Land Use Types		Land Use Area of Various Types (Unit: 10,000 Hectares)				
Number	**Name**	**Number**	**Name**	**In 1980**	**In 1990**	**In 2000**	**In 2010**	**In 2020**
1	Cultivated Land			554.02	552.45	551.08	545.96	539.56
		11	Paddy Field	137.71	136.77	135.91	134.53	131.39
		12	Dryland	416.31	415.68	415.17	411.43	408.17
2	Woodland			1736.23	1868.92	1998.19	2224.10	2418.67
		21	Closed Forest Land	961.27	1112.91	1414.58	1724.81	1884.72
		22	Other Forest Land	774.96	756.02	583.61	499.29	533.95
3	Grassland			578.38	532.64	481.25	325.65	181.12
		31	Pasture with High Coverage	370.00	340.02	307.02	195.20	105.36
		32	Pasture with Medium and Low Coverage	208.38	192.62	174.23	130.46	75.76
4	Waters			47.60	48.14	49.34	53.28	56.09
		41	Rivers and Lakes	32.02	31.96	31.78	31.47	31.18
		42	Reservoir and Pond	15.58	16.18	17.56	21.81	24.91
5	Construction Land			57.87	61.78	66.72	86.73	129.69
		51	Urban Construction Land, Rural Settlement Area and Land for Mining and Industry	47.64	50.82	54.84	74.86	109.17
		52	Other Building Land	10.23	10.96	11.88	11.87	20.52
6	Unused Land			868.33	778.50	695.85	606.71	517.30
		61	Bare Land	117.36	105.56	96.13	92.95	80.62
		62	Other Land Types	750.96	672.94	599.72	513.76	436.68

2.3. Methods of EVE

2.3.1. Basic Ideas and Indicator System for EVE

(1) Basic Ideas for EVE

This study is based on the awareness that regional ecological vulnerability is the result of "innate" natural ecological vulnerability (INEV) and the land use ecological vulnerability (LUEV) and land cover ecological vulnerability (LCEV) formed by human acquired socioeconomic activities. Consequently, the EVE of research is mostly a comprehensive assessment that takes county-level administrative regions as the assessment unit and, based on RS image interpretation of LULC information, organically integrates the three dimensions of INEV, LUEV and LCEV in the counties, evaluating the comprehensive conditions of ecological vulnerability within the counties. The quantitative multi-indicator comprehensive evaluation method and qualitative comprehensive analysis method are organically combined, and the degree of INEV, LUEV and LCEV in each county over 5 periods is computed. Furthermore, these three indicators are seamlessly combined to compute the level of overall ecological vulnerability (OEV) across all counties over the past 40 years in order to acquire a comprehensive assessment and understanding of 129 counties and comprehensively measure and compare the situations of ecological vulnerability within these counties.

(2) Evaluation Indicator System

The evaluation indicator system to be built is primarily aimed at regional EVE. Referring to Zhang Fengrong et al. [57] (2003), the indicator system is classified into three levels (Table 3). They are generally determined based on the demands of assessment work and the accessibility of existing data from the 129 counties.

Table 3. EVE: indicator system, computing approaches, data acquisition techniques and evaluation criteria.

Indicators Category	Evaluation Indicators	Element Indicators	Computing Methods and Explanations	Primary Data Acquisition Methods	Optimal Relative Value
Degrees of Natural Ecological Vulnerability (D_{NEV})	1.1 I_{MA}	Mountain Area (M_{LA})	I_{MA} = (M_{AR} − Minimum M_{AR})/Minimum M_{AR} × 100	The Second National Land Survey in Yunnan Province Dam Area Special Survey	It depends on the background of the region. It takes the minimum M_{AR} in Yunnan province as the relative optimal value.
		Total Land Area (T_{LA})	M_{AR} (Mountain Area Rate) = M_{LA}/T_{LA} × 100%		
	1.2 I_{SSA}	≥25° Steep Slope Area (S_{SA})	I_{SSA} = S_{SAR}/Maximum S_{SAR} × 100	Special Survey of Land Area in Different Climatic Zones and Slopes in Yunnan Province	Considering the regional background and rural development needs, the S_{SAR} in the province's relatively largest county is taken as the relative minimum value. The closer the S_{SAR} is to 0, the better the I_{SSA}.
		Total Land Area (T_{LA})	S_{SAR} (Steep Slope Area Rate) = S_{SA}/T_{LA} × 100%		
	1.3 I_{HAA}	High-Altitude Area (H_A)	I_{HAA} = H_{AR}/Maximum H_{AR} × 100	Special Survey of Land Area in Different Climatic Zones and Slopes in Yunnan Province	Considering the background and the needs of rural development, the H_{AR} in the province's relatively largest county is the relative minimum. The closer the H_{AR} is to 0, the better the I_{HAA} is.
		Total Land Area (T_{LA})	H_{AR} (High-Altitude Area Rate) = H_A/T_{LA} × 100%		
	1.4 I_{AAR}	Average Annual Rainfall (A_{AR})	I_{AAR} =100 − A_{AR}/Relatively Optimal Value of A_{AR} × 100%	Yunnan Agricultural Climate Dataset	Considering the regional background, after removing extreme values, the average annual rainfall of relatively large counties in the province is taken as the optimal value.
Degrees of Ecological Vulnerability of Land Use (D_{EVLU})	2.1 I_{OR}	Land Suitable Reclamation Rate (L_{SRR})	I_{OR} = O_{RR}/Maximum O_{RR} × 100	Land Suitability Evaluation	Actual reclamation rate ≤ suitable reclamation rate (i.e., O_{RR} = 0).
		Actual Land Reclamation Rate (A_{LRR})	O_{RR} (Over-Reclaimed Rate) = (A_{LRR} − L_{SRR})/L_{SRR} × 100%	RS Image Interpretation	
	2.2 I_{BLA}	Bare Land Area (B_{LA})	I_{BLA} = B_{LAR}/Maximum B_{LAR} × 100	RS Image Interpretation	0
		Total Land Area (T_{LA})	B_{LAR} (Bare Land Area Rate) = B_{LA}/T_{LA} × 100%		
	2.3 I_{EI}	Paddy Field Area (P_{EA})	I_{EI} = 100 − E_{IR}/Maximum E_{IR} × 100	RS Image Interpretation	The higher the E_{IR}, the lower the vulnerability.
		Cultivated Area (C_A)	E_{IR} (Effective Irrigated Rate of Cultivated Land) = P_{EA}/C_A × 100%		
	2.4 I_{GY}	Total Yield of Grain Crops (T_{YGC})	I_{GY} = [ln(Maximum I_{GY}) − ln(I_{GY})]/[ln(Maximum I_{GY}) − ln(Minimum I_{GY})] × 100	Socioeconomic Statistical Yearbook	Considering the regional background, this paper takes the G_{YPUA} of the county with the highest grain yield in the province as the relative optimal value.
		Sowing Area of Grain Crops (S_{AGC})	G_{YPUA} (Grain Yield Per Unit Area) = T_{YGC}/S_{AGC}		
Degrees of Ecological Vulnerability of Land Cover (D_{EVLC})	3.1 I_{FC}	Closed Forest Area (C_{FA})	I_{FC} = F_{CR}/Maximum F_{CR} × 100	RS Image Interpretation	≥67% (Planning for F_{CR} in Yunnan province by 2035).
		Total Land Area (T_{LA})	F_{CR} (Forest Coverage Rate) = C_{FA}/T_{LA} × 100%		
	3.2 I_{SEA}	Soil Erosion Area (S_{EA})	I_{SEA} = P_{SEA}/Maximum P_{SEA} × 100	Existing Thematic Surveys	The larger the proportion of soil erosion area, the higher the vulnerability. This paper takes the proportion of soil erosion area in the county with the largest relative area in the province as the relative extreme value.
		Total Land Area (T_{LA})	P_{SEA} (Proportion of Soil Erosion Area) = S_{EA}/T_{LA} × 100%		

Table 3. *Cont.*

Indicators Category	Evaluation Indicators	Element Indicators	Computing Methods and Explanations	Primary Data Acquisition Methods	Optimal Relative Value
Degrees of Ecological Vulnerability of Land Cover (D_{EVLC})	3.3 I_{BRC}	Index of Biological Richness (I_{BR})	I_{BRC} = (Maximum I_{BR} − I_{BR})/(Maximum I_{BR} − Minimum I_{BR}) × 100 I_{BR} = A_{bio} × (Woodland Area × 0.35 + Grassland Area × 0.21 + Waters Area × 0.28 + Cultivated Land Area × 0.11 + Construction Land Area × 0.04 + Unused Land Area × 0.01)/Total Land Area A_{bio} = 511.2642 [58–60]	Calculate According to the Interpretation Results of RS Images	It depends on the background of the region. According to the counties in Yunnan province with the best ecological protection, the relative optimal value was determined.
	3.4 I_{ESV}	Value of Ecological Service per Unit Land Area (V_{ES})	I_{ESV} = (Maximum V_{ES} − V_{ES})/(Maximum V_{ES} − Minimum V_{ES}) × 100 Where, V_{ES} is calculated according to Xie Gaodi et al. [61,62]	Calculate According to the Interpretation Results of RS Images	Considering the regional background, the counties with the best V_{ES} were used to determine the relative optimal value.

