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Coupling Land Use Analysis and Ecological Risk Assessment: A Study of the Three Gorges Reservoir Area, China

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Exploring the ecological response of land use change is important for regional sustainable development and assists in understanding the profound consequences of this change. This paper proposes coupling a study of the evolution of land use with an assessment of ecological risk, based on a typical watershed in the hinterland of China's Three Gorges Reservoir area. Land use data for the Caotangxi watershed derived from Landsat images from 1990, 2000, 2004, and China–Brazil Earth Resource Satellite data from 2010 and 2016 were used to identify ecological risk based on land use changes. The spatial interaction process between land use and ecological risk changes from 2 spatial scales of grid and terrain was analyzed using geographic information system technology and an ecological risk index. The study area's ecological risk index demonstrated at first a worsening trend and then improvement during the period from 1990 to 2016. During 2004, there was a turning point in ecological risk evolution; this was most apparent in zones with a slope of 15–25 and >25°, as well as in the elevation zone between 300 and 1000 m. The proportion of serious-risk areas decreased sharply after 2010, and land function transformation resulted in improvement of ecological risk in the watershed during the 26 years from 1990 to 2016. Our study provides support for evaluating ecological risk trends and the development of land use transition theory in the Three Gorges Reservoir area. It is a typical description of land remediation and ecological restoration in this area.

Keywords: *land use change; ecological risk assessment; landscape-scale approach; Three Gorges Reservoir area; Caotangxi watershed.*

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Introduction

Human activities profoundly affect Earth's surface (Turner et al 2007). Anthropic driving forces on the structure of ecosystems and function of Earth's system have resulted in significant land changes (Pollack 2004), and different utilization patterns are formed at different stages of this evolution (Foley et al 2005). Ecological risk (ER) assessment can assess the potential for harmful ecological effects caused by stress factors associated with human activities (Norton et al 2010). However, current research on ER mainly focuses on analysis of microscale aspects, such as watersheds and wetlands from the perspectives of soil's heavy metal content and changes in hydrological conditions (Pascoe and Dalsoglio 1994; Cook et al 2010; Bai et al 2017; Jiang et al 2017).

Land use change has the most significant impact on terrestrial ecosystems and global biodiversity (Sala and Wall 2000). Some research shows that changes in the ecological environment and ecosystem services (ES) are closely related to land use change (Foley et al 2005; Huang et al 2016; Wang et al 2017). Urbanization development, transformation of cultivated land function, and dynamic change of forest vegetation caused by land use change have far-reaching influences on ecosystems (Ren et al 2007; Zhang and Wang 2012; Galler et al 2015), and change in natural forest led by regeneration and succession, human disturbance, and other factors directly affects the balance and health of terrestrial ecosystems (Alongi 2015). Summarily, land use change is an essential factor affecting ecosystems (Goldstein et al 2012; Lawler et al 2014; Song et al 2015). Land change science has thus become an essential component of global environmental change and sustainable development research (Veldkamp and Verburg 2004; Turner et al 2007; Li et al 2010).

The ecological effects produced by different patterns and intensities of land use have regional and cumulative characteristics, which may directly indicate the structure and composition of the ecosystem (Xu et al 2016). However, for ecologically fragile and stressed regions, the response process of ER to land use change is still poorly understood. The world's largest hydroelectric power project, the Three Gorges Dam, has been controversial since its establishment in 1992 and its construction in 1994. The dam has affected regional biodiversity and ecological processes by destroying and isolating surrounding habitats through its construction, with far-reaching and significant transformation of the area surrounding it (Wu et al 2003; Stone 2008). Meanwhile, it has had a significant impact on the wellbeing of humans (Kittinger et al 2009). Therefore, an approach based on landscape ecology is required to realize the sustainable development of the Three Gorges Reservoir area (TGRA) effectively (Shen and Xie 2004).

With the river closure of the Three Gorges Project in 1997, the resettlement project, and ecological construction policies, the land use of TGRA has changed (Cao et al 2011). Significant variations in land use and land cover change have occurred in TGRA (Zhang et al 2009; Seeber et al 2010; Schönbrodt-Stitt et al 2013). Although the 2007 land use policy stated that farmland with a slope greater than 25° should be transformed into forests or pastures, farmland still accounts for 20% of this area (Zhang and Wang 2012). Nearly 56% of households depend on agriculture (Xu et al 2015). However, despite obstacles such as migration, resettlement plans, and relocation of agricultural areas, the forest area of TGRA increased by 3.6% between 1987 and 2007 (Bieger et al 2015).

Recently, water storage of the Three Gorges Reservoir has resulted in severe droughts downstream of the dam. This has had several impacts on landscape changes (Liu et al 2016). However, there has been no ER assessment at the watershed scale in TGRA based on land use evolution (Zhang et al 2009; Li et al 2010). This study focuses on the Caotangxi watershed throughout the construction, water storage, and operation of the dam. The Caotangxi watershed is located in the hinterland of TGRA, where there is wide distribution of purple shale and limestone. The main objectives of this study were to (1) evaluate the ER of the study watershed, (2) reveal variations and trends of ER in the study watershed from 1990 to 2016, and (3) examine the regional ecological impact of land use transformation in depth. Thus, this study aims to define a sustainable pathway for TGRA's ecological construction, hydrofluctuation belt management, and water environment protection and provide a basis for mountain land use management in developing countries.

