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Assessing Landscape Ecological Risk Induced by Land-Use/Cover Change in a County in China: A GIS- and Landscape-Metric-Based Approach

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Abstract: Landscape ecological risk assessment (LERA) evaluates different types of potential environmental impacts and their cumulative effects, thereby providing policy insights for sustainable regional land-use and ecosystem management. In a departure from existing literature that heavily relies on low-resolution land-use data for LERA at provincial or municipal scales, this study applies high-resolution land-use data to a relatively small research area (county). In addition, this study modifies the evaluation units of LERA from equal-sized grids to watersheds and refines the ecological vulnerability weight on the basis of finer-resolution data. The main findings are summarized as follows: (1) In 2011–2013, nearly 866 ha of land use in Xiapu County changed; moreover, the construction land, which was mainly concentrated in Songgang Street and Xinan Town, increased the most (340 ha). (2) Landscape ecological risk (LER) was roughly maintained, and areas of high ecological risk were mainly concentrated along the coast. (3) The spatial distribution of LER maintained a relatively aggregated pattern, with no trend toward more aggregated or more dispersed change. This study further discusses the relationship between local LER and land-use change and how to balance global and local LER in planning practices.

Keywords: landscape analysis and planning; landscape ecology; geospatial analysis; spatial planning; land-use management

1. Introduction

Over the past two centuries, human flourishing has undeniably brought an enormous toll on natural, nonhuman environments and wildlife [1], posing serious ecological risks to ecosystems and human society. For this reason, timely reminders of potential anthropogenic and natural damages to ecosystems become increasingly important. Ecological risk assessment (ERA), which describes the probability of damage to the functioning or structure of ecosystems under certain anthropogenic activities and natural hazards [2], is conducive to prompting mankind to maintain the security and sustainability of ecosystems so that ecosystems can continuously provide their services (e.g., sequestration of pollutants) and goods (e.g., fresh water and food) to mankind and improve human wellbeing [3]. Consequently, ERA has become an important and effective way to determine ecological sustainability at the regional and landscape scales [4] and to ensure current human demands and future long-term benefits [5]. Therefore, the first ERA was proposed by Hunsaker in 1989 and was conducted on regional scales [6]. Subsequently, many efforts have been made to evaluate ecological risk caused by anthropogenic or natural disturbances in large areas, such as river reservoirs [7–9]. However, as expected, too many factors and ecological interactions affect the sustainability of ecosystems; consequently, unilateral risk management proposed in ERA becomes hardly effective in the management of open and complex systems [5]. Therefore, developing integrated and multilateral methods that include different influencing factors in ecological risk became critical. As a result, landscape ecological risk assessment (LERA) was conducted in the 2000s [10].

Landscape, defined as the "heterogeneous land area composed of a cluster of interacting ecosystems that are repeated in similar form throughout" [11], was regarded as a good proxy to evaluate different types of potential environmental impacts and their cumulative effects [5] because landscapes are typically influenced by multifold external disturbances [12,13]. Moreover, according to the principles of landscape ecology, landscape patterns could determine the ecosystem's equilibrium [14] because they are considered hierarchically linked to ecological processes [15–17]. Therefore, to elucidate relationships between ecological processes and spatial patterns, Romme [18] developed indexes for quantifying landscape patterns. Consequently, the development of various landscape pattern indices that capture important ecological processes at the landscape scale makes it possible to simplify regional ecological risk monitoring [19]. For this reason, LERA is more like an expansion and complement of ERA and was recommended due to its appropriate scale to study the impact of human activities on ecosystems [20,21] and the advancement of the spatial statistics approach [22]. In the 1990s, Fu found that the indexes for landscape fragmentation, separation, and dominance are generally proportional to the intensity of human activities [23], thus providing a track to evaluate landscape ecological risk on the basis of the degree of human interference in ecosystems. Afterward, a growing number of researchers have relied on or further developed Fu's findings to assess the LERA, whereas the roots of various models to assess LERA later are all based on the three abovementioned landscape indexes. The LERA approach used in this study is also based on the findings of Fu [23]. Specifically, as a macroscopic representation of terrestrial landscape [24], land use/land cover (LULC) is often treated as an object of explicit observation in LERA. Its change over time is a reflection and outcome of the interaction process between anthropogenic activities and the natural ecosystem at various spatiotemporal scales [25,26], reflecting the extent and manner of human intervention in nature [27]. Changes in landscape patterns (e.g., fragmentation, separation, and diminishment) due to inappropriate LULC change may have an adverse effect on, for example, circadian condition, biological diversity, climate change, and biogeochemistry [28,29]. Under such circumstances, the integration of geoinformatics and landscape ecology has made landscape patterns concerning configuration and composition can be quantified by landscape pattern metrics [30,31]; therefore, LERA based on LULC change has been conducted by many previous studies with differing degrees of depth and sophistication in different contexts. For example, Jin proposed LERA for Delingha City on the Tibetan plateau to provide scientific bases for ecological protection [32]. Mo analyzed the spatial and temporal changes of road networks and landscape ecological risk in Beijing to reveal the influence of road network expansion on ecological risk in the urban landscape [33]. Gong found that LERA combined with simulation-driven analysis is important for guiding the sustainable development of ecologically vulnerable land systems [34]. Similarly, Fan [27], Zhang [35], and Xie [36] conducted LERA on different research areas on the basis of landscape pattern metrics and spatial statistics, aiming to provide policy insights into regional sustainable land-use and ecosystem management.

Corresponding to the administrative management hierarchy, China's spatial planning system consists of five levels: national, provincial, municipal, county, and township [37]. LERA conducted at different planning levels could guide human activities and enable risk managers and planners to make rational environmental protection decisions in specific locations on the basis of the degree of ecological risk. However, previous studies nearly always focused on provincial and municipal scales (see, for example, Refs. [5,32,38–41]), leading to the absence of adequate environmental protection awareness within the planning process of counties and townships. Filling this gap is by all means meaningful and necessary because human impacts on the ecosystem are first accumulated and realized in small-scale areas. Additionally, as a spatial variable, ecological risk should be evaluated on the basis of appropriate evaluation units to ensure the reliability and accuracy of the assessment. By contrast, previous studies, regardless of the research scale, divided the study area into several equal-sized grids without exception. This kind of operation hardly makes every evaluation grid become an ecologically independent area because the continuous ecological process may be cut off by evenly distributed equal-sized grids. Instead, catchments are good alternatives, and they can be integrated with administrative units to support decision-making that is relevant to ecological issues during the planning process. Meanwhile, the unavailability of high-resolution research data makes it hard to distinguish the ecological vulnerability of different landscapes, which would further influence the calculation of ecological risk. Lastly, the problem of "emphasizing evaluation but neglecting application" existed in previous studies, that is, they only focused on evaluating and describing the results of ecological risks, but potential implications and applications of the evaluation results to planning practice were seldom discussed. To this end and in contrast to existing literature, this study does not follow conventional practices in terms of research scale, sampling method, and vulnerability weighting. Instead, it applies high-resolution land-use data to a relatively small research area (county) and chooses watersheds as the basic evaluation units of LERA. The implications of LERA for local planning practices are also discussed.