The INEV index is a fundamental indicator of the ecological vulnerability of the entire system, directly determining whether the county can sustain its inherent role and function in terms of ecology. Considering the actual conditions in various regions and the accessibility of existing data, the main indicators selected for assessing the natural ecological vulnerability status are the index of mountain area (I_{MA}), the index of steep-slope area with slope $\geq 25°$ (I_{SSA}), the index of high-altitude area (I_{HAA}) and the index of average annual rainfall (I_{AAR}).

The ecological vulnerability of land use mainly reflects the excessive development and use status of land as well as the level of resource transformation. For the former, the main indicators selected are the index of over-reclaimed rate (I_{OR}) and the index of bare land area (I_{BLA}). For the latter, the main indicators selected are the index of effective irrigated area of cultivated land (I_{EI}) and the index of grain yield per unit area (I_{GY}).

The ecological vulnerability of land cover mainly reflects the level of environmental protection and ecological value in various regions. For this study, the main indicators selected are the index of forest coverage rate (I_{FC}), the index of soil erosion area (I_{SEA}), the index of biological richness conversion (I_{BRC}) and the index of ecosystem services value (I_{ESV}). Of these, I_{BRC} is a significant index for evaluating eco-environment conditions, indirectly reflecting the richness of biological abundance in the evaluated areas [58–60]. It is positively correlated with the ecological benefits of resource utilization; the higher the I_{BRC}, the lower the ecological vulnerability in the region. I_{ESV} refers to the various benefits that people directly or indirectly obtain from the ecosystem. Sustainable utilization of resources and optimal ecological value are the fundamental aims of regional development strategies. The higher the I_{ESV}, the lower the DEV.

It might be pointed out that for the purpose of convenient contrast and analysis, a unified requirement has been proposed that all values of indicators could be converted into a value from 0 to 100, where values close to 100 indicate the highest vulnerability but lowest sustainability; values close to 0 indicate the lowest vulnerability but highest sustainability. Therefore, a process for transforming the index is also needed (Table 3).

(3) Assessment Criteria for EVE Indicators

The assessment criteria are also known as the threshold. Developing assessment criteria for each indicator is a very complex task; as a result, no uniform assessment criterion for EVE has been established so far, representing an issue that needs to be constantly explored [63]. Hence, the data and values of assessment criteria may be obtained through various approaches: First, some indicators (such as I_{SEA}) that have already been stipulated by the nation can be evaluated using standards formulated by the nation, local or industry. Second, for some restrictive indicators such as I_{OR}, it is necessary to use the bottom line or warning value acquired from the scientific study as the assessment criteria and reference. Third, for some indicators, their average value for the country (or the research area) or the target value of regional planning can often be used as the assessment criterion. In addition, there are also some indicators that need to be comprehensively analyzed according to specific regional conditions, such as I_{FC} and I_{BRC}, etc. In this study, the assessment criteria of the indicators of ecological vulnerability in Yunnan's counties were determined (Table 3).

2.3.2. Comprehensive Method for EVE

To quantitatively evaluate regional ecological vulnerability as a whole, four indicators of QMCE are proposed, namely, D_{INEV}, D_{EVLU}, D_{EVLC} and Degrees of Overall Ecological Vulnerability (D_{OEV}), which reflect the degree of INEV, LUEV, LCEV and overall ecological vulnerability (OEV), respectively. The "multi-index comprehensive evaluation method" [64] was used to determine the calculation method of these four comprehensive indexes.

(1) D_{INEV}.

D_{INEV} in the county is reflected through four indicators: I_{MA}, I_{SSA}, I_{HAA} and I_{AAR}. Consequently, based on separate calculations of these indicator values, the D_{INEV} value can be calculated using the following equation:

$$D_{INEV} = w_{11} \cdot I_{MA} + w_{12} \cdot I_{SSA} + w_{13} \cdot I_{HAA} + w_{14} \cdot I_{AAR} \quad (1)$$

In Equation (1), $w_{11}, \ldots, w_{14}$ are the weight values of the I_{MA}, I_{SSA}, I_{HAA} and I_{AAR}, respectively. The higher the D_{NEV} value, the more pronounced the degree of INEV and the lower the degree of sustainability.

(2) D_{EVLU}.

The four indicators that characterize D_{EVLU} are I_{OR}, I_{BLA}, I_{EI} and I_{GY}. On the basis of separately calculating these indicator values, the D_{EVLU} value can be quantitatively computed using the following equation:

$$D_{EVLU} = w_{21} \cdot I_{OR} + w_{22} \cdot I_{BLA} + w_{23} \cdot I_{EI} + w_{24} \cdot I_{GY} \quad (2)$$

In Equation (2), $w_{21}, \ldots, w_{24}$ are the weight values of I_{OR}, I_{BLA}, I_{EI} and I_{GY}, respectively. The higher the D_{EVLU} value, the more pronounced the degree of LUEV and the lower the degree of sustainability.

(3) D_{EVLC}.

There are also four indicators that characterize D_{EVLC}, namely, I_{FC}, I_{SEA}, I_{BRC} and I_{ESV}. On the basis of separately calculating these index values, the D_{EVLC} value may be quantitatively computed by using the following equation:

$$D_{EVLC} = w_{31} \cdot I_{FC} + w_{32} \cdot I_{SEA} + w_{33} \cdot I_{BRC} + w_{34} \cdot I_{ESV} \quad (3)$$

In Equation (3), $w_{31}, \ldots, w_{34}$ are the weight values of the I_{FC}, I_{SEA}, I_{BRC} and I_{ESV}, respectively. The higher the D_{EVLC} value, the more pronounced the LCEV and the lower the degree of sustainability.

(4) D_{OEV}.

The OEV is the organic combination of values of the aforementioned D_{INEV}, D_{EVLU} and D_{EVLC}. On the basis of separately calculating the values of these three comprehensive indicators, the D_{OEV} value of the study area can be quantitatively calculated as follows:

$$D_{OEV} = w_1 \cdot D_{INEV} + w_2 \cdot D_{EVLU} + w_3 \cdot D_{EVLC} \quad (4)$$

In Equation (4), w_1, w_2 and w_3 are the weight values of D_{INEV}, D_{EVLU} and D_{EVLC}, respectively. The higher the D_{OEV} value, the more pronounced the OEV level and the lower the sustainability level.

(5) Method for determining indicator weights and resulting values

The methods for determination of weight mainly include Principal Component Analysis (PCA), AHP and Delphi Method (or Expert Consultation Method), of which the latter approach is more commonly used to determine the weight coefficient. This study uses the frequently used Delphi method (expert consultation method) to determine the weight coefficients of each item. The specific approach is as follows: In November 2022, we organized 16 experts to assign weights to the various indicators of ecological vulnerability assessment in the above-mentioned regions. After providing feedback on the probability estimation results, the experts scored the weight of each indicator in the second and third rounds, gradually narrowing the scattered weights. Finally, we obtained a more coordinated and consistent weight value for each factor. After corresponding statistical processing, we obtained the weight value of each level of indicator. After the corresponding processing, the weight values of various levels of indicators were obtained (Table 4).

