Dynamic analysis of ecological security in central Yunnan province, China from 1990 to 2017

F Liu\textsuperscript{1,2,3,4}, C H Gao\textsuperscript{1,2,3}, J L Wang\textsuperscript{1,2,3}, J C H Zhou\textsuperscript{1,2,3} and J M Sha\textsuperscript{5}

\textsuperscript{1}Faculty of Geography, Yunnan Normal University, Kunming, Yunnan 650500, China
\textsuperscript{2}Key Laboratory of Resources and Environmental Remote Sensing for Universities in Yunnan, Kunming, Yunnan 650500, China
\textsuperscript{3}Center for Geospatial Information Engineering and Technology of Yunnan Province, Kunming, Yunnan 650500, China
\textsuperscript{4}Yunnan Research Academy of Eco-environmental Sciences, Kunming, Yunnan 65003, China
\textsuperscript{5}College of Geographic Sciences, Fujian Normal University, Fuzhou, Fujian 350007, China

E-mail: jlwang@ynnu.edu.cn https://orcid.org/0000-0001-7202-646X

Abstract. Ecological security is an important content of national and regional security research. The Central Yunnan Province (CYP) has important location factors and social and economic development status, so ecological security research in CYP is quite relevant. For the purpose of our research, we adopted the S-PRD (Ecological Insecurity-Pressure-Regulation-External Driving Force) conceptual model to establish an evaluation index system based on the four subsystems of water, land, atmosphere, and biology to evaluate the ecological security of central Yunnan from 1990 to 2017 and analyse the characteristics of dynamic evolution. We used the grey incidence matrix analysis method to conduct retrospective grey relational evaluation and retrospective grey sensitivity evaluation and analyse the influencing factors of ecological security. The study conclusions showed that the security of the water system has been fluctuating and rising, and has stabilized in the past five years. Both the land system and the biological system have shown an upward trend, but the degree of change was relatively small, and the atmospheric system was stable. The evaluation value of the ecological environment insecurity of the four cities is generally on the rise. The control measures have the greatest impact on ecological insecurity, the second important factor is an external driving force.

1. Introduction
Ecological security refers to the influence of negative factors in the outside world, where people and nature are not damaged, infringed, or threatened, and the survival development of human society can continue, and natural ecosystems can maintain their health and complete state [1-3].

Since the establishment of a global environmental monitoring system in 1975, the United Nations Environment Program has begun to systematically study the theory and methods of ecological security [4]. With the involvement of many scholars, the research focuses on the regional ecological security, ecological security assessment index system and model methods, and the actual problems we need to solve in ecological security research [5]. The content of ecological security research involves ecological security analysis, sustainability of ecosystem service functions, ecosystem health diagnosis, ecological...
security maintenance, etc. [6-7]. Most studies focus on ecological security evaluation, which is one of the most closely related aspects of ecological security research with humans. At present, research on ecological security evaluation models is mostly based on environmental exposure, spatial patterns, and the construction of ecological security evaluation indicators [8-9]. International agencies such as the United Nations Economic Cooperation and Development Agency, the United Nations Commission on Sustainable Development, and the European Environment Agency have formulated some commonly used ecological security evaluation frameworks such as PSR, DPSR, DPSIR, SRP [10-11].

In recent years, many new methods have been developed to enrich the technical methods of ecological security assessment such as energy analysis methods, genetic projection pursuit interpolation models, EES collaboration models, explanatory structure models, normal cloud models, ecological entropy, information entropy, Unascertained Measure Theory, and Consequence Reverse Diffusion Method [12-14]. The key points of ecological security research are different options and evaluation methods, research objectives, content, and side focus, which have achieved certain results in ecological security evaluation research [15]. The research into the dynamic changes of ecological security and the key influencing factors of ecological security needs to be in-depth. The dynamic evaluation and analysis is a key factor determining the role of ecological security. It is implemented to prevent control measures to enable regional ecology to maintain a safe state, which is the ultimate goal of ecological security research.

This study is based on the S-PRD model to evaluate the ecological security of the CYP from 1990 to 2017. Through the analysis of the dynamic evolution characteristics of ecological security as well as grey correlation evaluation and retrospective grey sensitivity evaluation, the factors affecting ecological security have been found. This research provides a scientific basis for maintaining the regional ecological security status.

2. Study area
The CYP consists of Kunming city, Yuxi city, Qujing city, and Chuxiong prefecture, and has a total area of 94,558 km², accounting for 24% of the Yunnan Province. The research area is located in the west of Yungui Plateau, which is a combination of the three natural geographic regions of the Yungui Plateau, the Hengduan Mountains, and the Qinghai-Tibet Plateau. The terrain is generally low in the northwest and the southeast, from the north to the south the geomorphology is dominated by mountains and basins, with a typical plateau lack area. It is upstream of the Yangtze River, Pearl River, and Red River. The main rivers are the Jinsha River, Nanpanjiang, and the Red River. The lakes include Dianchi Lake, Fuxian Lake, Yangzong Lake, Xingyun Lake, and Qilu Lake. The climate is a subtropical plateau monsoon type. Dry and wet seasons are distinct, the rainy season generally lasts from May to October, and the dry season generally lasts from November to April. Summer precipitation is mainly affected by the warm humidity of the Western Pacific and the Indian Ocean Bay of Bengal. Warm and dry winter and spring seasons are controlled by the dry heat and winter monsoon of the Indian subcontinent [16].