This study has the following three objectives: (1) applying the modified LERA to a county-scale study area by combining geographic information system (GIS) and landscape pattern analysis, (2) evaluating the spatiotemporal dynamic pattern of LULC change and ecological risk change using high-resolution land-use data, and (3) discussing the potential implications of LERA at the global and local levels. Specifically, existing studies heavily use equal-sized grids as evaluation units; such a strategy is useful and convenient for researchers, but remains subject to many shortcomings (e.g., the integrity of a local ecosystem is destroyed), some of which may considerably decrease the reliability and validity of the research findings. Furthermore, the low-resolution land-use data (30×30 m) used in previous studies were not precise enough to support ecological risk analysis in small research areas. A good illustration of this is that during the calculation of the LERA, the ecological vulnerability weights of different landscapes are difficult to differentiate because the number of extracted landscapes from low-resolution data is limited. Thus, in addition to some commonly used research methods, we modify LERA by taking watersheds as evaluation units, using high-resolution land-use data, and giving refined ecological vulnerability weights to different landscapes. This study, which conducts LERA at a county scale, is expected to fill the research gap and hence match the spatial planning systems of China. Additionally, this study is beneficial to the control of excessive and unreasonable LULC change resulting from illogical urban and landscape planning practices, providing policy insights for developing sustainable cities.

2. Materials and Methods

2.1. Study Area

Xiapu County (26°25′ N to 27°09′ N, 119°46′ E to 120°26′ E) is under the jurisdiction of Ningde City, Fujian Province, China, with a population density of 312/km^2. Xiapu County contains two streets and 12 towns, and is located in the northwest coast of the Taiwan Strait and in the northeastern part of Fujian Province (Figure 1a). Given its special location, Xiapu County has been known as the key point of the Zhejiang and Fujian provinces. It connects the Shanghai Economic Zone and Pearl River Economic Zone. The topography of Xiapu County is high in the northwest and low in the southeast, descending roughly in a three-stage staircase from northwest to southeast (Figure 1b). The land area in Xiapu County is approximately 1489.6 km^2, and the sea area is 29591.6 km^2. The coastline is 505 km, accounting for one-eighth of the province, ranking first in the entire Fujian Province. More than 400 islands and 138 ports are located in Xiapu County. By the end of 2015, the resident population in Xiapu was 464,500, with a small fluctuation in the resident population over the past decade, varying by approximately two to three thousand people. Xiapu County is China's coastal open economic county and in the second batch of the country's key agricultural development counties. Rich marine resources make Xiapu County dominate the maritime economy, including marine aquaculture and fishing, aquatic product processing, and the shipbuilding industry. By December 2019, the regional GDP of Xiapu County had reached up to 25.461 billion yuan, increasing 5.1% over the last year.

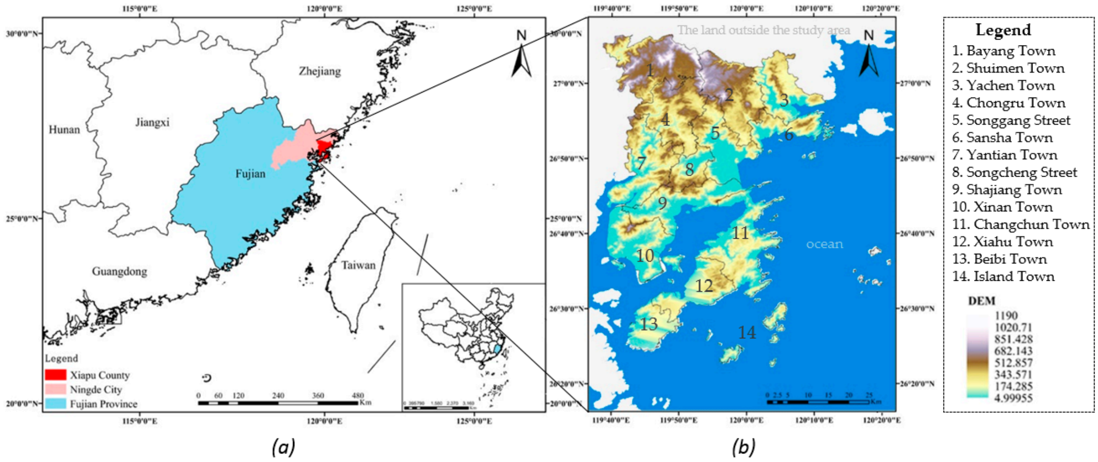


Figure 1. Location of Xiapu County, China. (**a**) Location of Xiapu County in Fujian Province; (**b**) elevation and sub-administrative units of Xiapu County.

2.2. Aspects of the Modified LERA

2.2.1. Finer-Resolution Land-Use Data

In a departure from existing literature that heavily relies on land-use information extracted from relatively low-resolution satellite images (30 × 30 m), the 2011 and 2013 land-use data used in this study are from the second national land survey of Xiapu County (resolution better than 5 × 5 m). Figure 2a shows Xiapu's land-use classification extracted from Landsat satellite images, whereas Figure 2b shows the land-use classification in the same year provided by the Xiapu County People's Government. Figure 2 shows that the latter land-use type is more specific than the former. For example, the construction land of the former could be further divided into town construction land, village construction land, highway land, and rural road in the latter one. In general, the usage of high-resolution data in ERA has several benefits. First, the land-use types are finely divided. In accordance with the Chinese land-use classification criteria (GB/T21010-2017), the landscape of Xiapu County could be divided into 28 types (see details in Table 1) when high-resolution land-use data are applied, whereas the number of land-use types was usually maintained below 10 in prior studies. Second, analyses of small-scale study areas could be supported. Low-resolution data cannot satisfy the requirement of analysis accuracy in small-scale research areas, such as towns or villages. Thus previous studies were mainly focused on cities or provinces. Lastly, analytic error due to data-related issues could be minimized as much as possible in LERA.

2.2.2. More Reasonable Evaluation Units: Watershed Basin

As formerly noted, although the grid sampling method was applied by many previous studies, it does not make the evaluation units become relatively independent research objects. The grid sampling method hardly guarantees that the interior of every evaluation unit maintains a comparatively complete ecological process. For example, some independent geographic units, such as mountain range, water surface, or basin, may be separated by the equal-sized grid, leading to discontinuous ecological processes within the evaluation units. In such a case, watersheds, which concern topography and hydrology processes, may be a good alternative because they could determine the ecosystem process in a comparatively independent and integrated area without being subjectively sliced [5].

Therefore, based on 1:10,000 topographic maps of Xiapu County (2015) and a digital elevation model image, the land side of the study area was divided into watershed basins with an average area of 1 × 1 km, whereas the offshore part of the study area (without watersheds), following the practice of previous studies, was divided into grids of 1 × 1 km. The watershed division of the study area was realized by the hydrological analysis module (Hydrology) of ArcGIS. Figure 3a,b shows the traditional grid assessing units and the watershed ones, respectively.

