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Assessing the landscape ecological risk of road construction: The case of the Phnom Penh-Sihanoukville Expressway in Cambodia

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A R T I C L E I N F O

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A B S T R A C T

Extensive development of expressway infrastructure alters the layout of terrain resulting and results in major ecological concerns. Therefore, it has become necessary to investigate how to assess the effects of land use changes on the landscape pattern and explore pertinent environmental concerns related to road construction. This study develops a numerical mothed to assess the ecological risk of road construction in terms of landscape pattern by combining the landscape disturbance index and the vulnerability index. The model is used to assess the landscape ecological risk of a particular portion of the Phnom Penh-Sihanoukville Expressway in Cambodia. The empirical study found that the rise in the amount of construction land was transferred from the area of grassland to cultivated land. It is identified through calculating the landscape pattern index that the integrity of the landscape decreases due to the expressway construction; ecological landscape tends to be complicated and fragmented; and the gravity center of the land use landscape pattern transitions in the same direction as the expressway construction. The ecological risk was assessed and it was found that the expressway construction led to a transition to poorer ecological quality along the road as a whole, and that areas of high ecological risk and higher ecological risk were gradually concentrated from the two ends to the central area. The study develops the landscape ecological risk assessment model and extends the landscape ecological risk assessment index to the ecological assessment of expressway construction. It can also effectively guide the ecological risk assessment of major international road projects.

1. Introduction

The construction of large roads, such as expressways affects the spatial configuration of different land use types, thereby changing the original structure and function of the ecosystem as well as causing changes in the integrity of the ecosystem along the route (Trombulak and Frissell, 2000). For instance, expressways may destroy topography and the surrounding landscape (Nedbal and Brom, 2018); result in changes in land use structure (Wu et al., 2014); and disrupt the water cycle (Loro et al., 2017). Furthermore, the gradual accumulation of traffic and road runoff after construction of the road also leads to habitat separation as well as potential impacts generated in the medium to long-term (Dong et al., 2007; Liu et al., 2006). In regard to the landscape pattern, the construction of large roads such as expressways can effectively divide the original landscape by creating high-contrast linear edges (Mehdipour et al., 2019). Indeed, accelerated changes in the landscape associated with the extension of expressways often exacerbates habitat fragmentation and degradation (Liu et al., 2014). The extent to which road construction affects the connectivity and ecosystem integrity of the landscape pattern is also determined by the timing of road development and the type of surrounding landscape(Mann et al., 2021). Moreover, the development of expressways increases the accessibility and mobility of human beings, while opening up land for resource extraction and other human activities, thereby increasing human disturbance to ecosystems (Selva et al., 2011).

Landscape pattern is the spatial distribution and combination of

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landscape units (i.e. patches) of different sizes, shapes and properties, and is a manifestation of landscape heterogeneity under the combined action of nature and human activity (Xu et al., 2020). It is closely related to ecosystem function and is an important expression of ecosystem structure and processes (Band et al., 2005). Patches are the basic unit for describing landscape patterns, and landscape indicators are now commonly used to describe the characteristics and spatial configuration of patches, thus reflecting changes in landscape patterns (Wang et al., 2020b). Landscape ecological risk describes the likelihood of and the degree of harm caused by the interaction of landscape patterns and ecological processes at the regional scale, and under the influence of natural or human-induced factors (Lu et al., 2018). Changes in landscape patterns caused by human disturbance significantly affect habitat quality and therefore reflect the magnitude of ecological risk in the landscape (Mann et al., 2021). Currently, research on landscape ecological risk in areas along roads focuses on the following two aspects. The first aspect is the overall impact of ecosystems. This research explores the differences in landscape ecological risk within different road classes and different buffer zones based on the soil erosion index and vulnerability index (Zhang et al., 2010), and has identified the geographic heterogeneity of the association between road networks and landscape ecological risk (Lin et al., 2019). The second aspect is the spatial autocorrelation of ecological risks. This research has assessed the spatial and temporal variation of road networks and topography on landscape structure and landscape ecological risks (Mann et al., 2021), and explored the spatial clustering distribution of ecological risk (Li et al., 2022).

The study of ecological landscapes risk reveals that due to the increase of unreasonable anthropogenic landscapes and the corresponding decrease of natural landscapes (where human activities change the pattern and composition of surface ecosystems) is leading to an imbalance in the ecosystem and a corresponding increase in ecological risk (Liu et al., 2020; Zhao et al., 2017). In addition to the above points, the ecosystem's ability to cope with external disturbances is a major factor. Moreover, the strength of the ecosystem's ability to cope with external disturbances can also lead to changes in ecological risk (Jiang et al., 2021). Indeed, the impact of roads and landscape patterns on each other and on the ecology of the landscape can be significant. Roads and landscape pattern influence and constrain each other. Consequently, studying the regional landscape pattern and dynamic changes as well as assessing the ecological risk of the landscape under the influence of human activities is conducive to determining the impact of roads on the ecological environment. Such an approach is also the basis for ensuring ecological security (Liu et al., 2011; Yang et al., 2020). In this regard, ecological risk assessment is a tool to effectively measure and assess the negative impacts of human activities or natural hazards on the composition, structure and function of regional ecosystems (Depietri, 2020).