Data and methods

Study area

TGRA is a typical mountainous area with a complex geological structure and landforms dominated by mountains and hills (Liang et al 2020). The Caotangxi watershed is located in eastern Fengjie County, which is the hinterland of TGRA. It is located at 108°24′32″–109°14′51″E and 30°35′6″–31°26′36″N. It is also a primary tributary of the Yangtze River, which is 33.3 km in length with a basin area of 210 km^2. The area with a slope above 15° accounts for 86.60%, and the zone with an elevation between 500 and 1500 m accounts for 77.38% (Figure 1). The region is in the Central Asian subtropical zone and has a continental monsoon climate, with an annual average temperature of 15°C and an average annual rainfall of 1200 mm. The purple soil (ie a special type of soil in China, which is composed of purple–red sandstone and shale rich in calcium carbonate) is widespread, with substantial soil erosion in some parts. Sloping land is widespread in the study area, and sloping farmland is the primary type of cultivated land, with woodland mostly located on ridges. The Caotangxi watershed is typical of the surrounding areas.

The study area also belongs to the Three Gorges immigration area. Three Gorges immigrants are mainly divided into 2 categories, of which 79% are "back to the mountain" and 21% are "emigration." The former refers to people migrating to mountains where space is still available for settlement, whereas the latter refers to relocation to other areas outside TGRA (Liang and Li 2019). According to the statistical yearbook (Local Chronicle Office of Fengjie County 2018), the permanent population of Fengjie County was 833,000 inhabitants in 1978, 989,800 in 2003, 834,300 in 2010, and 727,900 in 2017. Therefore, migration in Fengjie County is mainly local migration, with people moving back to the mountains. Generally, since the implementation of the immigration project, Fengjie County has had more people and less land, a low economic level, and a poor ecological environment. Because of continuous population growth, the permanent population of Fengjie County increased before and after the completion of the second phase of the Three Gorges Project (in 2003) and did not decrease until 2010, when the population fell because of the attraction of an urban economy. Farmers' livelihoods in the Caotangxi watershed tended to diversify from 2012 to 2017 (Liang et al 2020; Liang and Li 2019). Because of the large loss in labor force, there is an increasing trend of conversion to farmland–orchards on the sloping farmland in this region. A second land use trend is the abandonment of farmland.

Data sources and processing

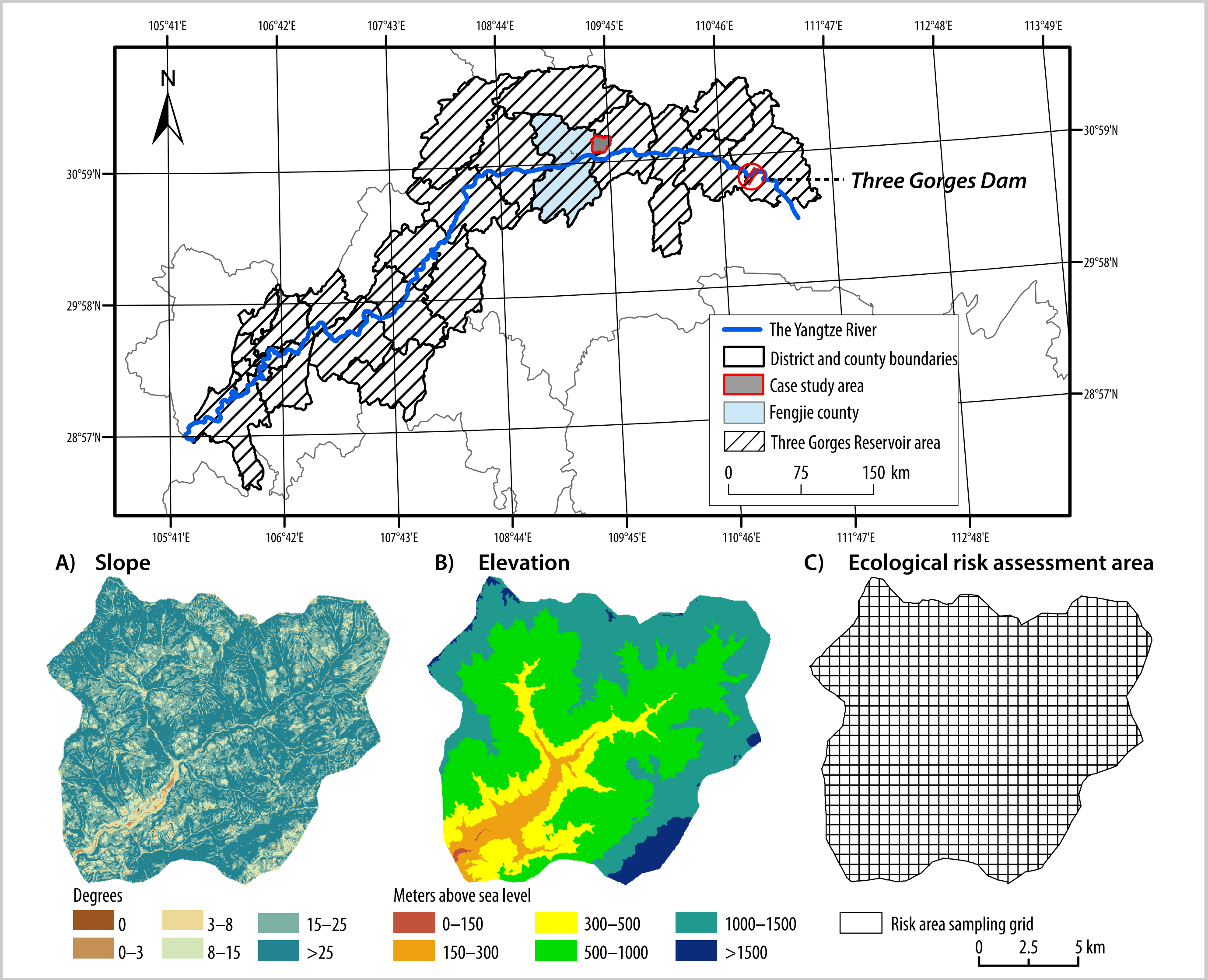
The main information source for the study area was remote sensing data, including Landsat images from 1990, 2000, and 2004 and China–Brazil Earth Resource Satellite remote sensing data from 2010 and 2016. ENVI5.2 was used to process the remote sensing images (including format conversion, geometric correction, noise cancellation, and unsupervised classification), in which the geometric correction error was within 1 pixel. A human–computer interaction system was used, and the properties and actual use of land resources in the study area were analyzed, with reference to the land use classification method in the Resources and Environment Data Cloud Platform (IGSNRR 2017). This allowed land use in the study area to be divided into 9 types (Figure 2). Based on 10-m resolution SPOT images of the study area, for 2011 and 2015, the validity of the land use result points in the field was verified twice, in February and May. The statistical interpretation accuracy of each land use was above 91%.