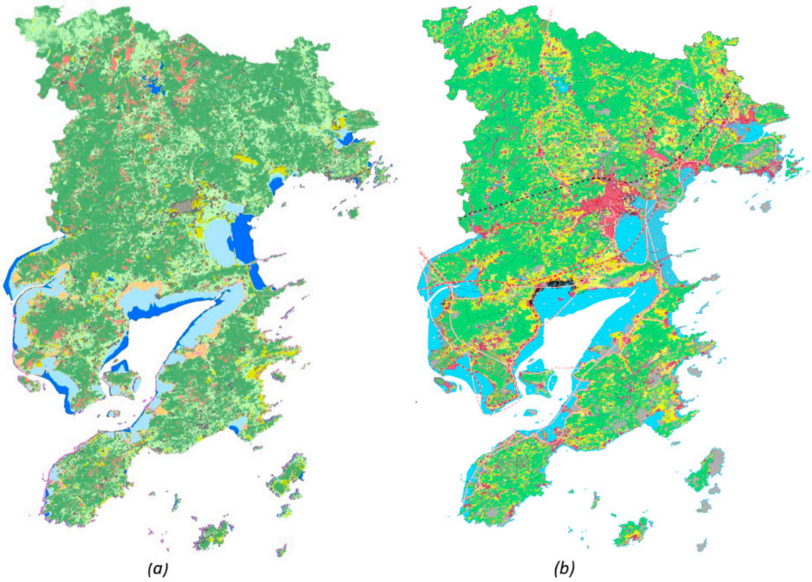


Figure 2. Comparison of extracted land information between low- and high-resolution data. (**a**) Land information extracted from low-resolution data; (**b**) Land information extracted from high-resolution data.

Table 1. Land-use types and their landscape vulnerability weight assignments in Xiapu County.

Land-Use Type	Normalization of the Vulnerability Weight	Land-Use Type	Normalization of the Vulnerability Weight
Paddy field	0.580	River	0.687
Irrigable land	0.527	Reservoir	0.633
Dry farm	0.527	Pond	0.687
Orchard	0.207	Coastal mud flat	0.740
Tea garden	0.207	Inland mud flat	0.740
Forest land	0.313	Irrigation canals	0.633
Shrubland	0.313	Hydraulic construction land	0.100
Other forestlands	0.313	Facility agricultural land	0.527
Artificial grassland	0.420	Saline–alkali soil	0.847
Other grasslands	0.420	Bare land	0.900
Railway	0.100	Town	0.100
Highway	0.100	Village	0.153
Village road	0.153	Mining land	0.153
Port wharf	0.100	Tourist attraction	0.100

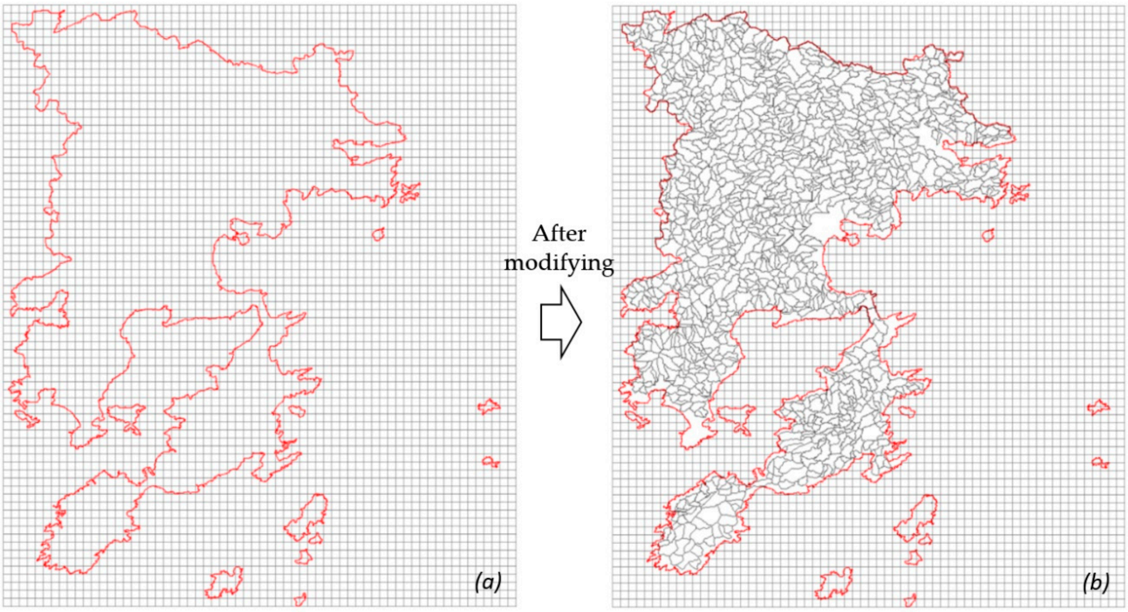


Figure 3. Comparison of traditional and modified sampling methods. (**a**) Traditional sampling method; (**b**) Modified sampling method.

2.2.3. More Refined Landscape Vulnerability Weight

The landscape vulnerability index (F_i) is a landscape pattern metric that calculates landscape ecological risk. It refers to the extent of ecosystem fragility to external disturbance [42]. If landscape types are steady and hardly affected by outside interference, then the inner ecosystem would be robust and have a lower ecological vulnerability [43]. Usually, the ecological vulnerability of different landscape types is given various weights. However, as a direct influence of the limited number of extracted land-use categories from low-resolution satellite images, the landscape vulnerability weight assignment on different landscapes would be rough. In such a case, the weight assignment would not be covered by the non-extracted subcategories of landscape and could thus further reduce the accuracy of the assessment. For example, the ecological vulnerability difference between "town" and "village" is ignored during the weighting; instead, they are regarded as the construction land with the same landscape vulnerability value. Benefiting from using the finer-resolution land-use data, the landscape vulnerability weight assignment becomes more specific and refined in this study (see details in Table 1) and, thus, favorable for improving the accuracy of LERA.

2.3. Construction of an LERA Model

Based on the principles of landscape ecology, the value of the landscape ecological risk of ecosystems is related to the extent of the external disturbance and the ecosystems' vulnerability. Methodically, landscape metrics can be used to assess ecological risk because landscape spatial patterns and external effects interact during ecological processes. In accordance with previous studies [24,27,32,33,35,36,38–41,44,45], the combination of the landscape disturbance index (E_i) and landscape vulnerability index (F_i) is usually chosen to represent landscape loss upon impacts of external interference.

2.3.1. Landscape Disturbance Index (E_i)

The landscape disturbance index (E_i) reflects the extent to which different ecosystems of landscapes are subject to external disturbances, characterizing the differences between landscape types in maintaining ecological stability. The less the system is disturbed (mainly by human activities), the more stable the internal ecology is and the more conducive it is to the survival of plants and animals.

Generally, a high E_i indicates a high ecological risk. It is developed on the basis of landscape pattern and can be expressed by the formula:

$$E_i = aC_i + bS_i + cDO_i$$

where C_i is the landscape fragmentation index used to express the extent to which the landscape is fragmented, and the landscape fragmentation is regarded as a major cause of loss of biodiversity and natural resources [46]. S_i is the landscape segmentation index that refers to the degree of separation of patches of a certain landscape type [41]. DO_i is the landscape dominance index that represents the dominance of patches in a certain landscape, reflecting their position within the landscape [41] and the magnitude of the impact of patches on the formation and changes of landscape patterns. The parameters a, b, and c are the weights of the above three landscape indexes, respectively, and $a + b + c = 1$. According to related studies, 0.5, 0.3, and 0.2 are assigned to the three parameters. The ecological implications of the abovementioned indexes can be seen in Table 2.