In the existing research body on ecological risk assessment, the source-sink approach and landscape index approach are methods for assessing ecological risk in landscapes (Chen et al., 2006). The source-sink approach is mostly suitable for risk assessment where the area has obvious threat factors and does not have the advantage of assessing the integrated nature of landscape risk (Cao et al., 2018). The landscape index method applies to multi-scale objects; requires fewer data to be obtained; and can be used to quickly and effectively determine the ecological effects of regional multi-risk sources by selecting the optimal grain size to divide the risk cells (Liu et al., 2018). In the landscape index approach research, there are three main methods for ecological risk assessment along roads, which are summarized as follows. Firstly, using road kernel density estimation and maximum covariance analysis to study the impact of road networks on landscape ecological risk (Mo et al., 2017). Secondly, using geographically weighted regression (GWR) models, which identify the geographical heterogeneity of the correlation between road networks and landscape ecological risk, and allows exploration of the spatial and temporal dynamics of landscape patterns and landscape ecological risk (Jiang et al., 2021; Mann et al., 2021). Thirdly, assessing the landscape ecological risk based on spatial principal component analysis through constructing a model based on minimum cumulative resistance (Yan et al., 2021). However, there are only a limited selection of methods available for assessing ecological risks to the landscape that are common along expressways, and no general method for assessing ecological risk in road construction according to studies in the extant literature. This research gap has led to the pressing need for assessment of landscape ecological risks along the road construction route with different requirements, which cannot presently, however, effectively and comprehensively measure the ecological changes along the route accurately.

In addition, developing countries are actively promoting the construction of road transportation infrastructure and in this context ecological environment protection along the expressway construction has attracted much attention. But there are few studies on environmental impact assessment for such applications. For example, as the first expressway in Cambodia, the Phnom Penh-Sihanoukville Expressway is a key transportation mega-project in the country. The project connects Phnom Penh, the capital of Cambodia, and Sihanoukville, the country's largest deep-water seaport, across five provinces, with a total length of 187.05 km, via a two-way four lane highway, and with eight toll stations, three service areas, and one parking area. The project will shorten the drive time from Phnom Penh to Sihanoukville to less than 2 h, which facilitates enhanced trade between the two major economic centers in Cambodia. However, so far, few studies have been carried out on the special topography and climatic environment that have focused on international major road engineering projects in Cambodia such as the road construction of the Phnom Penh-Sihanoukville Expressway. Furthermore, there are a lack of studies that have investigated the impact of such major road construction initiatives on the ecological index in the developing world. Therefore, this research problem is how to scientifically assess the landscape ecological risks of international major road engineering projects using a generic methodology.

In summary, the road landscape pattern of highways can be considered as the basis for road ecological risk and ecological risk assessment studies. As landscape ecological risk is influenced by land use or land cover (Ji et al., 2021), the human impact is most pronounced in areas with a high frequency of land use change(Jiang et al., 2021). Therefore, the use of Remote Sensing (RS) and Geographic Information System (GIS) techniques for buffer zones analysis along roads is essential. Such an approach also enables delineation of grids to obtain a comprehensive picture of land use change. Meanwhile, ecological risk assessment focuses on the spatial and temporal heterogeneity of ecological risks within a given region (Leuven and Poudevigne, 2002) and scale dependence (Parent and Volin, 2016). As a result, the landscape pattern index is used to explain and understand landscape functions; and represent landscape ecological risk using the landscape disturbance index; and the impact of the landscape vulnerability index based on landscape pattern levels (Shi et al., 2015). This study aims to take the grid of the area along the road as the assessment unit and constructs a generic numerical model for assessing the ecological risk of the landscape pattern of road construction by analyzing the landscape disturbance index and the vulnerability index. Using the Phnom Penh-Sihanoukville Expressway in Cambodia as a case study, the practicality of the model is tested, and the level of ecological risk caused by the expressway construction is assessed as well as the spatial and temporal variation of its land use ecological risk level is analyzed. The research study innovatively proposes the generic road construction area landscape ecological risk assessment model, which extends the landscape ecological risk assessment indexes used for river and protected area studies to the ecological assessment of expressway construction. The significance of this empirical study is that the ecological risk along the Phnom Penh-Sihanoukville Expressway is assessed from the perspective of landscape pattern, which helps to support the ecology along the Expressway through adopting relevant protection in a targeted manner during the construction phase of the expressway. At the same time, the generic road construction area landscape ecological risk assessment model proposed in this study also provides guidance for the assessment of the landscape ecological risk along similar expressway projects in other regions and countries across the world.

2. Material and methods

2.1. Study area

When completed the Phnom Penh-Sihanoukville Expressway link Sihanoukville, Cambodia's main seaport, to Phnom Penh and serve as an essential access route from Sihanoukville to the whole country. It is a key project involving high-quality cooperation between China and Cambodia under the framework of the Silk Road Economic Belt and the 21st-Century Maritime Silk Road. The entire route adopts Chinese design and quality assurance standards. According to the official website of the Cambodian National Institute of Statistics, at the end of 2013, the project area had a population of 3.93 million people. This accounts for 26.8% of Cambodia's total population and the project plays a critical role in the nation's economic development. The road passes through three provinces and two cities in Cambodia. The region of Cambodia between Phnom Penh and Sihanoukville is economically developed and densely populated areas, and the traffic between the two cities is heavy. However, the existing roads are not of a high grade, and the road conditions make it difficult to meet the needs of production and living materials transportation. This has a resulting significant negative impact on the social and economic development of the area. The study area for this research was chosen for the part of the Phnom Penh-Sihanoukville Expressway close to Phnom Penh. The reason for this is that Phnom Penh is the capital of Cambodia and has a high intensity of engineering construction. The significance of assessing the ecological risk in this area is more significant (as shown in Fig. 1).

2.2. Data collection and processing

Landsat 8 OLI images from the 2018 and 2021 Phase II Geospatial Data Cloud (https://www.gscloud.cn/) were selected for this study and imaged in March 2018 and March 2021 respectively. The RS images were integrated with geometric correction and image alignment in ENVI software. Obtaining the precise extent of the study area from Google Maps (https://www.google.com/maps).