The study area was divided into 6 elevations, 0–150, 150–300, 300–500, 500–1000, 1000–1500, and >1500 m, according to the 1:50,000 digital elevation model (DEM). The slope of the study area was divided into 6 levels, 0, 0–3, 3–8, 8–15, 15–25, and >25°, according to the actual situation in the study area and the grading standards for sloping cultivated land (MLR 2007). This was supported by the spatial analysis function of ArcGIS based on DEM data.

Methods

This study aimed to identify the relationship between land use change and ER change. Most international ER assessment methods were based on sampling soil or water quality on a

FIGURE 1 Location of the study area. (Map by Xinyuan Liang)



microscale to measure the content of heavy metals or chemical pollutants (Islam et al 2015; Maanan et al 2015; Dudhagara et al 2016). Spatial assessment of ER on the landscape scale within the overall regional context is lacking. This study attempted to understand spatial interaction processes between land use and ER change by defining an ecological risk index (ERI) from a grid scale and different terrain scales using a geographic information system technology platform.

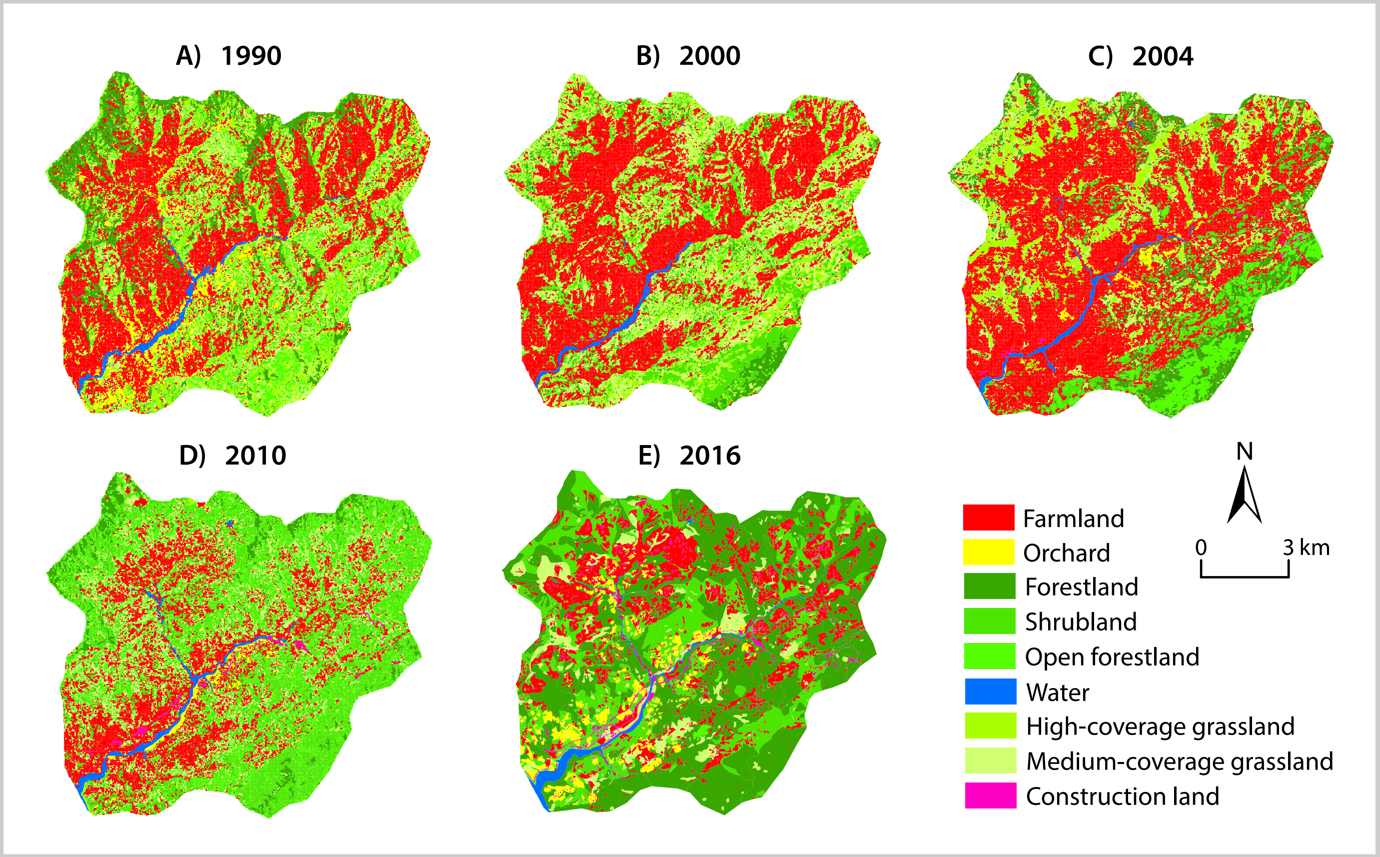
Ecological risk index: Different land uses have different ES values, and land use change (land use patterns and land management) is the main driving force for spatial pattern and supply change of ES (Xu et al 2016). Changes in land use cause variations in corresponding ES, inducing changes of ER; therefore, adjustment of land use structure within a specific spatial unit inevitably leads to transformation of regional ER. To correlate land use and ER, this study used the acreage proportion of the types of land use to build an ERI (Zeng and Liu 1999). It was used to identify the comparative value of comprehensive ER in a piece of sample land to convert the spatial structure to variables of ER through sampling (Bai et al 2011). It was computed using the following equation:

$$\mathrm{ERI} = \sum_{i=1}^{n} \frac{A_i W_i}{A}, \tag{1}$$

where i is the different types of land use, A_i is the whole acreage of the i land use type in the sample land, A is the total acreage of the sample land, W_i is the weight value of ER reflected from the i land use type.