The soil type is mainly purple soil, red soil, paddy soil, yellowish, yellow soil, and lime soil. The CYP is the core area where the population and economic development of Yunnan Province are concentrated. GDP accounts for 58.2% of the total province, and the population accounts for 40% of the province and 45% of urbanization. The area under study is a typical area of intensive social and economic development in Yunnan Province, the environment is sensitive and fragile, facing soil erosion, rocky desertification, water pollution, agricultural pollution, soil weight metal pollution, and other environmental problems. With the rapid development of the social economy, the contradiction between human activities and the environment will be more prominent, so the study of ecological security in the CYP is of great significance for the assessment of the regional ecological security at the regional and even national levels.
3. Materials and Methods

3.1. Data source
The data required for research mainly includes statistical data, survey data, planning documents, and other information. The data sources of 1990-2017 used in the research are shown in Table 1 [17-18].

Table 1. Main data source.

| Type               | Data name                                                                 | Source                                                                                                                                                                                                 |
|--------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Statistics         | Kunming City, Yuxi City, Qujing City, Chuxiong                           | Kunming City, Qujing City, Yuxi City, Chuxiong Prefecture Statistics Bureau Website(http://tjj.km.gov.cn/, http://www.yuxi.gov.cn/, http://www.qj.gov.cn/, http://tjj.cxz.gov.cn/) |
|                    | Prefecture Statistical Yearbook and National Economic and Social Development Statistical Bulletin (1990-2017) |                                                                                                                                                                                                   |
|                    | Kunming City, Yuxi City, Qujing City, Chuxiong                           | Websites of Ecological Environment Departments of Yunnan Province, Kunming City, Qujing City, Yuxi City, and Chuxiong Prefecture(http://sthtj.yn.gov.cn/, http://sthtj.km.gov.cn/, http://sthtj.qj.gov.cn/) |
|                    | Prefecture Bulletin of environmental status                               |                                                                                                                                                                                                   |
|                    | (1990-2017)                                                               |                                                                                                                                                                                                   |
| Yunnan Water Resources Bulletin |                                                                 | Website of Yunnan Provincial Department of Water Resources (http://web.yn.gov.cn/)                                                                                                                                                                        |
| Meteorological statistics |                                                                 | China Meteorological Data Service Centre (National Meteorological Information Centre http://data.cma.cn)                                                                                                                                               |
| Hydrological statistics, briefings on major drinking water sources in |                                                                 | Yunnan Hydrological and Water Resources Information Network (http://www.ynswj.cn/)                                                                                                                                                                     |
important cities in Yunnan Province

| Planning documents | Ecological function zoning | http://www.mee.gov.cn/gkml/hbb/bgg/201511/t20151126_317777.htm |
|--------------------|---------------------------|------------------------------------------------------------------|
|                    | Plan for national economic and social development | Development and Reform Commission of Yunnan Province, Kunming City, Qujing City, Yuxi City, and Chuxiong Prefecture |
|                    | Environmental protection plan | Ecological and Environmental Protection Bureau of Yunnan Province, Kunming City, Qujing City, Yuxi City, Chuxiong Prefecture |

| Literature          | Related books, papers     | Library, Cnki |
|---------------------|----------------------------|---------------|
|                     | Kunming City, Yuxi City, Qujing City, Chuxiong Prefecture Work Report (1990-2017) | Websites of the People's Governments of Kunming City, Qujing City, Yuxi City and Chuxiong Prefecture (http://www.km.gov.cn/, http://www.yuxi.gov.cn/, http://www.qj.gov.cn/, http://www.cxz.gov.cn/) |

| Vector layer        | The vector layer of the administrative area | National Catalogue service For Geographic Information (https://www.webmap.cn) |

3.2. Research method

3.2.1. City Natural Ecology Security and S-PRD Model. UNES (Urban Natural Ecological Security) refers to the pressure stress of external factors driving the regulatory integration and urban natural system against risks, thus maintaining their security and the development of human ecosystem function. The model has its relative and dynamic characteristics [19-20]. The S-PRD (Insecure ecological state-press-regulation-external driving force) conceptual model based on the urban natural ecological security shows that the result of ecological insecurity is mainly caused by the interaction of three elements. The first is the pressure of the social-economic system on nature (P), i.e. the adverse effects of economic development on the natural environment, including environmental pollution, ecological damage, and irrational use of resources, which lead to ecological insecurity. The second is the economic regulation of natural ecological insecurity (R), that is, the social restoration of the bad condition of the ecological environment through human means, which mainly includes environmental pollution control, ecological restoration, resource management, etc. It has a positive feedback effect on ecological security. Third, the population growth, land-use changes, and the economic development of the social-economic system, which are considered as external driving forces (EXD).