Table 4. The weight of indicators in various levels for regional ecological vulnerability evaluation.

First-Level Indicators	Weight	Second-Level Indicators	Weight
1. D_{INEV}	0.35	1.1 I_{MA}	0.38
		1.2 I_{SSA}	0.24
		1.3 I_{HAA}	0.18
		1.4 I_{AAR}	0.20
2. D_{EVLU}	0.33	2.1 I_{OR}	0.35
		2.2 I_{BLA}	0.18
		2.3 I_{EI}	0.22
		2.4 I_{GY}	0.25
3. D_{EVLC}	0.32	3.1 I_{FC}	0.27
		3.2 I_{SEA}	0.29
		3.3 I_{BRC}	0.23
		3.4 I_{ESV}	0.21

2.3.3. Ecological Vulnerability Grading System and Associated Standards

After calculating the DEV of the study region, it is also necessary to use this as a basis to classify the regional ecological vulnerability, aiming toward qualitatively assessing the DEV at different levels and combining qualitative and quantitative research results to better provide a scientific reference and guidance for implementing regional measures to meet the SDGs.

For a long time, there has been no specialized exploration or research on the regional ecological vulnerability classification system and standards. Here, based on our awareness and experience gained through serial surveys in various regions, combined with real conditions of the background and with reference to the rating system built by Yang Renyi et al. [21] (2021) and Yang Zisheng et al. [60] (2007), the regional DEV is divided into five levels (Table 5). In addition, the grading standard and the main meaning of each grade are shown (Table 5).

Table 5. Grading standard and main meaning of regional ecological vulnerability.

Grades of Ecological Vulnerability	D_{OEV}	Meaning
1. Very Slightly Vulnerable	<35	The DEV of regional development is very low; regional resource development and utilization activities have not caused significant impact or damage to the ecological environment; it can ensure the ecological sustainability of regional development.
2. Lowly Vulnerable	35~45	The DEV in regional development is not high; regional resource development and utilization activities have caused a certain degree of impact and damage; by adopting general measures, the ecological sustainability of regional development can be ensured.
3. Moderately Vulnerable	45~55	The DEV in regional development is relatively high; regional resource development and utilization activities have caused significant impact and damage; effective measures need to be taken to ensure the ecological sustainability of regional development.
4. Highly Vulnerable	55~65	The DEV in regional development is high; regional resource development and utilization activities have caused great impact and damage; strong measures need to be taken to ensure the ecological sustainability of regional development.
5. Very Highly Vulnerable	≥65	The DEV in regional development is very high, and the degradation and deterioration of the ecological environment are particularly prominent; regional resource development and utilization activities have caused tremendous impact and damage. It is necessary to fundamentally reverse the ways of resource utilization and regional development and take significant measures to ensure the ecological sustainability of regional development.

3. Results and Analysis

According to the above comprehensive EVE method, D_{INEV}, D_{EVLU}, D_{EVL} and D_{OEV} in 1980, 1990, 2000, 2010 and 2020 were quantitatively calculated. The county-level evaluation map of INEV (Figure 4), LUEV (Figure 5), LCEV (Figure 6) and OEV (Figure 7) in Yunnan province from 1980 to 2020 was compiled. Based on the calculation results, the spatiotemporal changes in INEV, LUEV, LCEV and OEV of Yunnan province can be analyzed.

3.1. The Spatiotemporal Evolution Characteristics of INEV and Its Spatial Difference

The D_{INEV} of Yunnan province is 58.21, which corresponds to the "highly vulnerable" level. It means that for Yunnan province as a whole, the D_{INEV} is high. This is the first characterization of the INEV in Yunnan province. This feature is mainly caused by the high and steep mountain terrain characteristics.

The second remarkable characteristic is that the spatial difference in D_{INEV} value is large in the province and the "innate" natural ecological environment of the high mountain and canyon area in northwest Yunnan is the most fragile. In the region, Nujiang prefecture, Diqing prefecture and Lijiang city have D_{INEV} values of 81.02, 84.51 and 69.79, respectively, which correspond to the "very highly vulnerable" level, followed by the northeast mountainous area of Yunnan, where most counties have D_{INEV} values of more than 55, with the highest being over 75 (i.e., Dongchuan, Qiaojia), and most counties are classified as "highly vulnerable" and "very highly vulnerable". In addition, the D_{INEV} values are also high in central and southeastern Yunnan, with most counties reaching over 55, and the region of southern Yunnan and southwestern Yunnan has a relatively low D_{INEV}, for example, with a D_{INEV} of 42.23 in Dehong prefecture. Considering the overall situation of the 129 counties in the province, most have a high D_{INEV}. Table 6 and Figure 4 show that 16.28% of the counties were classified as "very highly vulnerable", 36.43% as "highly vulnerable", 26.36% as "moderately vulnerable" and 13.18% as "low vulnerable", and "very slightly vulnerable" counties accounted for only 7.75%. In other words, 79.07% of counties were classified at the "moderately vulnerable" level or above. The reason why the INEV of Yunnan province is of great spatial difference is mainly due to the significant spatial difference and the superposition effect of the four indexes I_{MA}, I_{SSA}, I_{HAA} and I_{AAR}.

Table 6. Statistics of counties with INEV in Yunnan province.

Grades of Ecological Vulnerability	1. Very Slightly Vulnerable	2. Lowly Vulnerable	3. Moderately Vulnerable	4. Highly Vulnerable	5. Very Highly Vulnerable
County number	10	17	34	47	21

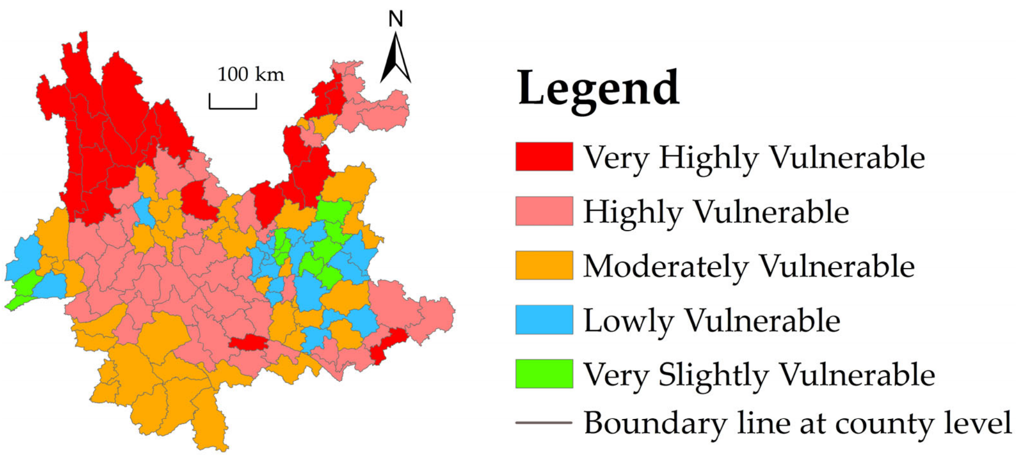


Figure 4. Classification map of INEV in Yunnan province.

3.2. The Spatiotemporal Evolution Characteristics of "Acquired" LUEV and LCEV

3.2.1. The Spatiotemporal Evolution Characteristics of LUEV

Figure 5 shows the spatiotemporal changes in D_{EVLU}, and the main characteristics of its grades for the whole province and 129 counties from 1980 to 2020 will now be discussed.