In addition, based on the actual situation in the Caotangxi watershed and ER levels of different land use types on soil erosion and water environment, the analytic hierarchy process was used to determine W_i, the ER intensity parameter of land. First, a semiquantitative assignment method through expert judgment was used to determine the relative risk level value of each type of land use. Then, the relative importance of each factor (soil, biodiversity, hydrothermal conditions, etc) and the relative importance order of each type of land use to a particular factor were calculated. Finally, the risk intensity parameter value of each type of land use was obtained. The risk weight values of every

FIGURE 2 Land use maps for 5 periods.

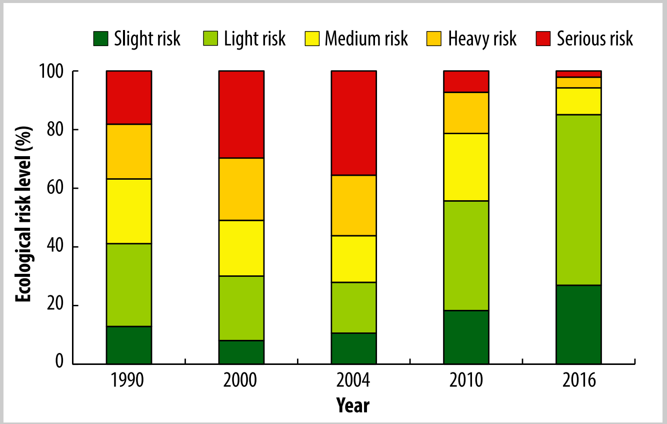


land use type were as follows: 0.95 for farmland, 0.82 for orchard, 0.12 for forestland, 0.20 for scrubland, 0.32 for open forestland, 0.15 for high coverage grassland, 0.53 for medium coverage grassland, 0.16 for water, and 0.72 for construction land.

Assessment unit setting and index classification: The Caotangxi watershed was divided into 841 risk assessment samples with a size of 500 × 500 m to combine vector evaluation units with grid point evaluation units (Figure 1). Grid distribution data of ERI indicators was acquired through spatial sampling of indicator variables. The actual acreage of grids with an area of less than 500 × 500 m was used to obtain the percentage of all land uses within that grid.

The natural breaks method was used to grade ERI of different evaluation units. ERI values were divided into 5 levels: slight risk (<0.3), light risk (0.3–0.5), medium risk (0.5–0.6), heavy risk (0.6–0.7), and serious risk (>0.7). Furthermore, ERI values in every sample were regarded as the attributive values of their center, and the ordinary Kriging method of the geostatistical module in ArcGIS10.2 software was used to acquire the spatial interpolation of ERI to reflect the visualized spatial distribution of ER in the study area.

FIGURE 3 Percentage ER level by acreage from 1990 to 2016 in the study area.