3.2.2. Ecological Security evaluation index. Based on the S-PRD conceptual model of urban natural ecological security, we have constructed an ecological security evaluation index system in the CYP. We have built an ecological security evaluation system based on four subsystems of water, atmosphere, land, and biology, taking into account the fragility and insecurity of the ecosystem (S) and ecological environment pressure of the social-economic system on the ecological service functions (P), human regulatory impact on ecological security issues (R), and the external driving force of social and economic development (EXD). We have explored the characteristics of the ecological security system constituted by the interaction of these elements, and then developed an ecological security evaluation model [21]. Based on the principles of science, practicality, conciseness, comprehensiveness, dynamics, and completeness, this paper presents an ecological security evaluation indicator system with 50 indicators at the system, element, and indicator levels, which includes 13 state indicators, 16 pressure indicators, 15 control indicators, and 6 external driving force indicators [22] (table2). In order to accurately analyse
the mutual influence of various elements within the ecosystem and determine the index weight scientifically, objectively, and reasonably, this study uses the entropy method in the objective weighting method to determine the index weight [23-24].

**Table 2.** Index table of ecological security evaluation system.

| System          | Elements                      | Explain                                                                 | Indicator layer                      | Weight |
|-----------------|-------------------------------|------------------------------------------------------------------------|--------------------------------------|--------|
| **Ecological insecurity** | S1                            | Surface water quality and water ecosystem vulnerability                 | Water quality compliance rate of drinking water source (%) | s1 0.0084 |
|                 |                               |                                                                        | Domestic water consumption(t)        | s2 0.0240 |
|                 |                               |                                                                        | Water area (km²)                     | s3 0.0154 |
| **Water Ecosystem** | Pressure P1                   | Water pollution, and water resource utilization                        | COD emissions in industrial wastewater (t) | p1 0.0204 |
|                 |                               |                                                                        | Industrial value-added wastewater discharge intensity (t) | p2 0.0182 |
|                 |                               |                                                                        | COD production in urban domestic sewage (t) | p3 0.0133 |
|                 |                               |                                                                        | Nitrogen emissions in urban life sewage (t) | p4 0.0292 |
|                 |                               |                                                                        | Urban sewage emissions (t/day)        | p5 0.0179 |
|                 |                               |                                                                        | Per capita daily life water (L)       | p6 0.0245 |
| **Regulatory impact** | R1                            | Industrial wastewater discharge compliance rate (%)                  | Centralized treatment rate of domestic sewage (%) | r1 0.0096 |
|                 |                               |                                                                        | Sewage treatment rate (%)             | r2 0.0100 |
| **Atmospheric ecosystem** | Pressure P2 | Comprehensive pollution                                               | The number of days of the API index ≤ 100 accounts for the total number of days (%) | s4 0.0133 |
|                 |                               |                                                                        | SO₂ concentration annual average (mg/m³) | s5 0.0095 |
|                 |                               |                                                                        | NO₂ concentration annual average (mg/m³) | s6 0.0220 |
| **Regulatory impact** | R2                            | Atmospheric pollution control                                          | Industrial smoke and dust up-to-standard emission rate (%) | r4 0.0101 |
|                 |                               |                                                                        | Environmental noise compliance area coverage (%) | r5 0.0083 |
|                 |                               |                                                                        | Smoke control area coverage (%)      | r6 0.0230 |
|                 |                               |                                                                        | Clean energy usage (%)               | r7 0.0606 |
| **Land ecosystem** | S3                            | Land vulnerability                                                    | Annual precipitation(mm)             | s7 0.0131 |
|                 |                               |                                                                        | Maximum precipitation during the year(mm) | s8 0.0100 |
|                 |                               |                                                                        | The effective irrigation area ratio of cultivated land (%) | s9 0.0521 |
|                 |                               |                                                                        | Drought and flood storage area (ha)  | s10 0.0083 |
| **Pressure P3** | Soil pollution                | Agricultural fertilizer application (t/ha)                           | Intensity of total pesticide (t/ha)   | p12 0.0646 |
|                 | Land resource load            |                                                                        | Population density                   | p13 0.0136 |
|                 |                               |                                                                        | Urban construction land area (km²)    | p15 0.0577 |
| **Regulatory impact** | R3                            | Land pollution control                                                | Industrial solid waste disposal utilization (%) | r8 0.0090 |
|                 |                               |                                                                        | Domestic garbage harmless treatment rate (%) | r9 0.0197 |
|                 |                               |                                                                        | Medical hazardous waste disposal rate (%) | r10 0.0298 |
|                 |                               |                                                                        | Total annual investment in environmental pollution control | r11 0.0242 |
We have analysed and evaluated the dynamic evolution characteristics of ecological security through the four-element indexes of water, atmosphere, land, and organisms established by UNES. The UNES Composite Index can be calculated from the following formula:

\[ y_i = \sum_{j=1}^{m} a_{ij}x_{ij} \]  

(1)

\[ x_{ij} = \frac{x_{ij}}{\sqrt{\frac{1}{n-1} \sum_{j=1}^{n}(x_{ij} - \overline{x_{ij}})^2}} \quad (j = 1, 2, ..., m) \]  

(2)

where \( y_i \) is the index value of the \( j \)-th element of the ecosystem, \( a_{ij} \) is the weight of the \( j \)-th index of the \( i \)-th sub-element, \( x_{ij} \) is the index value of the \( i \)-th index of the \( j \)-th sub-element, \( x_{ij} \) is the raw data of the \( i \)-th index of the \( j \)-th sub-element, \( \overline{x_{ij}} \) is the multi-year average of the \( i \)-th index of the \( j \)-th sub-element. \( n \) is the number of indices contained in the \( j \)-th sub-element, and \( m \) is the number of elements [25].