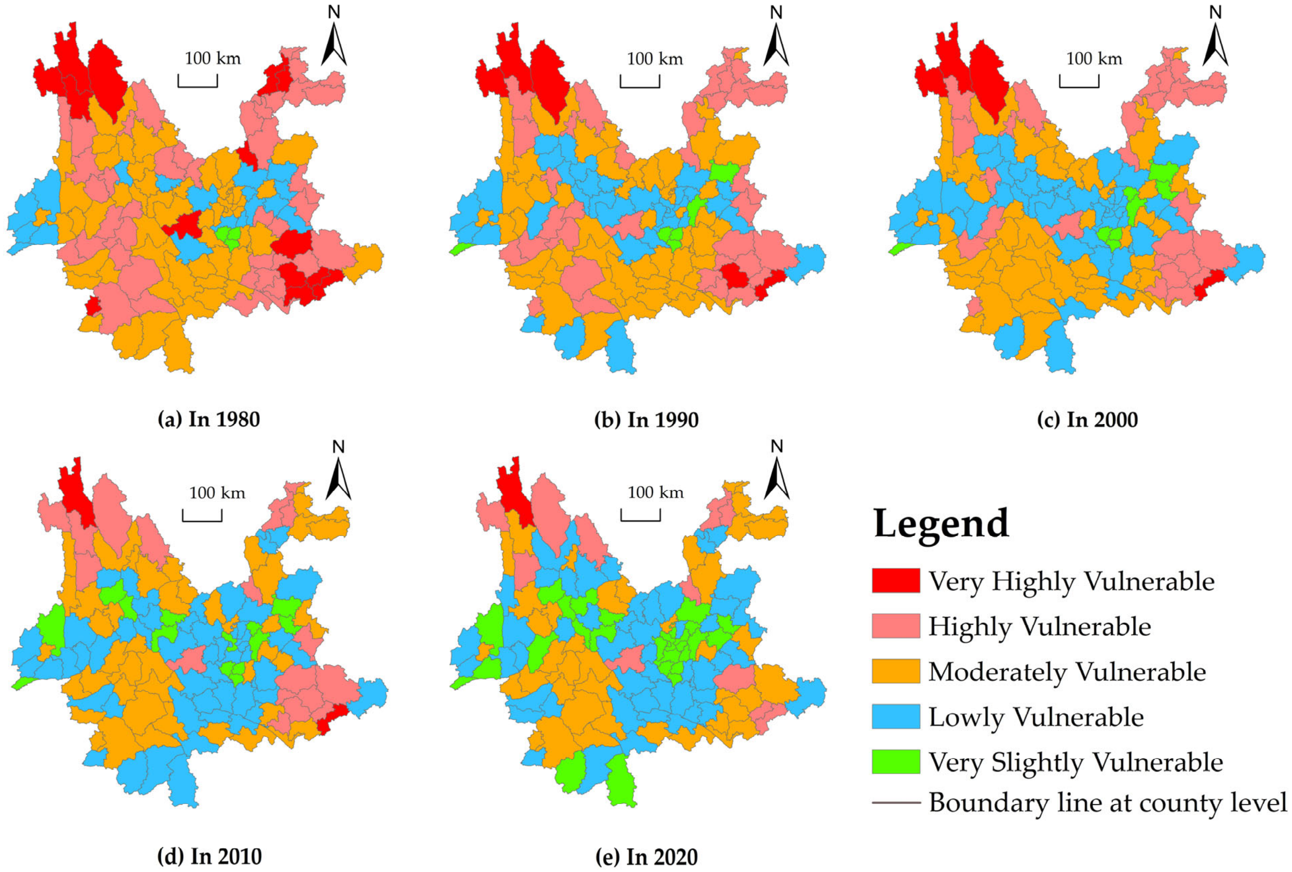


Figure 5. EVE of land use in Yunnan province from 1980 to 2020.

First, the D_{EVLU} values of Yunnan have gradually dropped from 1980 to 2020, and the corresponding level of LUEV was reduced from the "moderately vulnerable" to the "lowly vulnerable" level. The average value of D_{EVLU} was 53.50 in 1980, and it dropped to 43.94 in 2020, with a net decrease of 9.56. It means that in the past 40 years, significant progress has been achieved as a result of the measures to protect and construct the ecological environment in land use in Yunnan province. In particular, due to the implementation of crucial ecological preservation measures in the past decade, such as comprehensive management of sloping cultivated land, the average annual decrease in D_{EVLU} of Yunnan province from 2010 to 2020 was 0.76%, and the grade of LUEV improved to the level of "lowly vulnerable".

Second, from 1980 to 2020, the LUEV in counties has changed significantly, and the general rule is that the number of counties with high D_{EVLU} significantly decreased while the number of counties with low D_{EVLU} significantly increased. Figure 5 and Table 7 show that over the 40-year period from 1980 to 2020, the number of "very highly vulnerable" counties decreased from 14 to 1, with a net decrease of 92.86%; the number of "highly vulnerable" counties decreased from 41 to 11; the number of "moderately vulnerable" counties decreased from 53 to 41, with a net decrease of 22.64%; the number of "lowly vulnerable" counties increased from 18 counties to 49 counties, with a net increase of 1.72 times; and the number of "very slightly vulnerable" counties increased from 3 to 27, with a net increase of 8 times. This indicates that the many ecological protection measures that were taken in the past 40 years have been effective, with obvious effects observed.

Table 7. Number of counties with different LUEV grades in Yunnan province from 1980 to 2020.

Year	1. Very Slightly Vulnerable	2. Lowly Vulnerable	3. Moderately Vulnerable	4. Highly Vulnerable	5. Very Highly Vulnerable
1980	3	18	53	41	14
1990	6	33	51	34	5
2000	8	43	47	27	4
2010	14	51	45	17	2
2020	27	49	41	11	1

Third, the regional difference in LUEV is large. Although the values of D_{EVLU} have decreased to different degrees from 1980 to 2020, the annual average decreases are quite varied. Overall, the annual average decrease in D_{EVLU} value of central, southern and southwestern Yunnan is relatively large. The annual average decrease in D_{EVLU} value for most counties in these areas is more than 0.60, and the decrease in values reached more than 1.00 in Chenggong, Hongta, Guandu, Xishan, Qilin, Wuhua and Anning, while smaller annual decreases were observed in the northwest, northeast and southeast Yunnan, where the average annual decrease in D_{EVLU} was less than 0.40 in most of these counties, with Yanjin, Daguan, Fugong, Ninglang, Shangri-la, Lanping and Lushui dropping below 0.30. This is mainly related to the condition of land over-exploitation (mainly land over-cultivation and bare land) and the level of resource transformation (mainly E_{IR} and G_{YPUA}).

3.2.2. The Spatiotemporal Evolution Characteristics of LCEV

Figure 6 shows that from 1980 to 2020, the spatiotemporal evaluation of D_{EVLC} and its grades in the whole province and all counties also exhibit the following three remarkable characteristics.

First, the D_{EVLC} values in Yunnan have obviously dropped from 1980 to 2020. The corresponding level of vulnerability dropped from the "highly vulnerable" to the "very slightly vulnerable" level. In 1980, the average D_{EVLC} value of the whole province was 55.79. By 2020, the D_{EVLC} value decreased to 30.01, the net decrease value reached 25.78 and the annual average decrease was 1.16%, which is equivalent to 2.6 times the average annual decrease in D_{EVLU}. This means that over the past 40 years, Yunnan province has achieved remarkable results in improving land cover (especially forest cover rate) and ecological service value while controlling soil and water loss. In particular, 2000 marked the beginning of measures for the conversion of cultivated land to woodland and grassland (CCWG), rocky desertification land consolidation, afforestation and greening of barren mountains and other major ecological construction projects with comprehensive effect. From 2000 to 2020, the average annual decrease in D_{EVLC} of Yunnan province was 1.70%, with the reduction of LCEV to the "very slightly vulnerable" level.