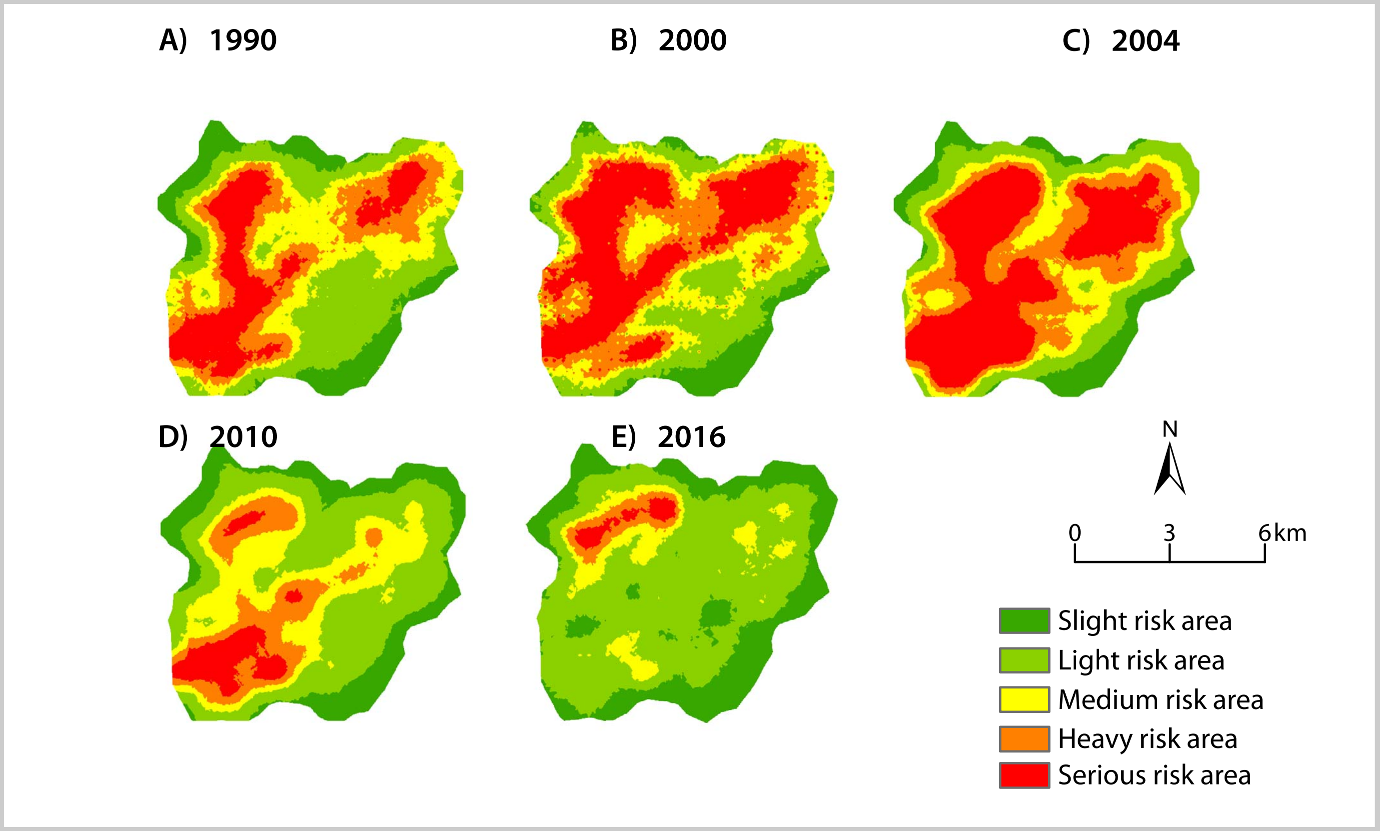


Results and analysis

Temporal variation characteristics of ER

In the study area, ER during 1990 to 2016 first deteriorated and then improved (Figure 3). Generally, the proportion of medium-risk, serious-risk, and heavy-risk areas showed a downward trend. ERI average values of the Caotangxi watershed during 1990, 2000, 2004, 2010, and 2016 were 0.3745, 0.4174, 0.4236, 0.3309, and 0.3564, respectively, indicating first a trend of deterioration and then improvement with a change in land use. The overall trend of ecological security was consistent with the change in sloping farmland, indicating that the change in sloping farmland plays a prominent role in changes in the ecological security of the Caotangxi watershed. As shrubbery, open woodland,

FIGURE 4 Interpolation surface of ERI values using the Kriging method from 1990 to 2016.



and medium coverage grassland increased, the ER in the study area gradually decreased.

Variations in the spatial pattern of ER

In the study area, the spatiotemporal pattern of ER changed significantly from 1990 to 2016 (Figure 4). In 1990, serious-risk areas were mainly distributed in the southwest, northwest, and northeast. In 2000 and 2004, serious-risk areas increasingly extended to places around the water's edge, mainly distributed in southwest, northwest, northeast, and central areas. In 2010, serious-risk areas decreased drastically and were mainly distributed in the southwest part and the mainstream Caotangxi watershed. In 2016, serious-risk areas were concentrated in the residential areas of the northwest of the watershed.

There was a significant spatial correlation between the distribution pattern of ER and the distribution of farmland, orchard, and areas where water concentrates. The closer it was to water, farmland, or orchard, the higher the ERI; the farther it was from these land use types, the lower the risk. After 2010, rapid development of rural residential land reduced high ERI caused by the growth of construction land in the river valley, which led the serious-risk regional center to deviate. Generally, the risk level was low around the edge of the study area, increasing with proximity to water and construction land.