In order to study the impact of land use change on the landscape pattern around a road, the zone of influence along the road should be identified first, which can be achieved through adopting buffer zone analysis. Buffer zone is a method of analysis that extends geographic data information in two dimensions by forming a range of polygonal entities around GIS point, line and surface vector data according to set distance conditions (Zhao et al., 2022). The difference in the range of distances the buffer zone reflects the ecological impact of the road construction on the landscape of the areas on both sides of the road (Nedbal and Brom, 2018). Buffer zone analysis is applied to examine the relationship between distance from the road and changes in landscape indicators (Porter-Bolland et al., 2007). In order to show the impact of the road construction on the landscape pattern, an accurate assessment of the ecological risks was conducted. In this research, a 1 *km* buffer zone was generated on both sides of the Phnom Penh-Sihanoukville Expressway using the buffer function of ArcGIS to study the impact of land use change on the landscape pattern around the Expressway.

In this research, the study area is divided into several grids using a grid GIS analysis and then converted into grid data for subsequent study (Chen et al., 2021). The scale of the grids was defined as 1 km × 1 km square, and each grid was coded, and the number of sampling points (i.e. points that fall within the *i*-th grid with an area of more than 50% of the grid area) was determined with the center of each grid as the valid sampling point (Rangel-Buitrago et al., 2020). The resulting buffer zone of the Phnom Penh-Sihanoukville expressway was divided into 81 grids and with 50 valid sampling points (as shown in Fig. 2).

On this basis, it is also necessary to classify the landscape types along the Phnom Penh-Sihanoukville Expressway. The landscape types of the study area were classified into six categories, namely: Cultivated land, water bodies, woodland, grassland, construction land, and unused land (Li et al., 2022; Ran et al., 2022; Wang et al., 2021). The land use type maps of the study area during 2018–2021 were obtained with the support of ArcGIS software and human–computer interaction (as shown in Fig. 1).

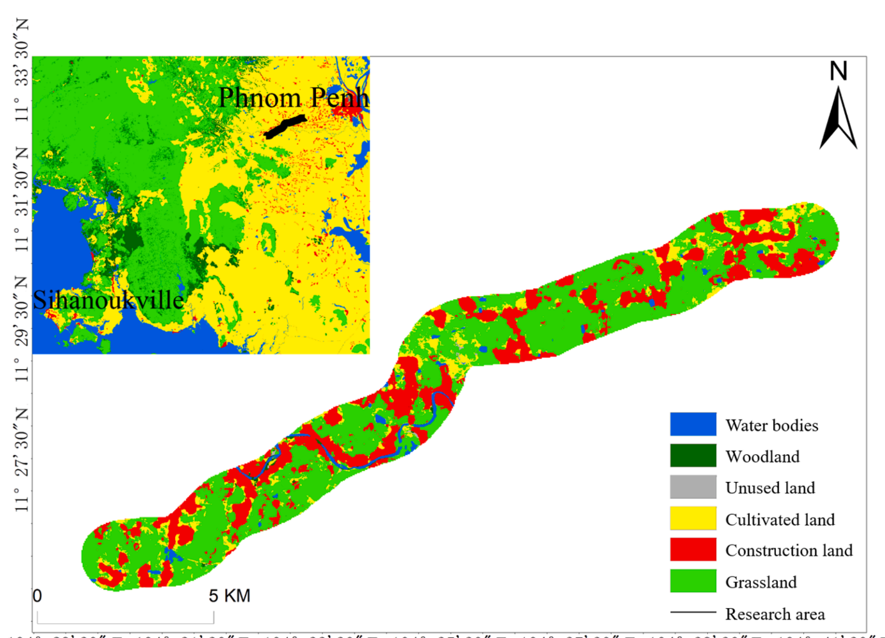

Fig. 1. Location and Land use types map.

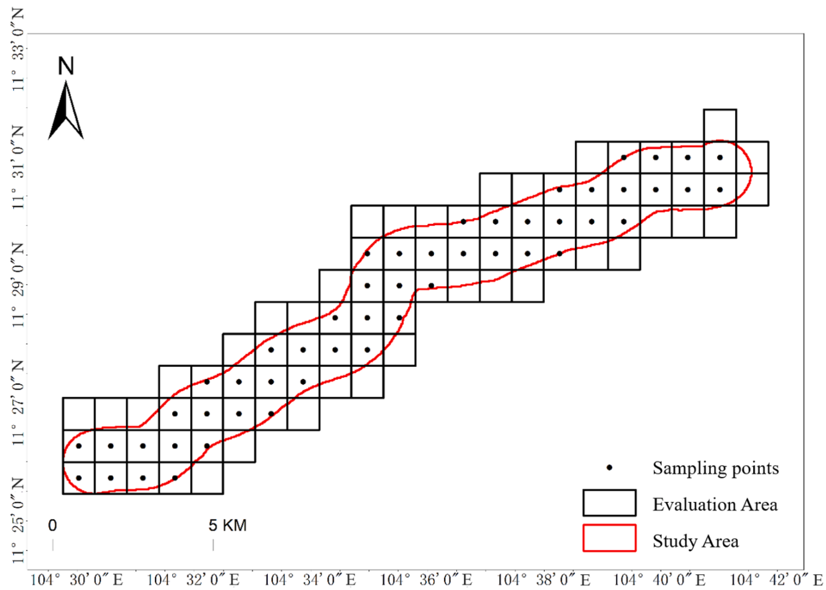

Fig. 2. Study area grid division map.