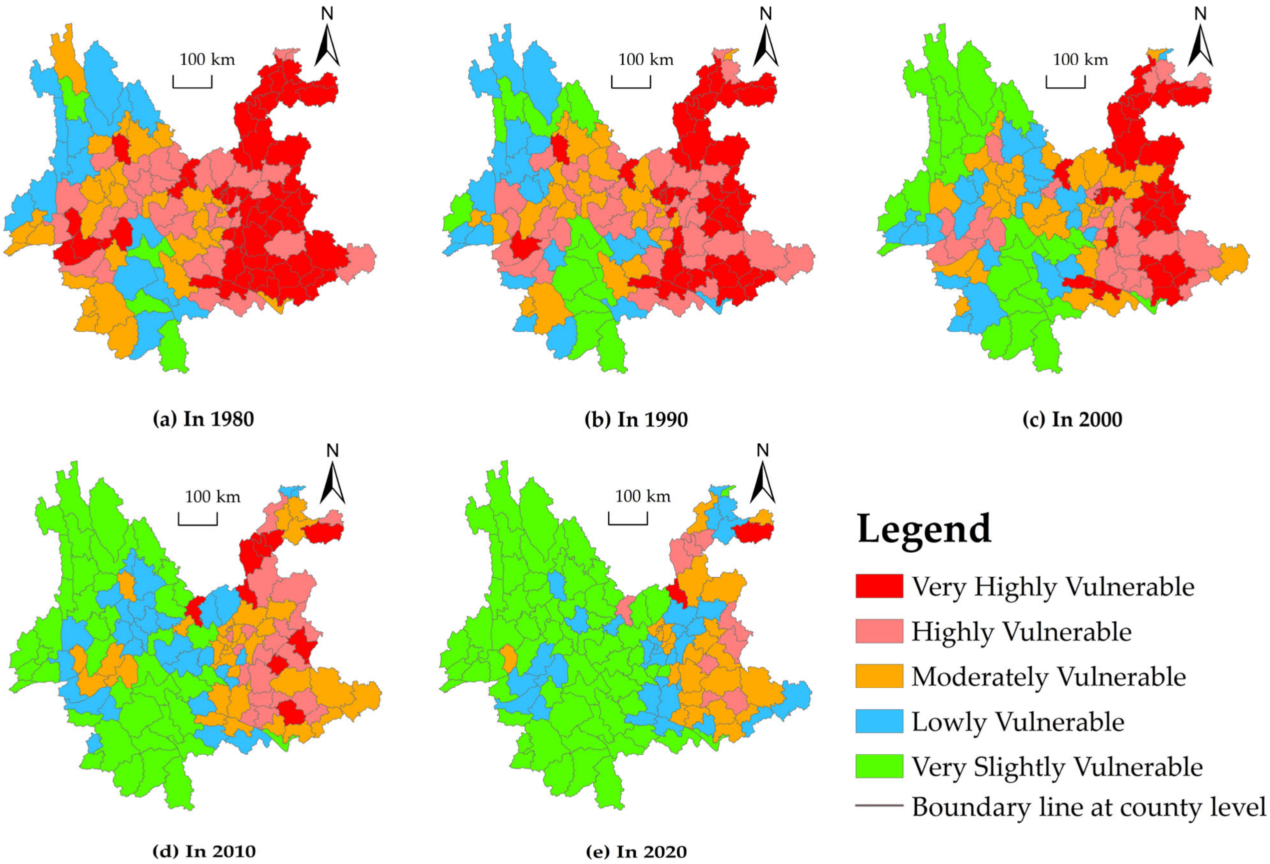


Figure 6. EVE of land cover in Yunnan from 1980 to 2020.

Second, the LCEV in counties has changed greatly from 1980 to 2020. The basic rule is that the number of counties with high D_{EVLC} greatly decreased while the number of counties with low D_{EVLC} greatly increased. Figure 6 and Table 8 show that over the 40-year period from 1980 to 2020, the number of "very highly vulnerable" counties decreased from 48 to 2, with a net decrease of 95.83%; the number of "highly vulnerable" counties decreased from 33 to 8, with a net decrease of 75.76%; the number of "moderately vulnerable" counties decreased from 29 to 24, with a net decrease of 17.24%; the number of "lowly vulnerable" counties increased from 15 to 29, with a net increase of 93.33%; and the number of "very slightly vulnerable" counties increased from 4 to 66, with a net increase of 15.50 times. This shows that in the past 40 years, the counties have taken numerous effective measures for ecological construction, such as CCWG, rocky desertification land consolidation, afforestation and greening of barren mountains.

Table 8. Number of counties with different LCEV grades in Yunnan province from 1980 to 2020.

Year	1. Very Slightly Vulnerable	2. Lowly Vulnerable	3. Moderately Vulnerable	4. Highly Vulnerable	5. Very Highly Vulnerable
1980	4	15	29	33	48
1990	12	21	24	36	36
2000	26	22	30	25	26
2010	42	29	30	19	9
2020	66	29	24	8	2

Third, the change in the LCEV presents remarkable regional variations in geographical space. In the past 40 years, the values of D_{EVLC} have decreased to differing degrees, while the regional difference in annual average reduction is very significant. In general, the annual average decrease in D_{EVLC} values of northwest, southwest, south and central Yunnan is relatively large, and the annual average decrease in D_{EVLC} values in most counties in these regions is more than 1.20, reaching 1.50 or more in Jiangcheng, Ning'er, Jingdong, Simao, Shangri-la, Zhenyuan, Jinggu, Yingjiang, Dayao, Ninglang, Jinghong, Fugong, Mojiang, Yunlong, Weixi, Mengla, Yongping, Nanhua, Tengchong, Yulong, Lufeng, Lushui, Gongshan, Deqin, Yongren, Zhenkang and Chuxiong. The annual average decrease in D_{EVLC} was less than 0.90 in most counties in northeastern, eastern and southeastern Yunnan, where it fell below 0.60 in Luxi, Mi'le, Shilin, Fuyuan, Luoping, Zhenxiong, Zhaoyang, Kaiyuan, Dongchuan and Qiubei. This is mainly related to the state of forest cover rate, soil erosion, biological abundance and ecological service value in different periods.

3.3. The Spatiotemporal Evolution Characteristics of OEV

3.3.1. Characteristics of OEV Change in the Past 40 Years

Figure 7 indicates the changes in D_{OEV} and OEV levels in various regions from 1980 to 2020, primarily exhibiting two features.

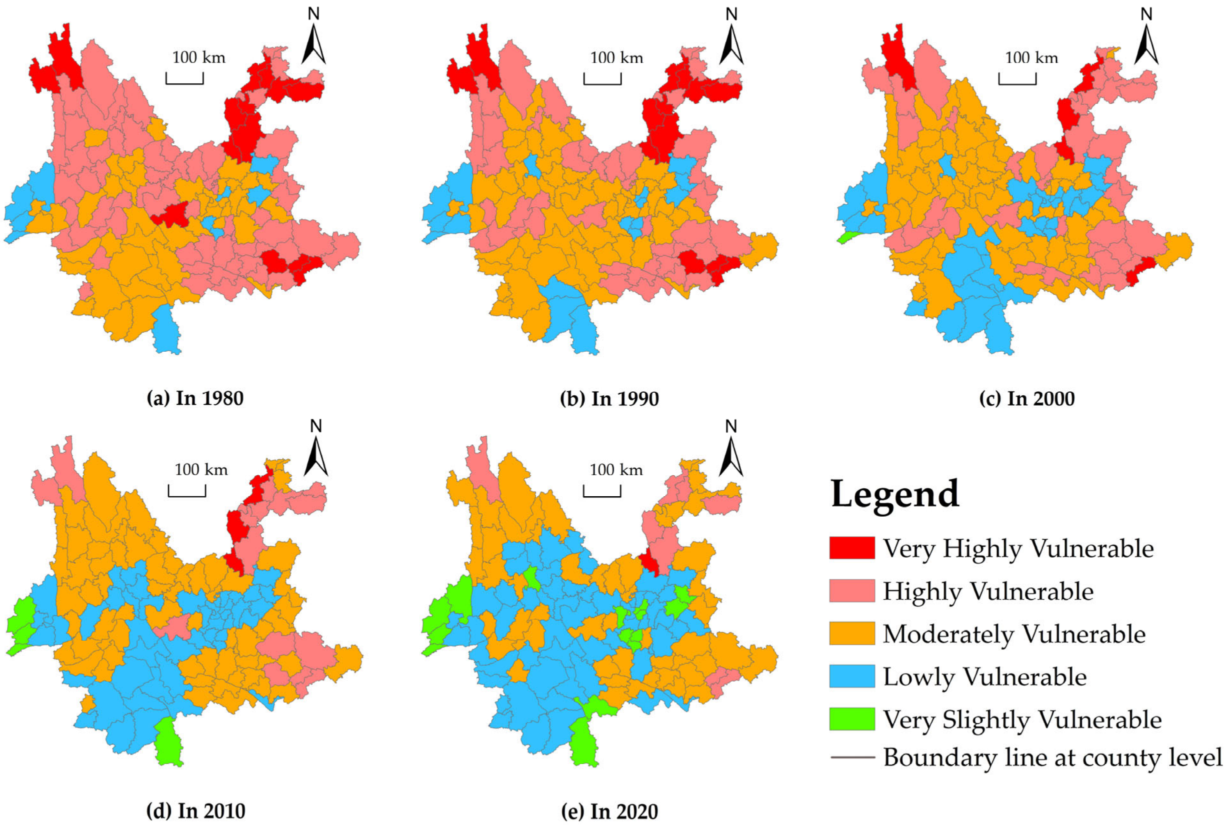


Figure 7. OEV evaluation in Yunnan province from 1980 to 2020.