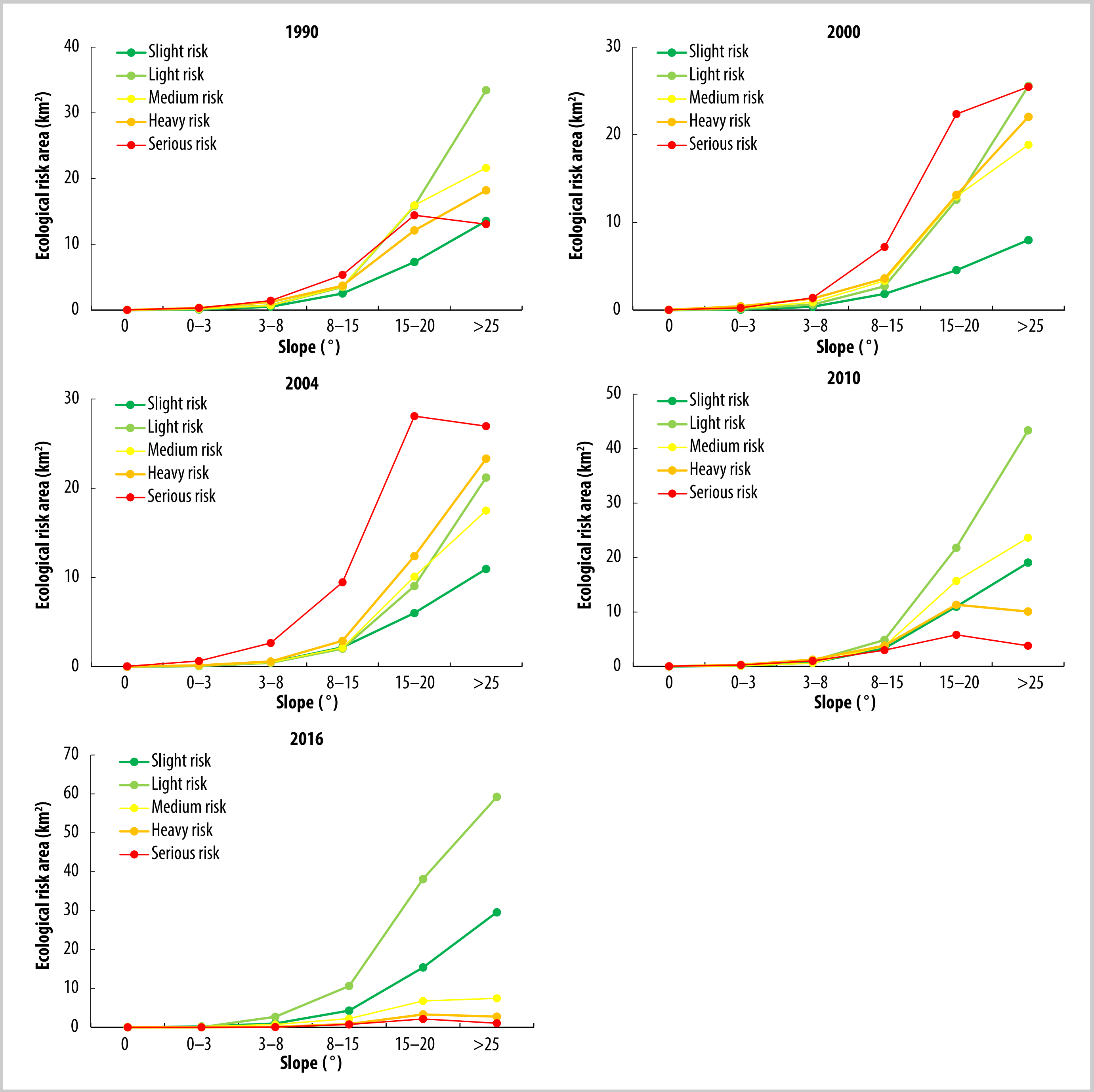
Changes in ER of different slope zones

The areas of different ER levels corresponding to all slope zones were calculated by superimposing the slope map and ERI values map (Figure 5). The 5 risk levels in the study area were mainly distributed in 3 slope zones, 8–15, 15–25, and >25°, especially in zones with a slope of 15–25 and >25°. Slight-risk, light-risk, and medium-risk areas were mainly distributed in zones with a slope of >25° during 1990–2016. Heavy-risk areas were mainly distributed in zones with a slope of >25° during the period between 1990 and 2004, whereas between 2010 and 2016, they were mainly distributed in the zone with a slope of 15–25°. Serious-risk areas were mainly distributed in the zone with a slope of >25° in 2000, and at other times, they were mainly distributed in the zone with a slope of 15–25°. In terms of quantity, serious-risk areas in the zone with a slope of >25° at first increased and then decreased, falling sharply throughout the period from 1990 to 2016; a turning point was observed in 2004.

Changes in ER of different elevation zones

By superimposing the elevation map and ERI values map, the areas of different ER levels corresponding to different elevation zones were obtained (Figure 6). The 5 risk levels were mainly distributed in 2 elevation zones of 500–1000 and 1000–1500 m, and they constituted more than 70% of the total area of each risk level. Slight-risk areas were mainly distributed in the elevation zone of 100–1500 m from 1990 to 2016. Light-risk areas were mainly distributed in the elevation zone of 1000–1500 m from 1990 to 2004 and shifted to the elevation zone of 500–1000 m during 2010–2016. Medium-risk and heavy-risk areas were mainly distributed in the elevation zone of 500–1000 m. Serious-risk areas were mainly distributed in the elevation zone of 300–

FIGURE 5 ER area in different slope zones for 1990, 2000, 2004, 2010, and 2016.



500 m in 2010, and at other times, they were mainly distributed in the elevation zone of 500–1000 m. In general, serious-risk areas in the elevation zone of 300–1000 m showed changes in the trend, increasing at first and then decreasing from 1990 to 2016, followed by a sharp decline; a turning point occurred in 2004.