Table 2. Calculation of the landscape disturbance index (E_i).

Index	Equation	Meaning of Parameters
Landscape disturbance	$E_i = aC_i + bS_i + cDO_i$	a, b, and c represent the weights of C_i, S_i, and DO_i. a + b + c = 1.
Landscape fragmentation	$C_i = \frac{n_i}{A_i}$	n_i stands for the patch number of landscape i; A_i represents the total area of landscape i; A is the total area of all landscape types.
Landscape segmentation	$S_i = \frac{A}{2A_i}\sqrt{\frac{n_i}{A}}$	
Landscape dominance	$DO_i = \frac{Q_i+M_i}{4} + \frac{L_i}{2}$	L_i = The area of the landscape i divided by the total area of the sampling unit; M_i = the number of the patch of landscape i divided by the total number of the patch in the sampling unit; Q_i = the number of sampling units with the path I divided by the total number of sampling units.

2.3.2. Landscape Vulnerability Index (F_i)

As mentioned in Section 2.2.3, the landscape vulnerability index (F_i) is a reflection of the resistance ability of the external stressors within different landscape types [47], also indicating the probability of a certain landscape to deviate from its stable state [5]. The higher the value of F_i of a certain landscape type, the more vulnerable and unstable that type of landscape is, that is, the more likely it is for such a landscape to undergo ecological loss and physical change in response to external disturbances. For example, construction lands are in a relatively more stable state and are less prone to new physical changes; thus, their ecological vulnerability is relatively low, with a typical value of 1 in existing studies. To this end, according to the service value of the world's ecosystem assessed by Costanza [48] and the vulnerability value employed in previous studies, the relative ecological vulnerabilities of 28 landscapes types in this study were evaluated by using the Analytic Hierarchy Process (AHP) and were determined by normalizing the landscape vulnerability index value of each landscape, as shown in Table 1.

2.3.3. Landscape Ecological Risk Index (ERI)

On the basis of the abovementioned landscape vulnerability index (F_i) and landscape disturbance index (E_i), the landscape ecological risk index (ERI) is constructed. To acquire the relative value of integrated ecological risk in each evaluation unit, the landscape pattern is converted into a spatialized variable of ecological risk by dividing the study area into numerous watershed units [34,36]. The ERI can fully reflect the ecological risk changes caused by landscape pattern changes [33] and is expressed by the following formula:

$$ERI_i = \sum_{i=1}^{N} \frac{A_{ki}}{A_k} \sqrt{E_i * F_i}$$

where N is the number of landscape types. E_i is the disturbance index of landscape i. F_i is the vulnerability index of landscape i. A_{ki} is the area of landscape i in the evaluation unit k. A_k is the total area of the evaluation unit k.

In accordance with the above calculation method of the ERI, the ecological risk value in each evaluation unit can be calculated using Fragstats software. Then, on the basis of the ecological risk values in these evaluation units, the LERA results of the entire Xiapu County in 2011 and 2013 can be spatially visualized by the KRIGING interpolation algorithm, which can provide the optimal estimation for unmeasured points and the error and accuracy of the estimated values. The visualization of ecological risk in this research area was achieved using ArcGIS Spatial Analyst Tools.

2.4. Spatial Statistical Analysis

2.4.1. Land Transfer Analysis

Land-use changes and transfers in different periods can be quantitatively described by a transfer matrix, which can show the characteristics, direction, and structure of land-use changes. The transfer matrix can not only reflect the land-use types at the beginning and end of the study period, but also describe the relationship and quantity of land-use conversion before and after the change. As such, through the description of the destination and quantity of land-use transfer, the reasons for the shifts between land-use types can be further analyzed and explained. Based on the land transfer matrix, visualization analysis allows for an improved and clear analysis of the spatial characteristics and evolutionary patterns of land-use changes. Thus, we choose the Sankey diagram, a type of flow diagram that can emphasize transfers or flows in a system, as the visualization tool for the land transfers of Xiapu County between 2011 and 2013. The land transfer matrix can be expressed by the following formula:

$$s_{ij} = \begin{bmatrix} s_{11} & s_{12} & \Lambda & s_{1n} \\ s_{21} & s_{22} & \Lambda & s_{2n} \\ \Lambda & \Lambda & \Lambda & \Lambda \\ s_{n1} & s_{n2} & \Lambda & s_{nn} \end{bmatrix}$$

where S represents the land area; i and j denote the type of land use at the beginning and end of the study period, respectively; n represents the number of types of land use.

2.4.2. Spatial Autocorrelation Analysis

Spatial autocorrelation analysis is a statistical method for testing whether variables in a unit of evaluation are significantly correlated with variables in its neighboring units [49,50]. It can determine how variables are spatially related to each other and whether this interrelationship affects the spatial distribution of the variables [51]. Spatial autocorrelation analysis includes two levels: global and local spatial autocorrelations. Global spatial autocorrelations are used to express the spatial autocorrelation patterns of the overall variable values in the study area and their significance, including discrete, aggregated, and random patterns. Moran's I index is usually used as the indicator to measure global spatial autocorrelation, and it can be expressed by the following formula:

$$I = \frac{\sum_i^n \sum_{j \neq i}^n W_{ij}(x_i - \overline{x})\left(x_j - \overline{x}\right)}{\frac{1}{n}\sum_i^n (x_i - \overline{x})^2 \sum_i^n \sum_{j \neq i}^n W_{ij}}$$

$$\overline{x} = \frac{1}{n} \sum_{i(j)}^{n} x_{i(j)}$$

where n is the total number of the observed units. x_i and x_j are the observed variable values in spatial unit i and unit j, respectively. $\bar{x}$ is the mean value of regional variables. W_{ij} is the spatial weight value between unit i and unit j, and if they are adjacent, then $W_{ij} = 1$; if not, $W_{ij} = 0$.

Local spatial autocorrelation can identify the local spatial aggregation characteristics of statistically significant variable values by measuring spatial disparity degrees between a unit and its peri-units. Local Moran's I can reveal the degree of spatial autocorrelation of each evaluation unit; it is the indicator related to global Moran's I in the internal connection [52]. The calculation formula of the local Moran's I is as follows:

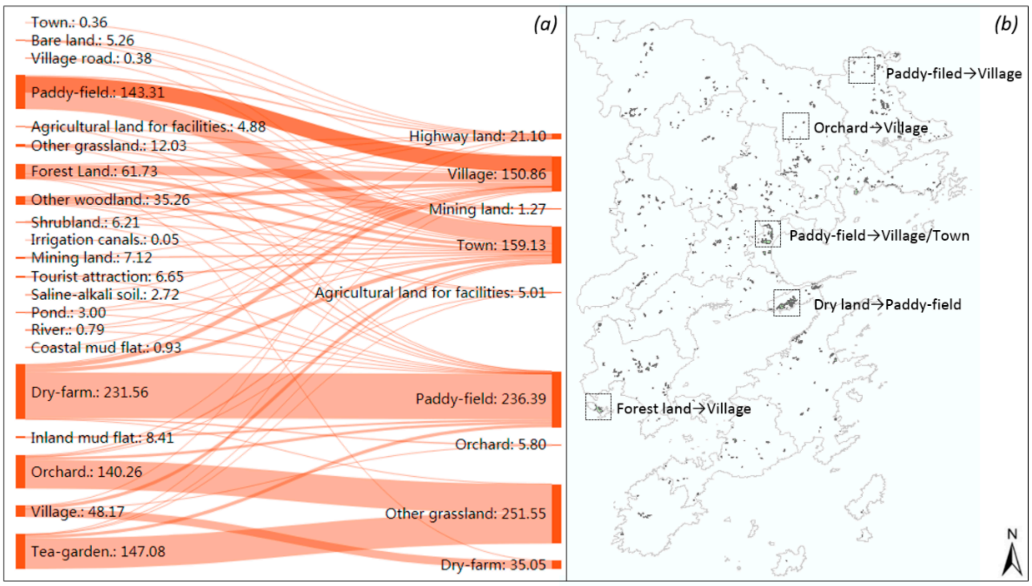
$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{i,j}(x_i - \bar{x})\left(x_j - \bar{x}\right)}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} W_{i,j}\right)\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

where x_i and x_j are the values of the variable at location i and j, respectively; W_{ij} indicates the spatial weight that determines the relationship between i and j.

3. Results

3.1. LULC Change

In 2011–2013, a total of 866.17 ha of land changed in Xiapu County, with an increase of 331 ha of construction land. The spatial locations where land changes occurred were relatively concentrated in Songgang Street, Songcheng Street, Shuimen Town, and Yacheng Town (Figure 4b). As illustrated in Figure 4a, the land types that decreased in the area include non-built lands, such as paddy fields (143 ha), forested land (61 ha), dry land (231 ha), orchards (140 ha), and tea gardens (147 ha). By contrast, the types of land that increased in the area include highway lands (21 ha), villages (150 ha), towns (159 ha), paddy fields (236 ha), other grasslands (251 ha).



Note: A total of 886 hectares of land changed, of which construction land increased by 331 hectares.

Figure 4. The transfer relationships of land uses and their spatial locations in Xiapu County from 2011–2013. (**a**) Transfer relationship of land uses; (**b**) Locations of land-use change

Overall, several findings were obtained on the basis of the characteristics of LULC change between 2011 and 2013 in Xiapu County. First, the total amount of land change in Xiapu County between 2011 and 2013 was relatively large, with construction and development focused on Songgang Street and Xinan Town. Consequently, the use of prime arable lands, such as paddy fields, for development was particularly frequent in Songgang Street (see details in Section 3.2.2); this situation might be the reason for the increase of landscape ecological risk in Songgang Street. Second, as a balanced approach of converting non-construction lands to human settlement areas, some land types, such as paddy fields that were bound to be exploited due to their close location to current human habitation, obtained supplements from other land types, such as dry farms in other locations. In this manner, the local government was attempting to maintain the area of non-construction lands at a relatively stable level, ensuring the stability of the ecosystem at the macro level. Lastly, the decrease in orchard and tea garden areas manifested the policy adjustment of primary industry in 2011–2013 in Xiapu County; this adjustment could be supported by documents of the local government.

3.2. Dynamic Spatial and Temporal Features of LER

3.2.1. Spatial Interpolation of LER

As shown in Figure 5, the overall landscape ecological risk (LER) of Xiapu County in 2011 and 2013 was plotted using KRIGING interpolation. With ArcGIS, the degree of LER was classified into nine levels: The value of LER gradually increased from level 1 (0–0.065) to level 9 (above 0.365). Areas of high ecological risk were mainly concentrated along the coast, e.g., the northern and southern coasts of the towns of Changchun, Xiahu, and Beibi. Nevertheless, in 2011–2013, the LER was kept roughly the same from a regional perspective in these two periods, even though 866 ha of land had changed in Xiapu County. At least, the change of LER in 2011–2013 was hardly observed from the regional level. However, based on the area statistics in regions of different LER levels (Table 3), more regions suffered from the increase in ecological risk in Xiapu County from 2011 to 2013. Specifically, the area of regions with the LER increase was 2451 ha in 2011, whereas that with decreases in LER was 1256 ha, indicating that the LER was relatively higher in 2013 than in 2011.

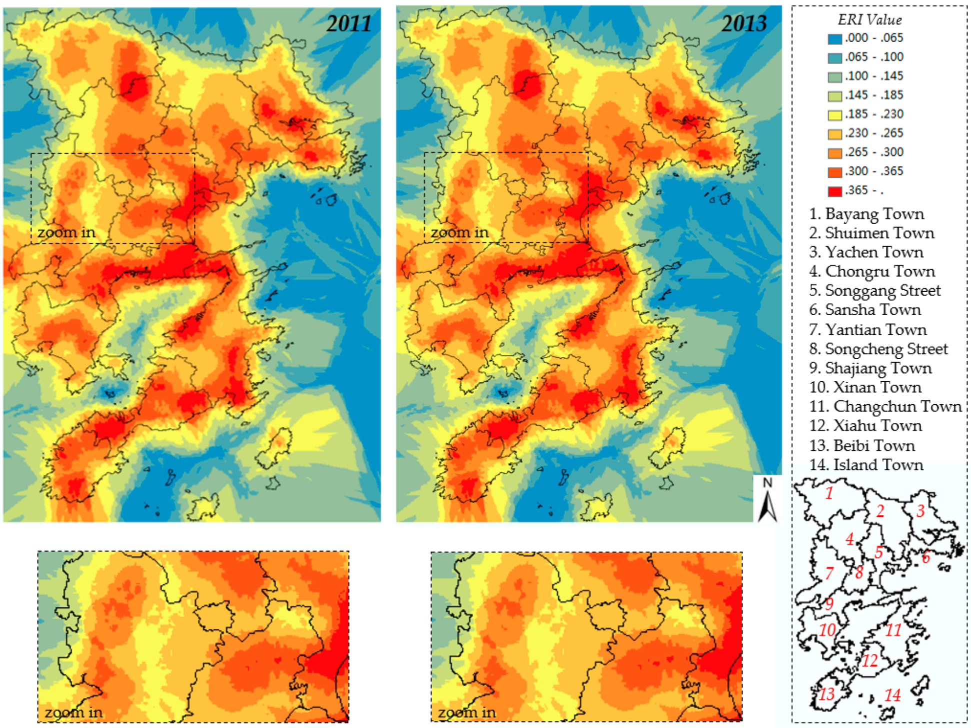


Figure 5. The landscape ecological risk assessment results of Xiapu County in 2011 and 2013.

Table 3. Statistics on the area transfer of areas with different ecological risk levels from 2011 to 2013.