First, the D_{OEV} in Yunnan obviously decreased, with the whole OEV grade changing from the "highly vulnerable" to the "lowly vulnerable" level. The average D_{OEV} of Yunnan province in 1980 was 55.88 and decreased to 44.47 in 2020, with a net decrease of 11.41. The OEV level of the whole correspondingly decreased from the "highly vulnerable" to the "lowly vulnerable" level. This means that the measures have achieved significant results in the past 40 years, which is also an important achievement following the vigorous implementation of the VECC strategy in Yunnan province.

Second, the regional differences in OEV level and D_{OEV} changes are large. From 1980 to 2020, in terms of the changes in the OEV level of 16 prefectures, Diqing and Zhaotong were both downgraded from the "very highly vulnerable" to the "moderately vulnerable" level. Nujiang, Lijiang, Qujing, Chuxiong, Lincang, Honghe and Wenshan were all downgraded from the "highly vulnerable" to the "moderately vulnerable" level. Kunming, Yuxi, Dali, Baoshan and Pu'er were downgraded from the "moderately vulnerable" to the "lowly vulnerable" level. Xishuangbanna was downgraded from the "moderately vulnerable" to the "very slightly vulnerable" level, and Dehong was downgraded from the "lowly vulnerable" to the "very slightly vulnerable" level.

In addition, the changes in the OEV level and D_{OEV} of 129 counties (cities and districts) in the past 40 years are rather complicated and can be classified into 9 types: (1) "very highly vulnerable" level to "highly vulnerable" level, involving 8 counties (6.20%); (2) "very highly vulnerable" level to "moderately vulnerable" level, involving 5 counties (3.88%); (3) "highly vulnerable" level to "moderately vulnerable" level, involving 44 counties (34.11%); (4) "highly vulnerable" level to "lowly vulnerable" level, involving 17 counties (13.18%); (5) "moderately vulnerable" level to "lowly vulnerable" level, involving 38 counties (29.46%); (6) "moderately vulnerable" level to "very slightly vulnerable" level, involving 6 counties (4.65%); (7) "lowly vulnerable" level to "very slightly vulnerable" level, involving 9 counties (6.97%); (8) maintaining the "very highly vulnerable" level (unchanged), involving 1 county (0.78%); (9) maintaining the "lowly vulnerable" level (unchanged), involving 1 county (0.78%). Over the past 40 years, 127 counties (98.45%) have experienced a decrease in their OEV levels, while 2 counties (1.55%) showed no change.

It is worth pointing out that the actual D_{OEV} values in the two counties that maintained at "very highly vulnerable" and "lowly vulnerable" levels without any level changes have shown a slow downward trend.

The results of the above-mentioned dynamic evolution caused the number of counties with different OEV levels to correspondingly change from 1980 to 2020. The basic rule is that the number of counties with high D_{OEV} significantly decreased while the number of counties with low D_{OEV} significantly increased (Table 9). From 1980 to 2020, the number of "very highly vulnerable" counties decreased from 14 to 1, with a net decrease of 92.86%; the number of "highly vulnerable" counties decreased from 61 to 8, with a net decrease of 86.89%; the number of "moderately vulnerable" counties increased from 44 to 50, with a net growth of 13.64% and the number of "lowly vulnerable" counties increased from 10 to 55, with a net increase of 4.50 times. In 1980, there were no "very slightly vulnerable" counties; by 2020, there were 15 "very slightly vulnerable" counties, accounting for 11.63%.

Table 9. The number of counties with different OEV grades in the province from 1980 to 2020.

Year	1. Very Slightly Vulnerable	2. Lowly Vulnerable	3. Moderately Vulnerable	4. Highly Vulnerable	5. Very Highly Vulnerable
1980	0	10	44	61	14
1990	0	17	57	42	13
2000	1	28	60	35	5
2010	4	45	62	15	3
2020	15	55	50	8	1

3.3.2. Spatial Differences in OEV of Yunnan Province

On the basis of the calculation results for 2020, the average D_{OEV}, on the whole, has dropped to 44.47, indicating that the OEV level of the province has decreased to a "lowly vulnerable" level. However, there are significant regional differences in the D_{OEV} value within the province. In general, the D_{OEV} value is lower in the southern, southwestern, western and central regions of Yunnan and higher in the northwest high mountain and canyon areas, the northeastern mountainous areas and some karst areas. From the county-level perspective, the OEV level is still relatively high, with 50 counties (38.76%) being "moderately vulnerable". Deqin, Daguan, Huize, Zhenxiong, Qiaojia, Yongshan, Xichou and Malipo are classified as "highly vulnerable". Dongchuan, known as the "mudslide museum", remains at the "very highly vulnerable" level.

3.3.3. Analysis of the Reasons for the Spatiotemporal Evolution of OEV

The main reason why the D_{OEV} in Yunnan has gradually dropped over the past 40 years is that Yunnan province has paid great attention to ecological construction and environmental protection and established a strategy of "constructing ecological province and prioritizing the environment". The tremendous efforts in protection and governance have obviously boosted the continual upgrading of the ecological environment in the province, evidently increased F_{CR} and gradually enhanced E_{SV}. From a provincial perspective, over the past 40 years, except for a slight decrease in the E_{IR} due to urbanization, industrialization and various infrastructure constructions occupying paddy fields, the other ecological vulnerability indicators of LULC have shown significant improvement (Table 10) from 1980 to 2020: the over-reclaimed rate (O_{RR}) decreased from 17.69% to 14.64%, with a decrease of 17.24%; the bare land area rate (B_{LAR}) decreased from 15.27% to 10.49%, with a decrease of 31.30%; the forest coverage rate (F_{CR}) increased from 25.02% to 49.05%, with an increase of 96.04%; the index of biological richness (I_{BR}) increased from 108.36 to 129.06, with an increase of 19.10% and the ecological services value per unit area (V_{ES}) increased from 96.09 to 129.63 CNY/hectare, with an increase of 34.90%. The O_{RR}, B_{LAR}, F_{CR}, I_{BR} and V_{ES} in the vast majority of counties have shown significant improvement. This is the basic reason why the OEV of Yunnan province and most counties is gradually decreasing.

Table 10. Changes in LULC ecological vulnerability indicators in Yunnan province from 1980 to 2020.