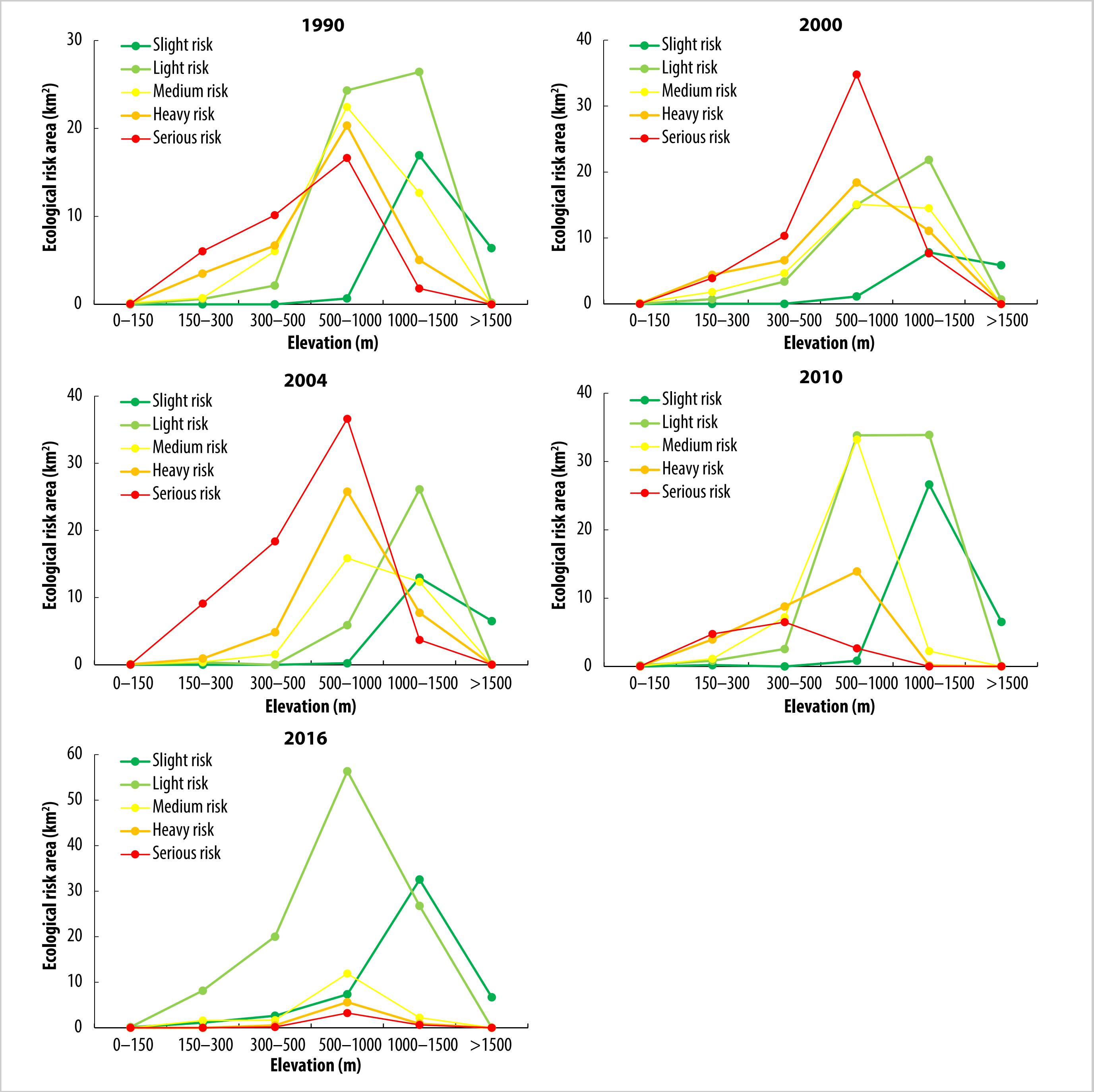
Discussion

Reasons for changes in ER

Because the previous immigration method was mainly based on the relocation of local people or those living nearby (Wang et al 2016), the arable land in the valley area was inundated after dam filling. The returning immigrants increased regional population pressure on the limited land, prompting deforestation and steep slope planting, which caused further deterioration of the reservoir area's ecological environment.

After dam completion in 2009, China attached more importance to the ecological environment of TGRA and implemented various measures to promote its management, such as the project of returning farmland to forests and the development of orchards. Therefore, traditional agriculture was no longer the preferred livelihood for local farmers

FIGURE 6 ER area in different elevation zones of 1990, 2000, 2004, 2010, and 2016.

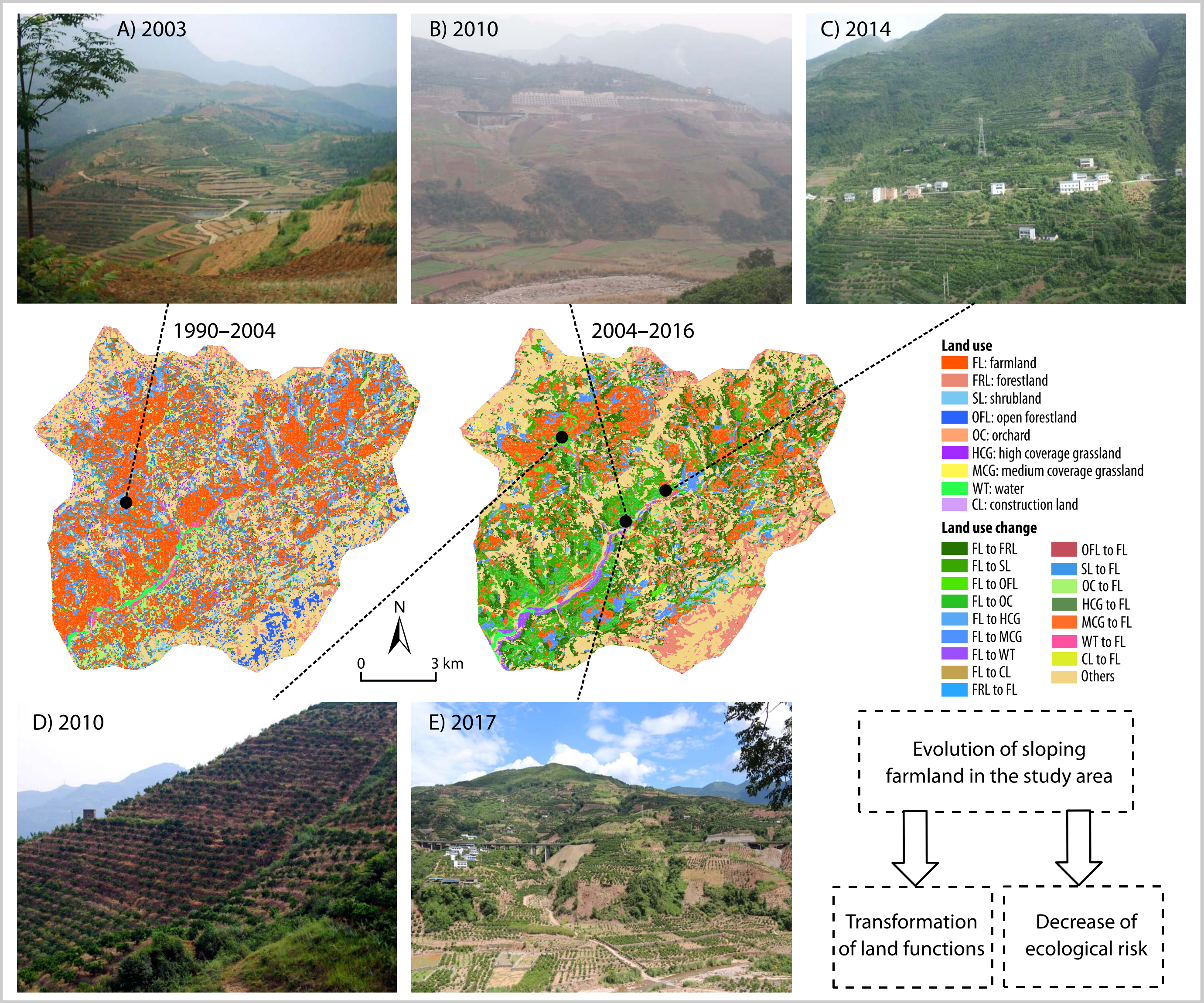


(Feng and Xu 2015), and the original sloping farmland ecosystem was transformed into orchards, forestland, and grassland (Figure 7). This improved the ecological environment. In other words, in the context of China's current rural transition, the sloping farmland in TGRA changed from traditional tillage to economic orchard planting. This process of land use transition emphasizes two-part improvement of economic and ecological benefits, thereby accelerating the optimization trends of ER. This supports the "win–win sustainable development strategy" demonstrated by Gao and Mao (2007).