	2011 (Level 1 is the Area of Lowest LER, Written as L1)									
2013	L1	L2	L3	L4	L5	L6	L7	L 8	L9	**Total**
L1										0.00
L2										0.00
L3										0.00
L4			79.31		14.54					93.85
L5				33.31		47.00				80.31
L6					548.05		341.43			889.48
L7						856.08		511.57		1367.65
L8							640.43		342.00	982.43
L9								294.29		294.29
total	0.00	0.00	79.31	33.31	562.58	903.08	981.86	805.86	342.00	3708.00
Area of increasing in LER: 2451.46ha					**Area of decreasing in LER: 1256.54ha**					

3.2.2. LER Change at the Local Level

The change of the regional LER of Xiapu County was not that significant in 2011–2013; thus, the detailed LER change at the local level was difficult to identify and analyze on the basis of the spatial interpolation results (Figure 5). However, by comparing the LER results of different years on the basis of evaluation units, the changes of LER within each evaluation unit over time can be observed. To this end, the proportion of change in the LER value of each evaluation unit is shown in Figure 6. It demonstrates that except for the units within Songgang Street, the spatial distribution of the unit with increased LER was relatively fragmented and mainly located in the coastal areas of the towns of Sansha, Xinan, Changchun, Xiahu, and Island. By contrast, the LER of several adjacent units in Songgang Street increased significantly. Overall, the LER of the majority of the evaluation units in Xiapu County remained stable in 2011–2013, whereas some units with increasing LER existed sporadically in the coastal area. Individually, some neighboring units in Songgang Street had a remarkable increase in LER.

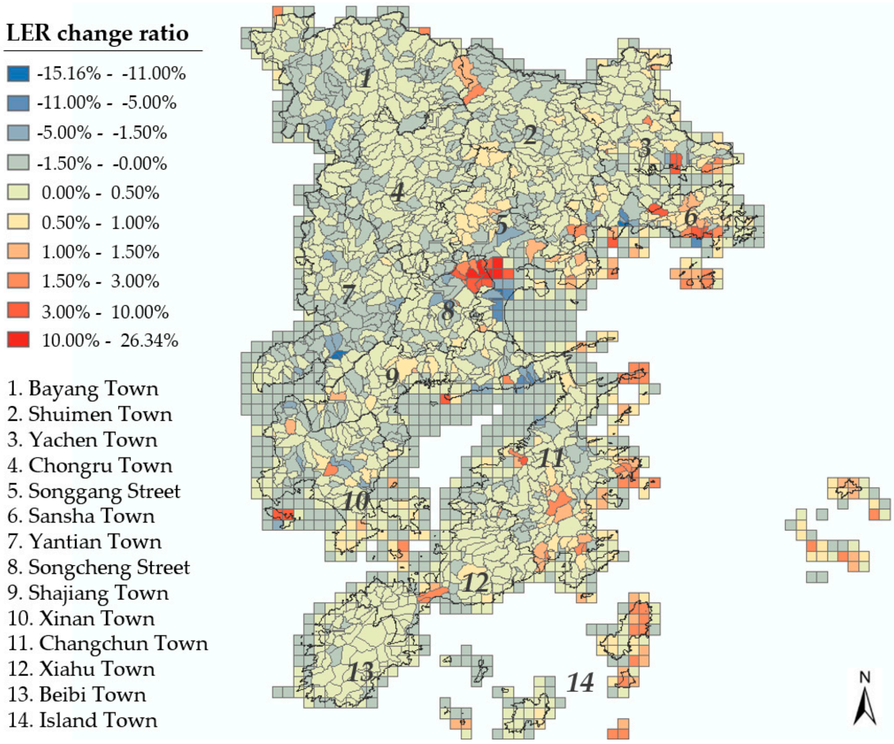


Figure 6. Changes in landscape ecological risk (LER) in Xiapu County by unit from 2011 to 2013.

3.3. Spatial Autocorrelation of LER

3.3.1. Global Moran's I of LER

The value of Moran's I ranges between –1 and 1. A value greater than 0 indicates that the variables tend to be spatially aggregated and exhibit positive autocorrelation; a value less than 0 indicates that the variables tend to be spatially dispersed and exhibit negative autocorrelation; a value equal to 0 indicates that the variables are spatially and randomly distributed, and no correlation exists between the variables. Thus, the global Moran's I of LER at various grain levels in Xiapu County is presented in Table 4. Moran's I values in this study are all greater than 0 under different grain levels in the range of 1.5–30 km, indicating the strong positive spatial autocorrelation of the LER and implying that the spatial distribution of the LER of Xiapu County shows an aggregated pattern. In addition, with the increase of grain levels, the spatial autocorrelation of ERI in 2011 and 2013 tended to decrease, indicating that the spatial distribution of LER has a significant scale dependence. Figure 7 shows the Moran's I scatter of the LER in 2011 and 2013, with roughly the same value. This result indicates that the overall ecological risk in Xiapu County did not change much in 2011–2013, and the spatial distribution of LER maintained a relatively aggregated pattern, with no trend toward more aggregated or more dispersed change.

Table 4. Moran's I of LER at different grain levels in Xiapu County.

Year	Grain Levels (km)						
	1.5	**3**	**5**	**10**	**15**	**20**	**30**
2011	0.574	0.439	0.353	0.302	0.247	0.201	0.164
2013	0.573	0.438	0.352	0.302	0.246	0.201	0.164

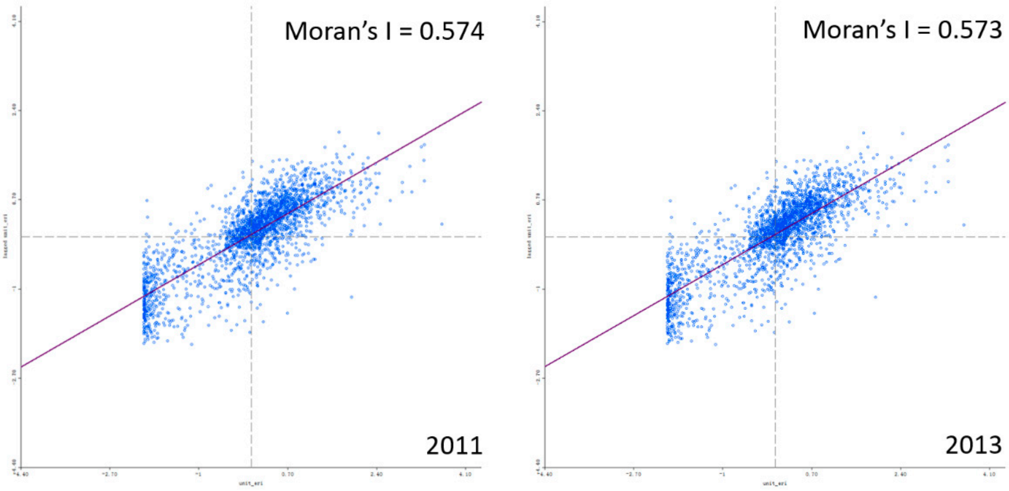


Figure 7. Global Moran's I and scatter plots of ecological risk in 2011 and 2013.

3.3.2. Local Moran's I of LER

In contrast to measuring the spatial relationship of certain variables within the entire study area, local Moran's I was used to describe the degree of spatial correlation of some geographic attributes values or regional phenomena in local evaluation units and their contiguous units [52]. For example, it can validate the spatial correlation of LER among several adjacent evaluation units. Figure 8 shows the results of the local spatial autocorrelation of LER, showing that the local Moran's I of LER barely changed from 2011 to 2013. Two types of significant spatial autocorrelation were observed in Xiapu County: high–high (HH) and low–low (LL); these two kinds of spatial clusters belong to positive spatial autocorrelation. The spatial cluster HH means that spatial units with attribute values above the mean are surrounded by spatial units with attribute values above the mean. In 2011 and 2013, the HH areas in Xiapu County were mostly located in the land part of the coastal area where the ecological risk was high (as shown in Figure 5). By contrast, most of the LL areas were found in the offshore areas and usually presented relatively low ecological risks. Moreover, most spatial clusters of the LER in 2011 and 2013 reached a significance level of above 0.05.