Years	O_{RR} (%)	B_{LAR} (%)	E_{IR} (%)	F_{CR} (%)	I_{BR}	V_{ES} (CNY/Hectare)
1980	17.69	15.27	24.86	25.02	108.36	96.09
1990	17.35	13.74	24.76	28.96	113.16	102.48
2000	17.06	12.51	24.66	36.81	117.69	111.29
2010	15.98	12.09	24.64	44.89	123.92	122.18
2020	14.64	10.49	24.35	49.05	129.06	129.63
Increase or decrease over 40 years (%)	−17.24	−31.30	−2.05	96.04	19.10	34.90
Average annual increase or decrease (%)	−0.43	−0.78	−0.05	2.40	0.48	0.87

However, considering all things, the D_{OEV} in Yunnan remains relatively high, which is an overall reflection of the "innate" situations of the natural environment, such as terrain, excessive long-term land development and resource transformation (consolidation) level. In terms of "innate" terrain, "there are many steep slopes and high mountains with lots of rocks, climbing when going out" is a basic reflection of the terrain characteristics of most areas in Yunnan province. About 77% of the land area has a >15° slope, and nearly 40% is steep slopes with a >25° slope. Over 56% of the counties have a >30% land ratio of steep slope, and over one-fifth of counties have a >50% land ratio of steep slope [50]. The result of long-term excessive development and use of land is particularly reflected in over-reclamation (including deforestation and cultivating on steep slopes) and the abundance of mountainous regions maintaining primitive, extensive and backward practices, accounting for the considerable proportion of slope-cultivated land [49]. According to the main data bulletin [65], slope cultivated land of >15° and ≤25° represents 27.22% and steep slope cultivated land of >25° (including terraced fields above 25°) 18.64%. The area of suitable cultivated land (including suitable cultivated land in existing cultivated land and unused land) was 4.7076 million hectares in 2020 in the whole province, representing a suitable cultivation rate of just 12.25%. However, the actual reclamation rate in 2020 reached 14.04%. Each county has varying degrees of excessive development and use. Overall, 68.22% of counties have an O_{RR} of over 10%, and around 25% of counties have an O_{RR} of over 20%. This is a core reason behind the generally weak ecological environment for Yunnan's socioeconomic development. Furthermore, the measures for resource transformation (consolidation) and ecological environment preservation have not maintained. For instance, the E_{IR} value is not large. The value of E_{IA} in the whole province in 2020 was less than 1.40 million hectares, and the value of E_{IR} was only about 25%. In addition, due to the long-term impact of different intensities and methods of land development and utilization, most counties have various distributions of B_{LAR}. In 2020, the proportion of B_{LA} in the province was 2.10%. Luoping, Guangnan, Xichou, Qiubei and Yanshan have more than 10% of their land classified as bare.

The obvious areal differentiations of the current OEV level within the province are related to the topographic pattern, LULC situation and ecological environment construction status in the various regions. Specifically, there are obvious areal distinctions in the 3 aspects and 12 indicators that reflect the regional OEV level mentioned above. For instance, in terms of landform pattern, the terrain of the high mountain and canyon area in the northwest and the middle high mountain area in the northeast is steep. The ratio of steep land with slopes greater than 25° in most counties is over 50%; however, in Gongsha, Fugong and Deqin, this ratio reaches 91.18%, 88.31% and 80.88%, respectively. The ratio of steep land with slopes greater than 25° in most counties of central and eastern Yunnan is less than 30%. From the perspective of F_{CR} in various counties, there are 50 counties with an $F_{CR} < 40\%$, whereas 9 counties have an $F_{CR} < 20\%$. In terms of the distribution of B_{LAR}, the values of B_{LAR} in Wenshan and Diqing are about 8%. From the perspective of county-level units, there are 55 counties in the province with a B_{LAR} of over 1%, among which 6 counties have a B_{LAR} of 5% to 10%, and 5 counties have a B_{LAR} of over 10%. From the perspective of E_{IR}, over 95% of counties have an E_{IR} below 50%, with about two-thirds of counties having an E_{IR} below 30%, and 25 counties having an E_{IR} below 10%. In addition, there are significant differences in I_{BR} and V_{ES}. About two-fifths of counties have $I_{BR} < 120$, and 13 counties have $I_{BR} < 100$. About two-fifths of counties have an average V_{ES} of <1.2 million CNY/km^2 and 20 counties have an average V_{ES} value of <1.0 million CNY/km^2.

4. Discussion

In this study, based on the five phases of LULC data obtained from RS image interpretation in Yunnan province, the three dimensions of ecological vulnerability of the INEV, and the "acquired" LUEV and LCEV formed by human social and economic activities, were organically integrated, and comprehensive evaluation of the OEV was carried out. Overall, from 1980 to 2020, Yunnan province gradually paid increasing attention to ecological environment preservation. Among some indicators related to LUEV and LCEV, except for a slight decrease in the E_{IR} due to urbanization, industrialization and various infrastructure constructions occupying paddy fields, the other indicators reflect significant improvements. The O_{RR}, the B_{LAR}, F_{CR}, I_{BR} and V_{ES} in the vast majority of counties have all significantly improved, which is the basic reason why the D_{OEV} of Yunnan province and most counties has gradually decreased over the past 40 years. This also fully reflects the significant achievements made in ecological environment preservation with advancements from 1980 to 2020, especially the important achievements in Yunnan in vigorously implementing the strategy of VECC.

However, because of the inherent terrain and other natural environmental conditions, as well as the comprehensive impact of long-term unreasonable development, the OEV level on the whole is still relatively high. The factor of terrain is the most important in terms of "innate" natural circumstances. Yunnan has 77% land area with a >15° slope, and about two-fifths of the land area consists of steep slopes with more than 25°. Over 56% of counties have a >30% land ratio of steep slope, and over one-fifth of counties have a >50% land ratio of steep slope. Therefore, the "innate" ecological vulnerability is relatively high. In terms of "acquired" factors, the high DEV of Yunnan province is first and foremost the result of excessive land development and utilization, particularly reflected in over-reclamation (including deforestation and cultivating on steep slopes) [60], and the abundance of mountainous regions maintaining primitive, extensive and backward practices has resulted in a considerable proportion of slope-cultivated land. The area of suitable cultivated land (including suitable cultivated land in existing cultivated land and unused land) was 4.7076 million hectares in 2020 in the whole province, with only 12.25% being suitable for cultivation. Each county has varying degrees of excessive development and use. Overall, 68.22% of counties have an O_{RR} of over 10%, and about 25% of counties have an O_{RR} of over 20%. This is the root reason behind the generally weak ecological environment for Yunnan's social–economic development. In addition, the measures of resource transformation (consolidation) and ecological environment preservation have not maintained, manifested in the low E_{IR}, with about two-thirds of counties having E_{IR} values of less than 30%. There are significant regional differences in F_{CR}, with some counties having F_{CR} values < 20%. In addition, there is a significant difference between the I_{BR} and the average V_{ES} in different regions. Consequently, it is extremely important to carry out great ecological preservation projects according to local conditions, especially in weak areas with high DEV [66]. To promote meeting the SDGs in Yunnan, it is urgent to further significantly reduce ecological vulnerability. Therefore, it is urgent to increase efforts in ecological civilization construction throughout the province, effectively implementing the strategy of VECC [67] and taking practical and effective ecological environment protection and construction measures according to local conditions, especially in terms of developing and utilizing various resources reasonably based on the principles of ecological suitability and environmental friendliness, to steadily reduce the D_{OEV} in various regions, ensuring the coordination of the "population, resources, environment, and economic development" system and the sustainability of regional development. For counties evaluated as being "moderately vulnerable", "highly vulnerable" and "very highly vulnerable", it is necessary to essentially change the mode of resource development and utilization and take ecological and environmental protection and construction measures to significantly reduce ecological vulnerability.

Overall, ecological vulnerability assessment is one of the core contents of vulnerability research, and the development of RS and GIS technology has provided convenient conditions for this study. However, based on existing research results, there is currently no comprehensive multi-phase ecological vulnerability assessment research based on RS and GIS for mountainous provinces. Correspondingly, a suitable, feasible and easy-to-use regional ecological vulnerability assessment system for mountainous areas has not been established, including the congenital natural ecological vulnerability evaluation and the "acquired" ecological vulnerability evaluation based on multi-phase LUCC; thus, it is difficult to judge and obtain the dynamic changes in the degree of ecological vulnerability in mountain areas. And this deficiency is the distinctive feature and innovation of this study. The research results of this study can be more conducive to the implementation of SDGs and the selection of countermeasures in mountainous areas.