2.3. Methods

2.3.1. Theoretical model and research framework

Based on the analysis of the research problem and research gap detailed previously, this empirical study proposes the generic road construction area landscape ecological risk assessment model basing on the basic structure and components of landscape pattern and ecological risk assessment (as shown in Fig. 3). The study builds on the current relevant research studies (Ai et al., 2022; Ran et al., 2022; Wang et al., 2021) and follows the idea of constructing a theoretical model (Ovezikoglou et al., 2020), Furthermore, the theoretical underpinning on landscape ecological risk is provided from the perspectives of Land Type Use Data, Buffer and Area Grid Analysis, Landscape Pattern Index Synthesis, Ecological Risk Index Synthesis, Kriging interpolation and Natural break Method, Risk Assessment.

In the assessment of the ecological risk on the road landscape, initially, the buffer zone along the road is set and divided into a grid using RS and GIS technologies to obtain data on the relevant land types along the road and calculate the landscape pattern index and ecological risk index respectively. On this basis, the temporal changes and spatial evolution of the landscape pattern and ecological risk along the road were further analysed. The research framework is shown in Fig. 4.

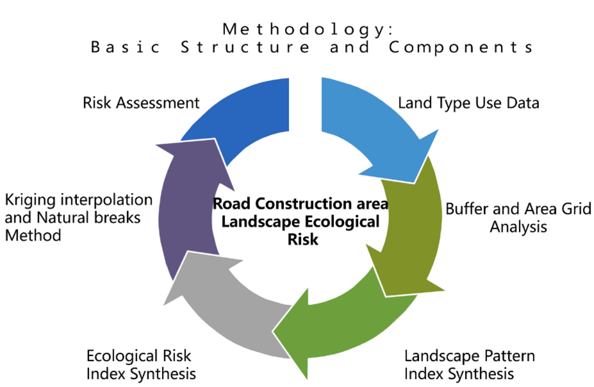

Fig. 3. The generic road construction area landscape ecological risk assessment model.

2.3.2. Landscape pattern index

Landscape pattern index describes landscape patterns; establish links between landscape structures and processes or phenomena; and explains and understands landscape functions (Rangel-Buitrago et al., 2020). In this study, landscape indices, such as the Number of Patches (*NP*), Class Area (*CA*), Percentage of Landscape (*PLAND*), and Shannon Evenness Index (*SHEI*) are selected since this approach reflects the landscape fragmentation degree and connectivity, dominant patches and diversity within the buffer zone, and thereby enables investigation of landscape ecological risk. According to existing studies the formulae for each index is as follows:

$$CA = \sum_{j=1}^{NP} A_{ij}\left(\frac{1}{10000}\right) \tag{1}$$

$$PLAND = P_i = \frac{\sum_{j=1}^{NP} A_{ij}}{A} \tag{2}$$

$$SHEI = \frac{-\sum_{i=1}^{NP}(P_i \times \ln P_i)}{\ln n} \tag{3}$$

PLAND calculates the relative proportion of a patch type to the total area of the entire landscape and is one of the key indicators for determining the dominant landscape. *SHEI* is also known as the landscape evenness index and the higher the value, the more even the patch type is (Song et al., 2016). A_{ij} is the area of the *j* patch of landscape type *i* in the study area. *A* denotes the total area of all landscapes in the formulae for *CA*, *PLAND* and *SHEI*.

2.3.3. Ecological risk index based on landscape patterns

The landscape pattern index is one of the most commonly used quantitative methods in landscape pattern analysis. The index provides a high level of information on the landscape pattern and reflects the quantitative characteristics of its structural composition and spatial configuration (Liang et al., 2018). The landscape disturbance index is depicted as (U_i) and the landscape vulnerability index is (V_i). The relationship between land use type and regional ecological risk was established, and an ecological risk index based on landscape patterns was built. The landscape splitting index (S_i), landscape fragmentation index (F_i), landscape loss index (L_i), landscape dominance index (D_i) and four other landscape ecological pattern index were developed in this study (Liang et al., 2018; Peng et al., 2015).

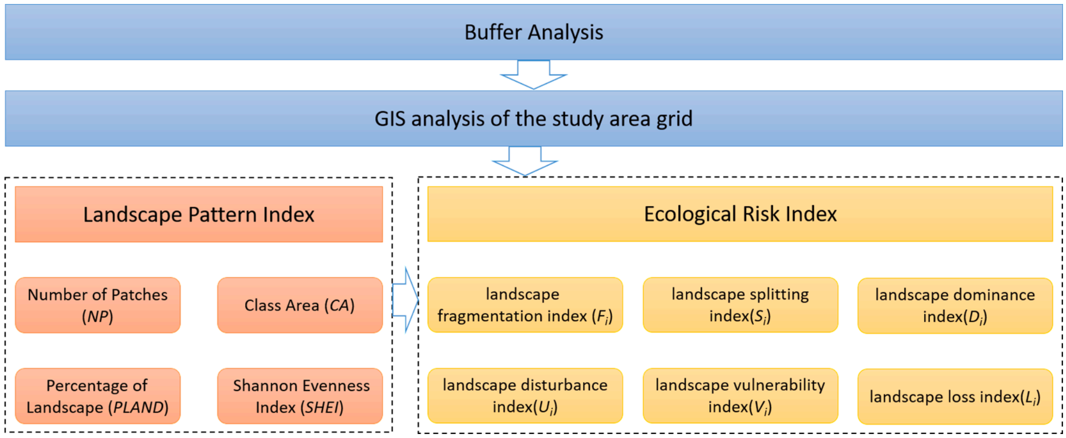

Fig. 4. Framework for ecological risk in road landscapes.