Reflection on research findings

Given the crucial indicative role of ER in regional resource development and ecological construction, ER assessment has become an essential method of macroecological management (Suter et al 2003). Compared with other regional ER studies that focus on the comprehensive superimposition of multiple risks (Landis 2003), ER assessment in this study is mainly based on the perspective of landscape ecology. This approach pays attention to the impact of landscape patterns on ecological processes or functions, regional spatiotemporal heterogeneity and its

FIGURE 7 Land use transition in the study area. Photographs B and E are the same observation points. Although photographs A, C, and D are different observation points, they show clear long-term evolution of sloping farmland. (Photos by Xinyuan Liang and Yangbing Li)



scale effect, the spatiotemporal differentiation of characteristics of risk, and the risk expression of specific spatial patterns on ecological function and process (Peng et al 2015b). This differs from traditional regional ER assessment, which focuses on quantitative assessment of the overall risk of the ecological environment. Therefore, landscape ER assessment based on land use change can be regarded as an extension of the landscape-scale approach of regional ER assessment (Peng et al 2015a).

Land use change affects the structure and mechanism of ecosystems and can change the supply capacity of ES (Pérez-Soba et al 2008; Verburg et al 2009). As the socioeconomic environment drives the evolution of land use, the level of ER will be reduced, and vice versa. That is, there is a coupling of the evolution of land use change and ER. Therefore, based on a background of greening and land use transition in the mountainous areas of central and western China (Foley et al 2005; Long and Qu 2018; Macias-Fauria 2018), our study suggests the influence of China's multiple driving factors, including construction of the dam, population pressure, immigration policy, urbanization, and social and economic development. A win–win situation from both ecological and economic perspectives could thus be achieved through a rational slope land use conversion process in TGRA. For a long time, excessive emphasis on the quantity of cultivated land protected in China has weakened the focus on other aspects, such as the degradation of quality and extensive management. Moreover, the matching of farmers' core interests with national policy has always been the primary goal of rural development in China. To a certain extent, the transformation of sloping farmland utilization improves the integration of farmers' interests and farmland quality protection policies. On the premise of safeguarding the collective economic interests of farmers, strengthening local enthusiasm for land remediation and adequately dealing with land degradation and soil erosion problems are of great significance for improving the quality and efficiency of land use in mountainous areas and improving rural production and living conditions. The verification process and conclusions of this study provide a useful reference for the optimization and management of mountain land use in developing countries.

In general, effective use and rational transformation of sloping farmland in mountainous areas will help to improve the agricultural economy and living standards of farmers in mountainous rural areas; at the same time, it will avoid the shortcomings of overexploitation of sloping land, such as soil erosion. Especially in developing countries with a large land area in mountainous areas, the mechanization level of agricultural development in mountainous areas is difficult to improve because of restricted access to traffic and complex natural conditions, which result in the rural population emigrating to developed cities in plains areas to pursue higher wages. As a result, the surplus rural labor force mainly comprises the elderly, women, and children. Their working ability is relatively weak and cannot meet a high-intensity farming process. Orchards are long-term income economic forests. Planting orchards not only can improve rural economic development by solving the employment demand for a surplus labor force but also can improve the ecological environment through soil and water conservation. Therefore, choosing orchards suitable for local growth to change the utilization of sloping farmland in mountainous areas has positively affected food security, rural economic improvement, and ecological environment governance in developing countries. Differing from large-scale fruit fields on the plains (site selection requires the investigation of local climate, soil, natural disasters, and topography), orchards in mountainous areas are mostly distributed on sloping farmland around residential areas. Because of the self-supporting planting mode of many small farmers, production and operation are relatively extensive, and local households lack enthusiasm for follow-up management and protection. In later stages, the land manager should fully consider the application of professional technical measures for orchard species, the improvement of infrastructure, and the establishment of a large-scale cultivation base.

Conclusions

This study investigated the evolution of ER in TGRA based on slope land use change through a case study of a typical watershed, the Caotangxi watershed, during the construction, filling, and operation stages of the dam under continual construction. The ER in TGRA during 1990–2016 showed at first a worsening trend and then an improvement, especially in serious-risk areas in the elevation zone of 500–1000 m and slopes of $>25°$, where the risk decreased sharply; a turning point occurred in 2004. In the study area, the transition of the sloping farmland ecosystem is the vital driving force for spatiotemporal changes in ER. Furthermore, planting suitable orchards changes the utilization mode of sloping farmland in mountainous areas and has economic and ecological benefits. Therefore, slope land use transition has positively affected food security, rural economic improvement, and ecological environment governance in developing countries.

There are some limitations in the study: ER assessment considers only the percentage of land use area and spatial location; it fails to consider fragmentation level, separation degree, connectivity, and other patch characteristics of land use types along the slope. Still, the results of this study objectively reflect ER change and possible impact. In addition, the purpose of this study is to reflect on the evolution of ER characteristics in TGRA through a landscape ecology approach and then provide a new perspective for observing ER evolution in mountain areas. Limited by length and data, the study does not cover the impact of dam construction on the regional cultural landscape, species richness, and other aspects. We will continue to focus on land use and ecological environment change processes of TGRA from a more global perspective in future work.

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