On the other hand, in terms of LUCC based on RS, the research on the spatiotemporal evolution characteristics of ecological vulnerability in all counties also represents a further refinement and extension of former vulnerability research. LUCC often has a significant influence on ecosystems, biogeochemistry cycles, climate change, biodiversity, etc. [68,69], which in turn affects regional ecological vulnerability. Therefore, since the 1990s, LUCC has been the core of global environmental change research [70,71], and study achievements continue to emerge. Recently, the study on LUCC has advanced to becoming an interdisciplinary and independent field termed land change science (LCS) [72], which has led to the formation of the land system science (LSS) research group organized by the global land program (GLP) project [73–75]. The ultimate goal of both LCS and LSS research is to reduce ecological vulnerability and enhance the sustainability of land use and regional development. Therefore, the research in this paper can, to a certain extent, promote the further refinement of LUCC research based on RS and the application of LCS and LSS in the field of regional EVE, sustainable land use and regional development.

Conducting a comprehensive evaluation of county ecological vulnerability and dynamic change research for a mountainous province is indeed a challenging task with extreme difficulty. Especially when collecting, organizing and analyzing basic data from various counties, we often encounter many obstacles. For example, some indicator data from a few counties in specific years may be incomplete or have obvious inaccuracies. This is why we are taking multiple measures simultaneously to overcome this obstacle:

Firstly, we will make full use of remote sensing image interpretation results to analyze and supplement missing and obviously inaccurate data. The second is to find ways to collect statistical data from various counties over the years and objectively analyze and determine data that are in line with reality. The third is to conduct necessary research on the ground and specifically implement the relevant situation. By combining these approaches, we can effectively overcome the obstacles encountered during the research process.

5. Conclusions

This study was based on five periods of LULC data (1980, 1990, 2000, 2010 and 2020) obtained from RS image interpretation, with the county-level region as the assessment unit, adopting organic combination methods of QMCE and QCA. Based on the establishment of an evaluation indicator system of three dimensions of INEV and "acquired" LUEV and LCEV in 129 counties of the province, the D_{INEV}, D_{EVLU} and D_{EVLC} were calculated for 129 counties in 1980, 1990, 2000, 2010 and 2020. The D_{OEV} of 129 counties from 1980 to 2020 was computed by organically combining the three indicators; this was used to analyze the characteristics of the OEV of each county in the province. The results indicated the following:

(1) The INEV of the province was high, and the D_{INEV} value reached 58.21, corresponding to the "highly vulnerable" level. This feature is mainly caused by the high and steep mountain terrain characteristics. In terms of 129 counties, 79.07% of counties were classified as "moderately vulnerable" or above. The regional difference in INEV is large. In the whole province, the "innate" natural ecological environment is the most fragile in the high mountains and canyons of northwest Yunnan, and most counties belong to the "very highly vulnerable" level; the second is the mountainous area of northeast, and most counties belong to the levels of "highly vulnerable" or "very highly vulnerable". Most counties in central and southeastern Yunnan are classified as "highly vulnerable", while the D_{INEV} is relatively low in south and southwest Yunnan.

(2) The D_{EVLU} and D_{EVLC} resulting from acquired human socioeconomic activities were higher in 1980 (40 years ago), and the average D_{EVLU} and D_{EVLC} values in Yunnan were 53.50 and 55.79, which correspond to the classification of "moderately vulnerable" and "highly vulnerable", respectively. After 40 years of ecological protection and construction, the average D_{EVLU} and D_{EVLC} values in Yunnan province fell to 43.94 and 30.01, respectively, in 2020, which are "lowly vulnerable" and "very slightly vulnerable", respectively. Over the past 40 years, the average D_{EVLU} and D_{EVLC} values in Yunnan province dropped by 0.45% and 1.16%, respectively. From 1980 to 2020, the values of D_{EVLU} and D_{EVLC} dropped to various degrees in each county. The basic rule of change of vulnerability grades is that the number of counties with high D_{EVLU} and D_{EVLC} greatly decreased while the number of counties with low D_{EVLU} and D_{EVLC} significantly increased.

(3) From 1980 to 2020, the OEV of Yunnan province and counties decreased significantly. The average D_{OEV} of Yunnan province decreased by 0.51% annually, and the OEV level changed from being "highly vulnerable" in 1980 to "lowly vulnerable" in 2020. This indicates the obvious success of ecological environment preservation, with advancements made from 1980 to 2020, which is also an important achievement from vigorously implementing the strategy of VECC in Yunnan province in recent years. From 1980 to 2020, the D_{OEV} of 129 counties dropped to varying degrees. In terms of the change in the OEV levels, 127 counties (98.45%) have seen a decrease in the level of OEV in the last 40 years. Although two counties (1.55%) had no change in OEV level, their actual D_{OEV} values showed a gradual but somewhat small decrease. During the past 40 years, the basic rule is that the number of counties with high D_{OEV} significantly decreased while the number of counties with low D_{OEV} significantly increased.

(4) There is a significant regional difference in the D_{OEV} within the province. In general, the OEV level is lower in the south, southwest, west and center while being higher in the northwest high mountain and valley areas, the northeast mountainous area and the east and southeast karst areas.

(5) Considering all things, the D_{OEV} of Yunnan province remains high. In 2020, 38.76% of the province's counties were "moderately vulnerable". Deqin, Daguan, Huize, Zhenxiong, Qiaojia, Yongshan, Xichou and Malipo are considered "highly vulnerable", and Dongchuan was classified as "very highly vulnerable". It is time to further enhance the establishment of ecological civilization of the whole province and to take effective measures to preserve and build a beautiful environment in accordance with local conditions, so as to steadily reduce the D_{OEV} in all areas.

6. Shortcomings and Prospects

Due to the complexity of the regional ecological vulnerability assessment system and the difficulty in obtaining some basic data, this study is not perfect either. For example, in constructing a county-level evaluation index system, due to deficiencies in basic data, various natural disaster data for each county were not obtained; therefore, natural disaster situations were not included in the county-level evaluation index system. For example, when conducting a unified and comprehensive assessment of county ecological vulnerability, typical thematic analysis has not yet taken into account the unique characteristics of some counties. In addition, the evaluation indicators constructed in this study do not involve the discussion of the human footprint, which needs to be addressed in future research. According to Williams et al. [76] (2020), changes in terrestrial human footprints will lead to sustained loss of intact ecosystems, and greater efforts are urgently needed to alleviate the pressure on terrestrial ecosystems from humans.

Therefore, in future research, the following studies are planned to be carried out in this field: The first is to further strengthen the collection and analysis of basic information and data (such as natural disaster data) in each county and to establish a more comprehensive and systematic evaluation system for county ecological vulnerability. The second is to carry out characteristic typical thematic research based on the special characteristics of some counties, so as to organically combine the unified county evaluation on the surface with the typical research on the points, and better provide a solid basis for the implementation of SDGs and the selection of countermeasures in mountainous counties. The third is to conduct research on the impact of human footprint on ecological vulnerability and further expand the ecological vulnerability assessment system. In addition, existing ecological vulnerability information should be combined with other environmental indicators based on monitoring, such as species monitoring based on standardized surveys. Tulloch et al. [77] (2023) showed that different monitoring and management strategies have long-term impacts on endangered animals; Bayraktarov et al. [78] (2021) argue that strengthening active management and monitoring of protected areas to track and report long-term trends across species is important for preventing biodiversity decline. Therefore, in future ecological vulnerability research, it can be combined with the monitoring of additional environmental indicators.

Author Contributions: Conceptualization, Z.Y. and R.Y.; methodology, S.Y.; software, Q.W.; validation, Z.Y., S.Y. and R.Y.; formal analysis, Z.Y.; investigation, Z.Y.; resources, Z.Y.; data curation, Q.W.; writing—original draft preparation, Z.Y., S.Y., R.Y. and Q.W.; writing—review and editing, Z.Y., S.Y., R.Y. and Q.W.; visualization, Z.Y.; supervision, Z.Y.; project administration, Z.Y.; funding acquisition, Z.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number: 41261018.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The RS image data in the study were collected from "https://www.resdc.cn/" (accessed on 23 August 2022). The DEM data were collected from "http://www.gscloud.cn" (accessed on 9 July 2022). The county boundaries of Yunnan province were from "https://yunnan.tianditu.gov.cn/MapResource" (accessed on 20 April 2022). The economic and social statistical data are from the following website: "https://www.epsnet.com.cn/index.html#/Index" (accessed on 2 December 2022).

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

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