3.2.3. Grey relational analysis. Grey relational analysis is a method to measure the correlation degree between the factors based on the degree of similarity or difference in the development trend between them. It can use less information and data to find the correlation between various changing and reference factors. Ecological security can be explored as a grey system. Ecological security has many influencing factors and the influencing process is more complicated. It is the focus of research to find out which key factors affect ecological security [26-27].

We use grey relational analysis to express the key elements and key indicators affecting ecological security in the CYP. The grey relational computing algorithm is as follows: to establish a grey relational factor set, decision matrix, and initialization processing; to calculate the grey relational coefficient; to calculate the grey relational analysis. The purpose of the retrospective grey relational sensitivity evaluation of the ecological security is to analyse the influence of each factor on the ecosystem function through the close degree of uncertain factors and ecological insecurity [28]. The grey relational sensitivity evaluation divides the four subsystems into the S, P, R, and EXD layers as the grey relational sensitivity analysis space. Based on the index data of each element of UNES, the grey sensitivity of the

| System               | Elements                                | Explain                                           | Indicator layer                        | Weight |
|----------------------|-----------------------------------------|--------------------------------------------------|----------------------------------------|--------|
| Biological ecosystem | Cultivated land protection              | Increase cultivated land area (ha)                | r12 0.0160                             |        |
|                      | Ecological insecurity                   | S4                                               |                                        |        |
|                      | Habitat vulnerability                   | Forest coverage (%)                              | s11 0.0108                             |        |
|                      | Ecological service                      | Green coverage rate in built-up area (%)         | s12 0.0136                             |        |
|                      |                                          | Public green area per capita (m²)                | s13 0.0149                             |        |
|                      | Pressure P4                             | Habitat disturbance                              |                                        |        |
|                      |                                          | Animal and plant resources production (t)        | p16 0.0269                             |        |
|                      | Regulatory impact R4                    | Habitat protection                               |                                        |        |
|                      |                                          | Nature protection area (ha)                       | r13 0.0237                             |        |
|                      |                                          | Park area (ha)                                   | r14 0.0103                             |        |
|                      |                                          | Habitat recovery                                 |                                        |        |
|                      |                                          | Return farmland to forest area (ha)              | r15 0.0129                             |        |
| Social-economic system | External driving force EXD             | Total population                                 | d1 0.0352                              |        |
|                      |                                          | Engel coefficient                                | d2 0.0223                              |        |
|                      |                                          | Gross product                                    | d3 0.0188                              |        |
|                      |                                          | Gross industrial output value above designated size | d4 0.0169                        |        |
|                      |                                          | Science and technology expenditure              | d5 0.0167                              |        |
|                      |                                          | Library book total collection                    | d6 0.0102                              |        |
indicators in each element layer is calculated, and the impact of ecological security indicators by grey sensitivity is defined.

4. Results and Discussion

4.1. Change characteristics of UNES split in 1990-2017
According to the ecological security evaluation index constructed above, the UNES sub-element system index of the CYP is calculated for four cities, where S is an ecological insecurity state, P is pressure, R is a regulatory impact. The larger the values S and P are, the more unsafe it is, while R is the opposite. P and R are the cause indices of the results of the ecological insecurity condition. P is the benefit index; R is the value of the cost index. Table 3 shows the dynamics of UNES sub-elements in the four cities in the CYP from 1990 to 2017.

Table 3. UNES sub-element index change characteristics.