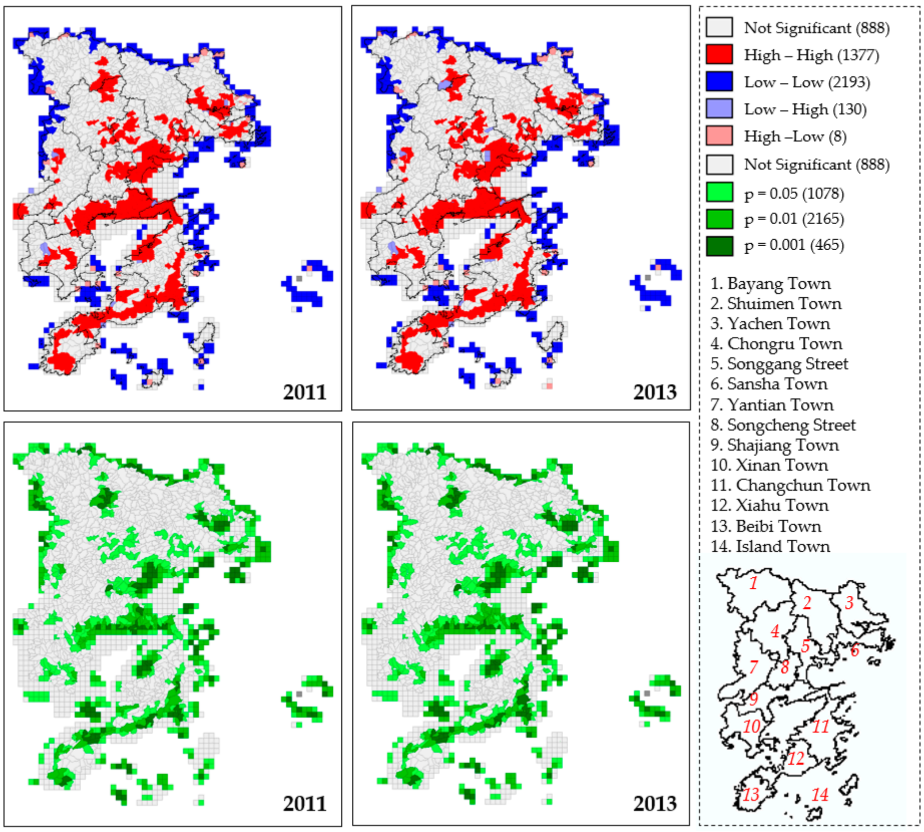


Figure 8. Local autocorrelation map of ecological risk and its significance in 2011 and 2013.

4. Discussion

4.1. Correlation between Local LER and LULC Change

From the above analysis, we understood the variation features of land use and ecological risk separately. However, in landscape and urban planning practices, the question planners are concerned about is how land-use changes would increase incomes instead of increasing landscape ecological risk. For this purpose, through overlay analysis of land-use changes and ecological risk changes, we preliminarily found that the increase in ecological risks at the local level is normally related to the increase in the area of the nearby construction land. For example, in Figure 9, we summarized the land-use change in units with significantly increased ecological risk in Sansha Town, Yachen Town, Songgang Street, and Xinan Town. The figure shows that when non-construction land is turned into construction land, such as towns, villages, and highways, the ecological risk of nearby units increases. This finding is in accordance with the people's common sense, namely, anthropogenic activities (e.g., urban sprawls) are usually disadvantageous to the natural environment. In this sense, planners should focus on and perform further scenario simulations when turning natural areas into construction lands.

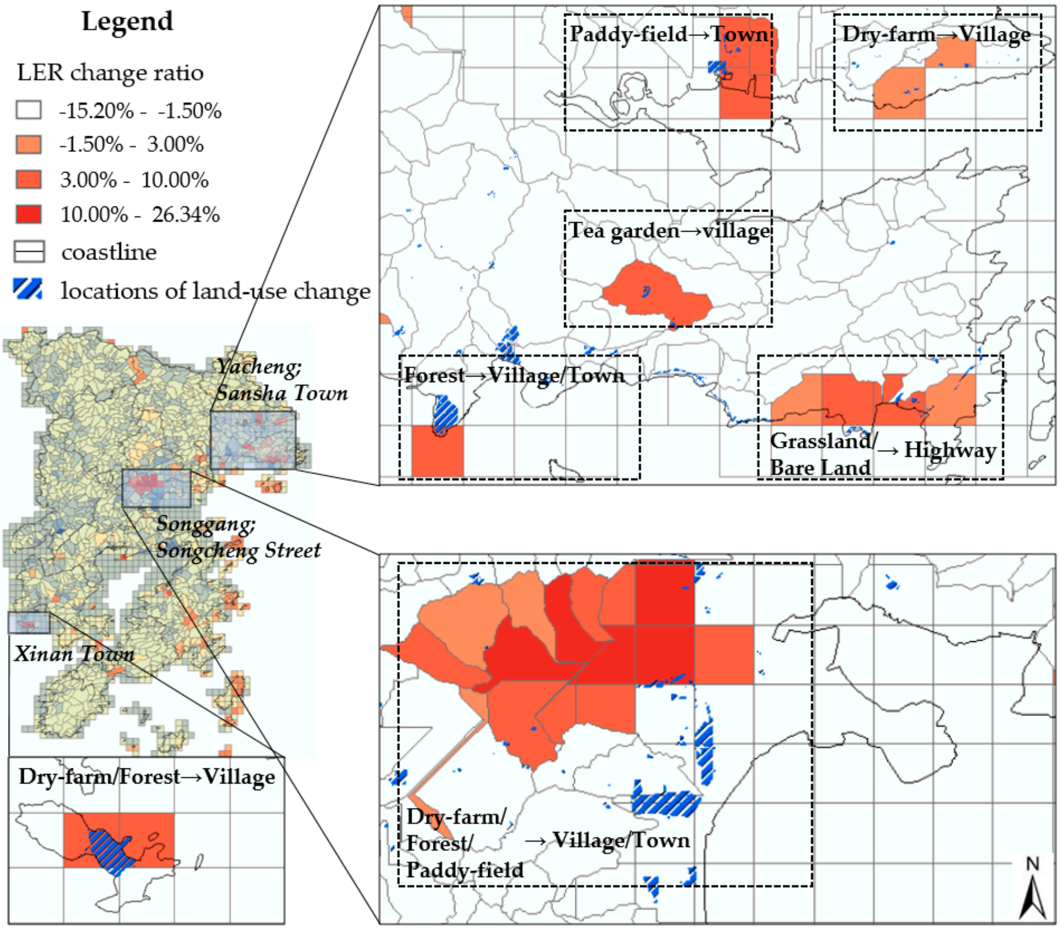


Figure 9. Land changes in units with increased ecological risk from 2011 to 2013.