(1) Landscape disturbance index (**U_i**)

$$U_i = a \times F_i + b \times S_i + c \times D_i \tag{4}$$

The U_i index is composed of the F_i, the S_i and the D_i, which reflects the resistance of the landscape pattern to external disturbance (Wang et al., 2020a). Where F_i describes the degree of fragmentation of patches in the landscape type, which can reflect to a certain extent the degree of disturbance to the landscape by human activities, thereby demonstrating the complexity of the spatial structure of the landscape. S_i indicates the degree of separation of the respective distributions of different elements or patches within a landscape type; with larger values implying a more geographically dispersed and complex landscape. D_i describes the degree of dominance of a type in the structure of the landscape, thus reflecting the influence of the landscape type on the formation and change of the landscape pattern. a, b, c indicate the weights of each index, and $a + b + c = 1$; based on the results of existing studies (He et al., 2020; Zhang et al., 2020), the weights of each index are now defined as follows.

$$a = 0.5, b = 0.2, c = 0.3 \tag{5}$$

$$F_i = \frac{NP_i}{A_i} \tag{6}$$

$$S_i = \sqrt{\frac{NP_i}{A}} / \left(\frac{A}{2A_i}\right) \tag{7}$$

$$D_i = 1 - SHEI \tag{8}$$

Where NP_i represents the NP of landscape type i; A_i represents the total area of landscape type i. The *SHEI* less than 1 is inversely proportional to landscape dominance. When it is close to 1, it means that there is no obvious dominant type in the landscape and the patches are evenly distributed in the landscape (Zhou et al., 2016). The abovementioned indices can also be obtained by running Fragstats 4.2 software.

(2) The landscape vulnerability index (**V_i**)

Landscape vulnerability refers to the sensitivity and fragility of different landscapes to external disturbances and is an assessment of the internal capacity of a landscape type to remain stable (Song et al., 2016). The higher the vulnerability, the lower the resistance of the landscape type to disturbance. Concerning the results of existing studies (Di et al., 2013; Hepinstall-Cymerman et al., 2013). The landscape vulnerability of the six land use types was ranked from lowest to highest, and a table of landscape vulnerability values was obtained and normalized (as shown in Table 1).

Table 1
Landscape vulnerability assignment.

Landscape type	Assignment	Normalized
Cultivated land	1	0.44
Water bodies	2	0.56
Wood land	3	0.21
Grass land	4	0.33
Construction land	5	0.10
Unused land	6	0.79

(3) Landscape Ecological Risk Index

Based on the average area of the decoded patches, the study area was divided into a number of valid sampling areas for equally spaced sampling. The ecological risk level of each sampling area is calculated from the Ecological Risk Index (ERI, ERI_k) at the center of the area. *ERI* is constructed based on the proportion of area and landscape loss of different land use types(Wang et al., 2021). The *ERI* reflects the relative magnitude of the combined ecological stress caused by external disturbance and internal vulnerability in a study area; it is able to change the spatial structure of the landscape using sampling. The higher the *ERI* value, the higher the level of risk in the assessment unit. ERI_k is the landscape ecological risk index for the area of the k-th sampling area. The ERI_k is calculated as follows:

$$ERI_k = \sum_{i=1}^{n} \frac{A_{ki}}{A_k} \times L_i \tag{9}$$

where, in the k-th sampling area, the A_{ki} denotes the area of landscape type i-th in the k-th sampling area, and A_k denotes the area of the sampling area, and n-th refers to the total number of landscape types.

$$L_i = U_i \times V_i \tag{10}$$

The L_i is expressed as the product of the U_i and the V_i, and reflects the differences in ecological loss caused by disturbances to different landscape types(Wang et al., 2020a).

3. Results

3.1. Characteristics of changing land use type

The changes in land use types along the road during the construction of the Phnom Penh-Sihanoukville Expressway were compared by processing data from the study area over the period 2018–2021 (as shown in Fig. 5).

The raster data of the study area was transformed using ArcGIS tools into vector surface data. The change in the study area land use types

Fig. 5. Changes in land use types during 2018–2021.

during 2018–2021 was obtained by using the overlay analysis function (as shown in Table 2).

It can be observed that the land use type changes in the study area during 2018–2021 are relatively significant. In 2018, the study area is mainly dominated by grassland, construction land and cultivated land. Grassland covers 58.80% of the study area and is the largest proportion of land use type in the study area. In 2021, the study area is also dominated by grassland, construction land and cultivated land, with construction land accounting for 62.26% of the total study area. During 2018–2021, the area of construction land has the largest increase with 1.65 km^2, followed by grassland with 1.63 km^2. Cultivated land has the largest decrease with 2.84 km and the other land use types has little change over the period.

The land use type area transfer matrix is shown in Table 3. The area transfer matrix for land use types shows that the increase in grassland area during 2018–2021 under road construction is mainly due to a decrease in cultivated land, construction land, and water bodies area. The increase in construction land arises from a decrease in cultivated land, grassland and woodland. Combining the data in Table 2 and Table 3 shows that the study area is dominated by the interconversion of cultivated land, grassland and construction land in the study time domain. The new construction land is mainly derived from the original grassland and cultivated land types in the study area, and to a lesser extent from the unused land and woodland types; thereby suggesting that the expansion of construction land areas has come at the expense of the occupation and reduction of grassland and cultivated land.

Table 2
Surface area and proportion change for land use type of study area during 2018–2021.

Type of land use	2018 Surface area (km^2)	Proportion (%)	2021 Surface area (km^2)	Proportion (%)	Change Surface area (km^2)
Cultivated land	4.50	9.50%	1.66	3.50%	−2.84
Water bodies	1.16	2.45%	0.94	1.98%	−0.22
Woodland	0.17	0.36%	0.03	0.06%	−0.14
Grassland	27.85	58.80%	29.48	62.26%	1.63
Construction land	13.57	28.66%	15.22	32.13%	1.65
Unused land	0.11	0.23%	0.03	0.07%	−0.08
Total	47.35	100.00%	47.35	100.00%	–

3.2. Characteristics of temporal changes in landscape patterns

In this study, the calculation of class and landscape-levels by Fragstats 4.2 software was used to obtain a table of relevant landscape pattern index (as shown in Table 4) and each land use type during 2018–2021 (as shown in Table 5).