| City  | Index | Water system | Atmospheric system | Land system | Biological system |
|-------|-------|--------------|-------------------|------------|------------------|
| Kunming | S     | The upward trend, Small decline in 2008-2011. | More stable, slightly rising. | The upward trend, a significant increase after 2008. | The trend of rising, but change is relatively small. |
|       | P     | Decreased volatility, the rise in 1996, declined after 2006. | Rising volatility, decline in 2005-2008. | High-value fluctuations, large changes in 2007 ~ 2014, first rise, then fall. | In the upward trend, but the value is low. |
|       | R     | Steady rise. | High value but stable, the maximum is achieved in 2010. | In the upward trend. | Rising volatility, falling in fluctuation from 2010. |
| Yuxi   | S     | It was on the rise before 2000 and then declined slightly overall stability. | More stable, slightly changes. | Stable rise, small changes. | Stable rise, large changes. |
|       | P     | Wave changes, a low value in 1994, Decline after peaking in 2005. It fluctuates slightly after reaching the highest value in 2000. | Stressful rise, Rise steadily and drop slightly after the 2011 peak. | Stable rise, small changes, a higher value. | Stable rise, small changes, low value. |
|       | R     | Stable rise, a higher value. | | Stable rise, a higher value. | Stable rise, a slight decrease in 2010-2014. |
| Qujing | S     | Stable rising, large amplitude. Large fluctuations, a slight upward trend after a decline before 2011. | Stable rise. | Stable rise. | Stable rise. |
|       | P     | Stable rise. | Stable rise. | Rise slightly. | Stable rise, small changes, low value. |
| City  | Index | Water system | Atmospheric system | Land system | Biological system |
|-------|-------|--------------|-------------------|-------------|-------------------|
|       | R     | Stable rise. | Stable rise, a higher value. | Overall rise, high value, decline after 2011. | Overall increase, downward trend after 2014. |
|       | S     | Significantly stable rise. | Stable rise. | Rise slightly. | Rising fluctuation. |
| Chuxiong | P     | Larger and in a downward trend. | Stable rise. | Fast rises in 2009, then decline. The decline after reaching the maximum in 2011, high value. | Stable rise, no fluctuation, low value. |
|       | R     | The upward trend, a small decline in 2006-2010. | Rise slightly, high value. | Overall rise, high value, decline after 2011. | Stable rise. |

The results of Kunming show that the water system among the four systems is the most unsafe. The regulation and the pressure of the water system have been increasing, but the security status of the water system has not dropped, indicating that the regulatory measures have not achieved significant results. The atmospheric system is relatively stable, its regulation level is high, and the pressure is also stable. The land system security value is stable, the regulation is high, but it has declined after 2012, and the pressure declines but is at a high level. The security status of the biological system is low and relatively safe, its regulation level is high, and the pressure value is small and stable. The dynamic evolution of Kunming's UNES sub-element index is shown in figure 2.

The results of Yuxi show that the water system among the four systems is the most unsafe. Pressure and regulation are fluctuating, and the trends are similar, indicating that the regulatory measures have not achieved significant results. The atmospheric system is relatively stable, with a high level of regulation and steady rise, and the pressure is relatively stable. The security value of the land system is at its lowest and is on the rise, but the pressure value is high and rising, and the regulation is fluctuating. The security status, pressure, and regulation of the biological system are all steadily increasing, but the pressure value is low, and the regulation impact is slightly reduced in 2010-2014.

The results of Yuxi show that the water system has the highest security value and an upward trend. The regulation value of the water system has steadily increased, and the pressure has declined after 2006 but has increased after 2011, indicating that the previous regulation has achieved certain results, but the security level has not been improved after 2011. The atmospheric system is relatively stable, its regulation level is high and steadily rising, and the pressure is relatively stable, indicating that its control measures have achieved results. The security status and regulation of the land system are similar to that of Yuxi, with higher regulation and pressure values. The biological system is also similar to Yuxi, and its pressure value is the smallest among the four systems.
Figure 2. Dynamic evolution evaluation of UNES splitter index in Kunming City (1990 ~ 2017): (a) Water system, (b) Atmospheric system, (c) Land system, (d) Biological system.

The Chuxiong water system security value is on the rise and has been stabilizing after 2010, the regulation value has risen steadily, and the pressure has dropped, indicating that the water system has achieved remarkable results. The atmospheric system had a relatively high security value before 1997 and then tended to be stable, and the regulation and pressure were relatively stable. The security value of the land system is on the rise, and it has been relatively stable after 2008, the regulation is at a higher value, and the pressure value has decreased. The security value of the biological system is on the rise, the value is low, and the pressure value is also small, which is a less risky system.

4.2. Retrospective analysis of the dynamic evolution trend of ecological security

The results of the study show that the evaluation value of the ecological environment insecurity in the four prefectures in central Yunnan has been on the rise from 1990 to 2017. During the Eleventh Five-Year Plan (2006-2010), the ecological environment of the four cities was affected by a certain degree of economic development. Figure 3 shows the ecological security evaluation values of the four cities from 1990 to 2017.
The results of Kunming City show that the ecological environment insecurity evaluation value $S$ is on the rise, with the largest increase in 2008. The pressure evaluation value $P$ and the regulation evaluation value $R$ are relatively stable and there is no obvious fluctuation. The increase in the external driving force EXD, which changed drastically in 2008, shows that the impact of the external driving force on Kunming’s ecological security is gradually increasing.

The results of Yuxi showed that its ecological insecurity evaluation value $S$ has an overall upward trend, except for a slight decrease in 2006-2007 and 2012-2013. The changes in the pressure evaluation value $P$ and the regulation evaluation value $R$ are relatively stable, indicating that the ecological environment security state of Yuxi tends to be stable.

The results of Qujing show that the evaluation value of ecological insecurity status $S$ is in an upward trend, with the largest increase from 2007 to 2009, and reached the maximum in 2009. The changes in the pressure evaluation value $P$ and the regulation evaluation value $R$ are relatively stable. It shows that the ecological security status of Qujing is also on the rise.

Chuxiong’s results show that the evaluation values of the insecure state of its ecological environment are on the rise, and the pressure evaluation value $P$ and the regulation evaluation value $R$ are all relatively stable. It shows that the ecological security status of Chuxiong is also becoming stable.