4.2. Balance of the Global and Local LER

The magnitude of the change of ecological risks induced by land-use change differs at the global and local levels. From the perspective of the entire study area, the ecological risk in Xiapu County in 2011–2013 changed slightly, whereas changes at the local level were evident. Therefore, when formulating land-use planning schemes, the relative balance of the global and local ecological risk change should be considered because the global landscape pattern consists of local landscape patterns, and local ecological risk is related to global landscape patterns. To this end, we propose the following roadmap for planners to balance the global and local ecological risk change when adjusting land use at the global and local levels (Figure 10):

- Step 1: The current ecological risk of local units and the entire study area must be understood. This information would be used to compare with the ecological risk after spatial planning and evaluate whether any increase in ecological risk occurs globally and locally.
- Step 2: In accordance with the planning goals and development speed of the administrative regions, the area of various land types in the entire study area that need to be adjusted is determined and planned, and then the area of various land types is allocated to local units.
- Step 3: On the basis of the allocated area of land types that need to be adjusted in local units, a local spatial planning scheme is formed, and then the ecological risk of the schemes in different units is assessed.
- Step 4: The local ecological risk of each unit before and after planning must be compared. If the result is acceptable (without significant LER increase), then the planning scheme of the entire

study area is formed; otherwise, the areas of different land types within each local unit (step 3) or the local spatial planning schemes are adjusted (step 3).

- Step 5: If the planning scheme of the entire study area is formed, then its LER is assessed and compared with the LER before planning. If the comparison result is acceptable, then the final spatial planning schemes at the local and global levels are formed; otherwise, step 2 or 3 is adjusted until the comparison result of LER is acceptable.

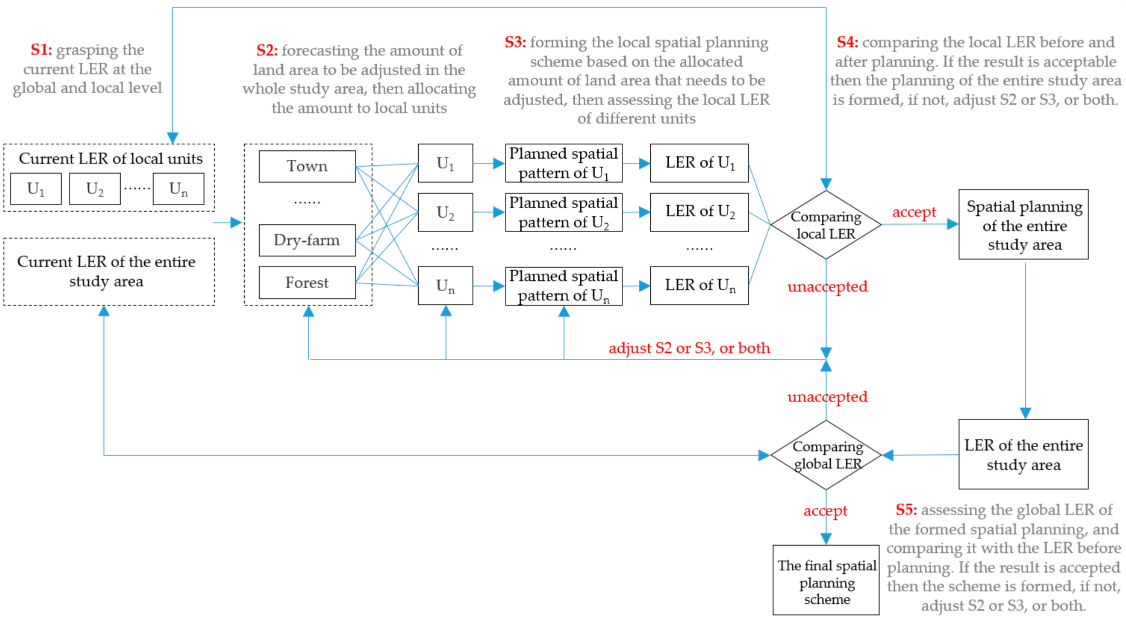


Figure 10. A roadmap for balancing global and local LER during the spatial planning process.

4.3. Limitations and Future Studies

This study has some limitations, and several improvements could be made. First, compared with previous studies, the research period of this study is relatively short, covering merely three years. Thus, the change of ecological risks at the global level is not that significant, although detailed information about land-use transfer has supported the analysis of the ecological risk change at the local level. Second, the proposed method (high-resolution data) has a dependency on data sources; currently, high-resolution data are not free of charge, and may thus cause an extra burden for researchers, as well as hinder the further application of this method. Therefore, further studies must focus on the quantitative relation between the acreage of the study area and required data resolution, which may help researchers accurately choose appropriate data to achieve their research objectives. Third, some weight assignments of the ERI calculation are based on previous studies and mainly rely on specialists' expertise, which is subjective and arbitrary. Therefore, objective weight assignment approaches, such as the principal component analysis and gray relation analysis, are expected in the ERA. Lastly, given that the ecosystem is a complex system, the landscape ecological risk described by the change of landscape patterns merely reflects the probability of ecological problems occurring from only one angle. Although landscape pattern metrics are widely used in landscape ecology research, their specific links to ecological processes, physical geographic processes, and anthropogenic interaction processes remain vague. The connection and integration between landscape patterns and ecological processes therefore become the focus of further studies. Specifically, some ecological indicators, such as wildlife population size, population growth rate, and area of soil erosion, can be associated with landscape patterns, and the relationship between specific ecological states (e.g., biodiversity and soil nutrients) and landscape patterns can be explored.

5. Conclusions

The major findings of this study can be summarized in three aspects. (1) LULC change: In 2011–2013, there were nearly 866 ha of land-use changes in Xiapu County, and construction lands, which were mainly concentrated in Songgang Street and Xinan Town, mostly increased (340 ha). In addition, the LULC change could also reveal the efforts of the local government to balance the overall ecological risk and the readjustment of industrial structure (the share of the primary industry was decreasing). (2) LER change: At the global level, the LER was kept roughly the same, and the areas of high ecological risk were mainly concentrated along coastal areas, such as the northern and southern coasts of the towns of Changchun, Xiahu, and Beibi. At the local level, some units with increasing LER sporadically existed in the coastal areas, whereas some neighboring units in Songgang Street had a remarkable increase in LER. (3) Spatial autocorrelation: The spatial distribution of LER maintained a relatively aggregated pattern, with no trend toward more aggregated or more dispersed change in 2011–2013. In 2011 and 2013, the HH spatial clusters were mostly located in the land part of the coastal areas where the LER is usually high, whereas most of the LL spatial clusters were mainly concentrated in the offshore areas and presented relatively low ecological risks. The relationship between local LER and LULC change was discussed, and a roadmap to balancing the global and local LER in planning practices was proposed.

This study contributes to an improved understanding of the spatiotemporal dynamic of ecological risk in a small research area by adopting high-resolution land-use data, and thus provides policy insights for sustainable regional land-use and ecosystem management. Moreover, given that the spatial planning system of China consists of five scales from national to town levels, this study is expected to fill the research gap, that is, LERA was seldom conducted on a county scale. The methods applied in this study are mainly based on previous studies, of which some parts (e.g., the evaluation units and the ecological vulnerability weighting) were modified. Such improvements help make the results of LERA more reliable and accurate.

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