From the perspective of the entire study area, the number of *NP* increased by 728 between 2018 and 2021, when the construction of Phnom Penh-Sihanoukville Expressway was construction, indicating a decrease in integrity along the road and more fragmentation in the ecological landscape. The *SHEI* increased from the original 0.4824 to 0.5688, an increase of 17.91%, indicating an increase in the homogeneity of the patch types. The indices S_i, U_i, V_i and L_i also increased, with S_i showing the largest increase of 23.44% and V_i the smallest at 1.76%. F_i and D_i decreased over the study time frame. This suggests that the expressway construction has led to a more dispersed and complex distribution of landscapes along the road, and relatively large differences in ecological loss when different landscape types receive disturbance.

During the period 2018–2021, cultivated land, water bodies, woodland, and unused land maintained growth in the *CA* and *PLAND*; while grassland and construction land maintained a decline, which was consistent with the area of each land use type. Although the overall number of *NP* in the study area has increased, there are differences in the number of *NP* by land use type. Cultivated land, woodland, grassland and unused land have all increased, while the rest of the land use types have decreased in *NP*. Further, cultivated land has increased the most, from 439 to 1012, and water bodies has decreased the most. This indicates that the expressway construction has taken up a large amount of cultivated land and disrupted its connectivity. A further factor are the ecological receptors of water sources in the study area, which can be divided into groundwater systems, riverine ecosystems and lake ecosystems (Zheng et al., 2015). As a result, water bodies are relatively little affected by the road construction. Whereas *SHEI* for each land use type rose in the same way as the *SHEI* for the study area as a whole.

Of the landscape index for each land type, only water bodies and construction land had all six landscape indices decrease, and only F_i had the largest decrease. This indicates that during the period of the expressway construction, both were more disturbed by human activities and the spatial structure of the landscape became more and more

Table 3
Area transfer matrix for land use type of study area during 2018–2021 (km^2).

Year	Type of land use	2021 Cultivated land	Water bodies	Woodland	Grassland	Construction land	Unused land	Total
2018	Cultivated land	0.64	0.06	0.01	2.70	1.09	0.01	4.50
	Water bodies	0.10	0.66	0.01	0.28	0.11	0.00	1.16
	Woodland	0.05	0.01	0.01	0.02	0.06	0.01	0.17
	Grassland	0.73	0.18	0.00	24.01	2.92	0.02	27.85
	Construction land	0.08	0.03	0.00	2.44	11.02	0.00	13.57
	Unused land	0.05	0.00	0.00	0.03	0.03	0.00	0.11
	Total	1.66	0.94	0.03	29.48	15.22	0.03	47.35

Table 4
Statistical table of landscape indices by study area during 2018–2021.

Year	NP (number)	*SHEI*	F_i	S_i	D_i	U_i	V_i	L_i
2018	1609	0.4824	0.2755	69.12	336.88	88.25	43.71	14.46
2021	2337	0.5688	0.2676	85.32	332.71	92.27	44.48	15.52
Change	728	0.0864	−0.0079	16.20	−4.17	4.02	0.77	1.06
Proportion of change	45.25%	17.91%	−2.87%	23.44%	−1.24%	4.56%	1.76%	7.33%

Table 5
Statistical table of landscape indices by type of use land during 2018–2021.

Type of land use	Year	CA (km^2)	PLAND (%)	NP (number)	*SHEI*	F_i	S_i	D_i	U_i	V_i	L_i
Cultivated land	2018	1.6573	3.50	439	0.4824	0.0912	22.0586	71.0524	20.8736	11.2381	3.9759
	2021	4.4958	9.50	1012	0.5688	0.0304	4.5272	72.5261	15.8786	10.8571	3.0245
Water bodies	2018	0.9383	1.98	121	0.4824	0.0635	20.6089	56.7938	17.5732	12.1429	4.1841
	2021	1.1587	2.45	97	0.5688	0.0244	9.0483	48.2062	12.3679	10.2381	2.9447
Woodland	2018	0.0263	0.06	47	0.4824	0.0329	8.7688	12.9895	5.2450	1.0476	0.4995
	2021	0.1697	0.36	103	0.5688	0.0925	33.1892	29.8359	15.9702	2.4762	1.5210
Grassland	2018	29.4806	62.26	463	0.4824	0.0078	0.3272	89.7527	18.0526	11.1429	2.5789
	2021	27.8462	58.80	545	0.5688	0.0041	0.4896	73.3713	14.8232	8.8571	2.1176
Construction land	2018	15.2168	32.13	489	0.4824	0.0252	2.5575	87.4377	18.2674	3.5714	0.8699
	2021	13.5710	28.66	467	0.5688	0.0177	2.3787	71.5428	15.0310	2.9048	0.7158
Unused land	2018	0.0349	0.07	50	0.4824	0.0549	14.7996	18.8577	8.2389	4.5714	2.3540
	2021	0.1110	0.23	113	0.5688	0.0985	35.6897	37.2262	18.2014	9.1429	5.2004

complex. While the landscape index for cultivated land and grassland as a whole continued their downward trend, D_i for cultivated land and S_i for grassland are not consistent with such a trend. This indicates that these two land types are less resistant to external disturbance. Furthermore, as no other expressway construction was taking place during this period, this suggests that the change was mainly influenced by the expressway construction activities. In addition, only for woodland and unused land did all six landscape indices increase, with S_i, L_i and D_i increasing the most in both cases. This indicates that woodland and unused land are more geographically dispersed and complex, and that the ecological losses from road construction are significant. This is due to the expansion of the road construction area, the scope of which continues to encroach on the forest and unused land around the construction road, further reducing the area of green space. It can be observed that Cambodia is a rich country in natural resources, with abundant forestry resources and more than 200 species of timber, and the construction of roads and other related human activities have affected and changed the natural resource landscape of the studied area and posed emergent risks to its ecological environment.