4.3. Ecological security retrospective grey relational evaluation

The time series value of the ecological unsafe state $S$ is the characteristic value of ecological security system behavior, and its influencing factors include pressure $P$, regulation $R$, and external driving force EXD. Using the grey relational analysis method, we have calculated the interrelation between the impact factor and the ecological insecure state and ranked the influence degree of the three impact factors (pressure $P$, regulation $R$, and external driving force EXD) on the ecological insecure state $S$. The larger the value, the greater the degree of impact it has on the ecological insecure state $S$. The analysis has revealed the leading factors affecting the ecological insecurity status of the four cities in the CYP from 1990 to 2017. The calculation results of the grey relational impact are shown in table 4.
From the perspective of the composite index, all four cities have a great impact on the ecological insecure state $S$ by regulating $R$, followed by the external driving force $EXD$. It shows that the dominant factor affecting the ecological insecurity in central Yunnan is the regulation of $R$, which is consistent with the evaluation results of the dynamic evolution of the UNES subelement index. The ecological insecurity of the water system in three cities except Yuxi is mainly affected by domestic water consumption. The dominant factor affecting the unsafe state of atmospheric ecology in the CYP is the atmospheric nitrogen dioxide content, which requires the control of industrial waste gas and automobile exhaust emissions. Land ecological insecurity mainly comes from land productivity. Due to uneven topography and precipitation in the CYP, the grey sensitivity of annual precipitation is also high, and attention needs to be paid to preventing drought and flood disasters. Forest coverage has a significant impact on the biological system security state.

From the perspective of each sub-system division, the water and biological insecurity in Kunming and Yuxi is deteriorating, and further regulation is needed. Qujing and Chuxiong’s air and land regulation has a less grey relational impact than the pressure, which shows that Qujing and Chuxiong also need to strengthen the ecological protection of the atmosphere and land to prevent deterioration. Among these four subsystems, the water system is the least safe, but Yuxi City is the least safe in terms of its biological system. The atmospheric system and the land system are relatively safe. This means Yuxi needs to pay attention to the protection of biological resources, while Kunming, Qujing, and Chuxiong need to strengthen the regulation of water resources.

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Table 4. Ecological security grey relational impacts in the CYP (1990-2017).

| Ecological Security Relevance | LP | LR | LEXD |
|-----------------------------|----|----|------|
| Kunming S Grey relational impact | 0.5846 | 0.8997 | 0.6022 |
| LP1 | LP2 | LP3 | LP4 | LR1 | LR2 | LR3 | LR4 |
| 0.9455 | 0.7236 | 0.8577 | 0.7620 | 0.6365 | 0.8522 | 0.8574 | 0.5365 |
| LS1 | LS2 | LS3 | LS4 |
| 0.6233 | 0.5014 | 0.6109 | 0.6428 |
| Yuxi S Grey relational impact | 0.5920 | 0.8655 | 0.5932 |
| LP1 | LP2 | LP3 | LP4 | LR1 | LR2 | LR3 | LR4 |
| 0.9374 | 0.7623 | 0.8514 | 0.7682 | 0.5711 | 0.8952 | 0.8366 | 0.5336 |
| LS1 | LS2 | LS3 | LS4 |
| 0.6347 | 0.4958 | 0.5710 | 0.6477 |
| Qujing S Grey relational impact | 0.5599 | 0.8987 | 0.5722 |
| LP1 | LP2 | LP3 | LP4 | LR1 | LR2 | LR3 | LR4 |
| 0.9364 | 0.7385 | 0.8344 | 0.7621 | 0.5877 | 0.8980 | 0.8326 | 0.5444 |
| LS1 | LS2 | LS3 | LS4 |
| 0.6334 | 0.4970 | 0.5745 | 0.5803 |
| Chuxiong S Grey relational impact | 0.5622 | 0.8746 | 0.5821 |
| LP1 | LP2 | LP3 | LP4 | LR1 | LR2 | LR3 | LR4 |
| 0.9147 | 0.7382 | 0.8547 | 0.7666 | 0.6030 | 0.8744 | 0.8349 | 0.5210 |
| LS1 | LS2 | LS3 | LS4 |

4.4. Ecological security retrospective grey relational sensitive evaluation

The retrospective grey relational sensitive evaluation of ecological security is used to analyze the impact of each factor on the ecosystem by analyzing the degree of uncertain factors and ecological insecurity. Based on the retrospective grey relational sensitive evaluation of ecological security, we have examined strong and weak sensitive factors affecting ecological security in the CYP. The results
of the retrospective grey relational sensitivity evaluation research into ecological security are presented below.

Water ecological insecurity is classified as $S_2$ (Domestic water consumption) > $S_3$ (water area) > $S_1$ (Water quality compliance rate of drinking water source), the unsafe condition is mainly affected by domestic water consumption. $S_3$ (water area) ranks first in Yuxi's index grey sensitivity ranking. The reason may be that the lakes in Yuxi, especially the water area of Fuxian Lake, have a tendency to decrease, which needs attention. Pressure and regulation sensitivity index ranking are all related to urban sewage discharge and treatment. It shows that sewage, discharge, and treatment are most sensitive to the water system, and it is necessary to strengthen rain and sewage diversion, improve sewage treatment efficiency, and control sewage discharge.

The atmospheric ecological insecure conditions are classified as $S_6$ (the annual average of NO$_2$ concentration) > $S_4$ (the number of days of the API index ≤ 100 accounts for the total number of days) > $S_5$ (the annual average of SO$_2$ concentration), the dominant factor is NO$_2$ concentration, which requires to control industrial exhaust gases and automobile exhaust emissions. The pressure also mainly comes from industrial pollutants. The regulation is classified as (cleaning energy usage) > $R_6$ (smoke control area coverage), indicating that the sensitivity of the cleaning energy and the smoke control area coverage is relatively large, and it is necessary to continue to strengthen the promotion of clean energy use.

The unsafe condition of land emerges mainly from land productivity. With the acceleration of urbanization, the pressure becomes more and more sensitive to the area of urban construction land, and it is necessary to pay attention to controlling the trend of urban expansion onto ecological areas. The agricultural pollution caused by the amount of fertilizer application and the intensity of pesticide application also needs to be paid attention to, and the use of pesticides and fertilizers that are highly toxic and difficult to be degraded by the natural environment should be reduced. In regulation $R_3$, Kunming and Yuxi sensitivity rank as $R_{11}$ (total annual investment in environmental pollution control), and Qujing and Chuxiong sensitivity rank as $R_{10}$ (medical hazardous waste disposal rate) > $R_9$ (domestic waste harmlessness processing rate), indicating that the sensitivity of the cleaning energy and the smoke control area coverage is relatively large, and it is necessary to continue to strengthen the promotion of clean energy use.

Due to the large differences in the socio-economic development level, population size, gross domestic product and other socio-economic indicators of the four cities, the grey sensitivity rankings of the indicators in the external drive system are quite different. Kunming is greatly affected by Engel's coefficient. The total industrial output value of Yuxi is high, which is greatly affected by the total output value of industries above the designated size. Qujing is greatly affected by the total population and GDP, and Chuxiong is greatly affected by the GDP.

4.5. Related research comparison and discussion
We have compared this research with the related research results of Yunnan Province and Central Yunnan carried out by Chen Y, Liu F, Nong L, and Zhu H. The research methods are slightly different, but the results of changes, pressures, and impacts in various studies are comparable.

Chen Y et al. [29] used the DPSIR framework to evaluate the ecological security level of the CYP from 1995 to 2015. The comparative analysis of research results showed that the status and change trend of ecological security was slightly different before 2005, and the trend after 2005 was the same. This
study concluded that it continued to rise, and Chen Yun et al. showed a downward trend before 2005. The reason for the differences in conclusions may be due to the different ecological security assessment frameworks and data acquisition methods. The two conclusions have the same trend of pressure and regulation on ecological security. The pressure on ecological security has stabilized and increased, and at the same time, human regulation and response to it have been increasing.

Liu F et al. [30] used the landscape pattern research method to analyze the dynamic changes in Yunnan Province from 1980 to 2018, with a preference for landscape pattern and temporal and spatial dynamics. The steady increase in the security pressure of the biological system in this study is also consistent with the conclusion of the overall evolution of the landscape level to isolation. Liu Fang et al. concluded that the landscape pattern in the CYP is fragmented, the connectivity and aggregation of the landscape are poor, and the fragmentation tends to gradually expand. In Yunnan Province, this area has a high population density and frequent social and economic activities, which are the leading factors of fragmented landscape and poor connectivity. It is slightly different from the main factors affecting the security of biological systems in the conclusions of this study. The reason for the different conclusions is that the influencing factors in this study are aimed at the subsystems, while the influencing factors studied by Liu Fang and others are biased towards the landscape pattern.

Nong LP et al. [31] evaluated the ecological vulnerability of Yunnan Province from 2000 to 2018 based on the SRP framework. Although ecological vulnerability is slightly different from the concept of ecological security, it can reflect similar problems and conclusions. The conclusions of Nong LP et al. showed that the average ecological vulnerability and pressure in the CYP are at a relatively high level in Yunnan Province, which is consistent with the conclusions of Liu Fang et al. There are more ecological resilience cold spots in Chuxiong, and the hot spots are in the north of Qujing Yuxi and Kunming are scattered in cold spots. This is consistent with the conclusion that the biological system of Chuxiong has the lowest security value in this study, the biological systems of Kunming and Yuxi are relatively stable, and the biological systems of Qujing have higher regulatory values.

Zhu H et al. [32] monitored and evaluated the lake basin in central Yunnan from 2000 to 2018 based on the ecological carrying capacity model. However, there are no plateau lakes in Qujing and Chuxiong, only Kunming and Yuxi were used in the comparative analysis of the study. Zhu H et al. concluded that the changing trend first goes up and then down, the overall trend is upward, the period of 2015-2018 shows a downtrend, which is similar to the conclusion of our study on the overall upward trend. The reason for the inconsistent conclusions on the downward trend from 2015 to 2018 may be due to different analysis systems, followed by the decline in the management and governance of the lake basin in Kunming and Yuxi in recent years.