3.3. Spatial evolutionary characteristics of the landscape pattern

Combined with the gravity center migration model in ArcGIS, the standard deviation ellipse change and the gravity center migration map of land use landscape pattern during 2018–2021 were obtained (as shown in Fig. 6), which was linked to the natural conditions of this study area. Not only can we visualize the change for land use type, it is also possible to grasp the dynamic changes of the study area landscape pattern; highlight the influence of road construction on the expansion direction of the landscape pattern in the study area; and observe the development direction of the landscape pattern.

During the period 2018–2021, the gravity center shifts from the north-east to the south-west for all land use types, but to a lesser extent for construction land and water bodies, and to a greater extent for grassland. In addition, the standard deviation ellipse for grassland and cultivated land has decreased significantly, while the standard deviation ellipse for construction land has increased and extended to the south-west. This confirms that the construction of the Phnom Penh-Sihanoukville Expressway reduced the area of cultivated land and grassland landscape types and converted them mainly to construction land. As the study area is connected to the capital of Cambodia, Phnom Penh, in the northeast, and the expressway was constructed from the north-east to the south-west. This leads to a shift in the gravity center of all land use landscape patterns towards the south-west, while the standard deviation ellipse between grassland and cultivated land narrows towards the south-west and the standard deviation ellipse of construction land widens towards the south-west. Therefore, the construction of the Phnom Penh-Sihanoukville Expressway has, to some extent, changed the landscape pattern in the surrounding areas along its route, thereby causing the gravity center of each land use type in the study area to shift.

3.4. Characteristics of temporal changes in ecological risk in the landscape

Based on the landscape pattern index, the *ERI* was calculated for each land use type and the study area as a whole (as shown in Table 6). The

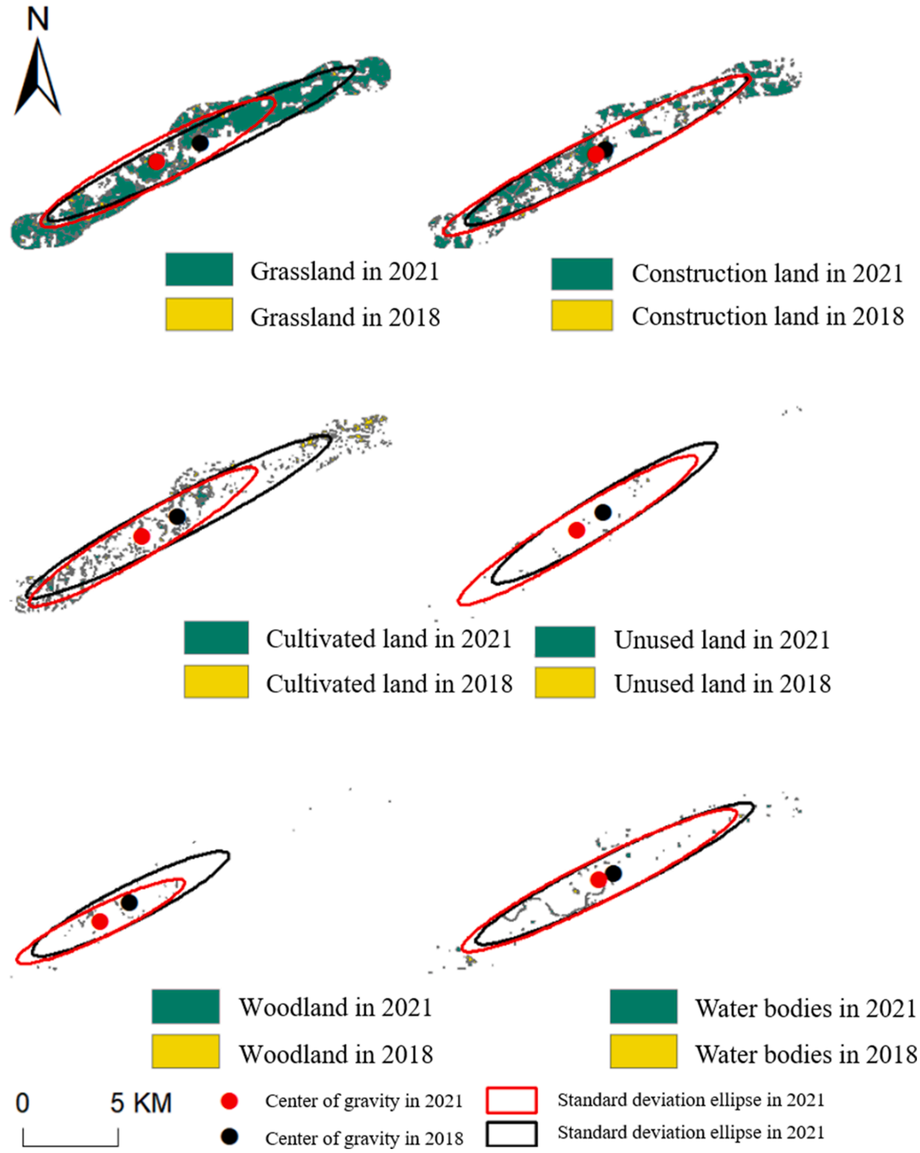

Fig. 6. The standard deviation ellipse change and the gravity center migration of land use landscape pattern during 2018–2021.

Table 6
Landscapeecological risk index (*ERI*) of study area during 2018–2021.