The several studies referred to above have analyzed the ranking of ecological security influencing factors. This study and the studies carried out by Chen Y, Liu F, etc. emphasize the impact of human society. The impact factors of Nong LP and Zhu H are biased towards natural factors. The main reasons for the differences in the main impact factors result from the different focus of each research evaluation, this research and the research carried out by Chen Y, Liu F, etc. focus on the ecological security of the system, and Nong LP and Zhu H are biased towards the ecological aspect. The specific content of each research conclusion is shown in table 5.

In the above comparative study, different data sets are used, and their spatial resolution levels are 100 m grid, 1 km grid, 5 km grid, different scales of county and city, and the results of different scales show certain consistency and differences. Some researchers have pointed out that spatial resolution has an impact on the research conclusions, but it remains to be explored on what scale and resolution to obtain the best results for ecological security assessment research.
Table 5. Comparison of related research results.

| Index       | Chen Y et al. [29]                                                                 | Liu F et al. [30]                                                                 | Nong L P et al. [31]                                                                 | Zhu H et al. [32]                                                                 |
|-------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| Status and change trend | The ecological security situation in the CYP first declined and then rose. A decline from 1995 to 2005, increase after 2005. | The landscape of Yunnan Province is evolving towards isolation, relatively slow in 1980-200, 2010-2015, with large variation. | The vegetation coverage of Yunnan Province increased slightly from 2000 to 2018 and is relatively stable. | The ecological carrying force rose first, declined in 2015-2018, the overall trend is rising. |
| Pressure    | The pressure of ecological security is increased. Pesticides, fertilizers, and floral films have adversely affected the environment. Urbanization has resulted in population agglomeration, increasing demand for resources, and stress on the environment. | The landscape pattern is broken; connectivity and the degree of polymerization are poor. High population density and social economy have a large influence on the landscape. It has gradually expanded trends. | The ecological fragility of the CYP is higher than that of Yunnan Province, and the fragile ecological environment is under greater pressure. | The gradual increase in the supply capacity of resources and environment indicates that the coordination between the social economy and residents’ living standards is not stable. |
| Regulation  | The behavior of human beings to adapt to environmental changes has been enhanced, and the environmental conditions have improved to a certain extent. It is consistent with the conclusion of the stabilization and enhancement of regulation in this article. | The shape index complexity in the CYP is relatively low. The concentration of built-up areas in the city leads to a uniform shape of the landscape. Plateau lake cluster area, with large water body landscape and small changes in water body range. | There are many ecological resilience cold spots in Chuxiong, hot spots are in the north of Qujing, and cold spots are scattered in Yuxi and Kunming. | The low value of ecological function elasticity is distributed in more human activities. High-value areas are with high vegetation coverage and low human interference. |
| Driving force | Human disturbances to the environment continue to intensify, leading to increased ecological fragility in the region. | Urban concentrated areas have high population density and frequent social and economic activities, which are the leading factors for fragmented landscapes and poor connectivity. | The order of impact factors from large to small is total primary productivity of vegetation >annual rainfall >elevation >rainfall erosion >vegetation coverage >density of geological disaster points. | The factors are ranked as ecological plasticity, biological abundance index, forest land proportion, and human disturbance index. |

Our research is a retrospective analysis of ecological security in CYP, and ecological security early warning has not been considered. The next step is to provide predictions for ecological security in the CYP based on the ecological security assessment and dynamic analysis by S-PRD. The early warning provides support for regional ecological security control and policies through ecological security early warning.
5. Conclusions
The ecological security evaluation values of the water system, atmospheric system, land system, and biological system in CYP have been on the rise from 1990 to 2017, and the largest changes were made between 2004 and 2008. The pressure value of the water system has a downward trend, while the pressure values of the atmospheric system, land system, and biological system have increased slightly, and the overall ecological security evaluation value is also on the upward trend. There is little change in the value of the ecological insecurity of the land system.

The water system in the CYP is relatively the most insecure, while the atmospheric system and land system are relatively safe. This is consistent with the special drought and water shortage in the CYP. Therefore, future ecological security maintenance should pay attention to the protection and regulation of water resources. The biological system of Yuxi is relatively insecure. As for the plateau lake gathering area, it is necessary to pay attention to the protection of biodiversity, especially the protection of fish resources in the plateau lakes.

The main influencing factor of the ecological security status S in the CYP is regulation R. Except for Kunming, the lowest is the external driving force EXD. The external driving force EXD promotes an increase in the severity of ecological insecurity in aspects such as population and land. The grey relational impact between the regulation of the atmospheric system and the land system and S is greater than the pressure, while the grey relational impact between the regulation power of the water system and the biological system is less than the pressure. The security status of the water system and the biological system is deteriorating, and further regulation and control need to be strengthened.

The ecological security assessment of the CYP analyzes its dynamic change characteristics. Important factors affecting ecological security are obtained through grey sensitivity analysis. The similarity with the related research results shows that the research results have a certain degree of credibility.

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