Year	Cultivated land	Water bodies	Woodland	Grassland	Construction land	Unused land	Study area
2018	0.001037	0.000666	0.000011	0.011984	0.00211	0.000042	0.0158
2021	0.003687	0.001063	0.000076	0.015313	0.00369	0.000163	0.0240

average ecological risk value of the study area increased from 0.0158 in 2018 to 0.024 in 2021. Therefore, it can be observed that ecological risk increased for all land use types in the study area, with the largest increase in ecological risk for woodland and the smallest for grassland. While the stability of ecosystem resistance was much higher in woodlands than in grasslands, the stability of ecosystem resilience was much lower in woodlands than in grasslands. Thus, for a Southeast Asian country like Cambodia, where expressway construction takes several years, the impact on the ecological risk of the landscape in woodland is still the greatest of all land use types.

Based on the landscape ecological risk index, the ecological risk indices of the study area in 2018 and 2021 were calculated and interpolated by Kriging, and the Natural break method in ArcGIS was used (Wang et al., 2020a). The study area was divided into five categories, namely: low ecological risk areas ($ERI \leq 0.12$), lower ecological risk areas ($0.12 < ERI \leq 0.15$), medium ecological risk areas ($0.15 < ERI \leq 0.17$), higher ecological risk areas ($0.17 < ERI \leq 0.22$), and high ecological risk areas ($ERI > 0.22$). The higher the ecological risk level, it means that the construction of expressway will cause stronger ecological disturbance and higher ecological risk in the study area. Finally, the study obtained the area and percentage of ecological risk levels of land use during 2018–2021 (as shown in Table 7).

By calculating the changes in ecological risk levels in the study area during 2018—2021, the statistical results that the study area are mainly dominated by medium, high and lower ecological risk areas in 2018, and the three regions account for 78.25% of the study area. The study area was dominated by medium, higher and high ecological risk areas in 2021, with the three areas accounting for 73.35% of the study area. This

Table 7
The area and percentage of ecological risk levels during 2018–2021.

Ecological Risk levels	2018 Surface area (km^2)	Proportion (%)	2021 Surface area (km^2)	Proportion (%)	Change Surface area (km^2)
Low Ecological Risk area	11.98	25.30%	6.94	14.66%	−5.04
Lower Ecological Risk area	2.80	5.91%	5.68	12.00%	2.88
Medium Ecological Risk area	12.79	27.01%	10.84	22.89%	−1.95
Higher Ecological Risk area	7.50	15.84%	9.67	20.42%	2.17
High Ecological Risk area	12.28	25.93%	14.22	30.03%	1.94
Total	47.35	100.00%	47.35	100.00%	–

indicates a transition towards poorer overall ecological quality in the study area. The area of the low ecological risk during 2018–2021 decreased and the area of reduction is nearly 0.5 times that of 2018. The medium ecological risk area in 2021 has also decreased compared to that of 2018, accounting for a lower area. The area of the lower, higher, and high ecological risk area has increased. This indicates that there is clearly a hazard to the ecological environment from road construction during the expressway construction activities during 2018–2021.

The results identify that each ecological risk level in the study area during 2018–2021 can transition to a lower or higher risk level compared to itself, in addition to transitioning to itself. The areas that transition to a lower ecological risk level compared to itself during 2018–2020 is 14.28 km^2 are mainly from high-risk areas and medium-risk areas. The area transition to a higher ecological risk level than itself is 21.75 km^2, mainly from low-risk areas and medium-risk areas. From an overall perspective, the study area as a whole transitioned to a higher ecological risk level compared to the previous situation before construction works commenced (as shown in Table 8).

The road construction in the study area was at the beginning of this period, and the environmental protection laws in Cambodia were not fully mature at this time. Consequently, there is a lack of environmental protection arising from established legal frameworks. The ecological risk level is generally transitioning to a higher level, which indicates that the ecological environment in the study area is poor during 2018–2021. Consequently, the study identified that there is ecological risk in the construction of the Phnom Penh-Sihanoukville Expressway. Moreover, the protection and restoration of the ecological environment is an important and lengthy process that should not only focus on development and construction, but also pay more attention to ecological protection while enhancing the human economy.

3.5. Spatial evolution of ecological risk in the landscape features

The data from the center of each area (as shown in Fig. 2) were interpolated using the Kriging interpolation method and graded using the Natural break method to obtain a map of the change in ecological risk in the study area landscape (as shown in Fig. 7).

During the period 2018–2021, the high and higher ecological risk areas in the study area moved towards the northeast of the study area; and the low and lower ecological risk areas in the southwest of the study area gradually evolved into medium and higher ecological risk areas. The main reason for this is the proximity of the study area to the city in the north-east and the start of the Phnom Penh-Sihanoukville Expressway, which in turn leads to a significant increase in ecological risk. In addition, the medium, higher and high ecological risk areas of the study area show a concentration towards the central part of the study area, and most of the central part of the study area became either high and higher risk areas during 2018–2021. This highlights that the study area is in a period of construction and development with a gradual change from a single land use type to a variety of land uses along with a gradual deterioration in the connectivity of each landscape, thus indicating the emergence of high risk areas in the study area.

For comparison, different buffer zones of 200 m, 500 m, 800 m and 1000 m were plotted the Phnom Penh-Sihanoukville Expressway during 2018–2021 (as shown in Fig. 8), respectively. Consequently, it can be observed that the ecological risk level map shown by the 1000 m buffer zone is more evident than that shown by the 200, 500 and 800 m buffer zones, and the ecological risk areas generated are more concentrated. Therefore, it can be verified that the selection of the 1000 m buffer zone is more appropriate for the study.

4. Discussion

The land use data within the 1000 m buffer zone of some sections of the Phnom Penh-Sihanoukville Expressway was processed and applied to the generic road construction area landscape ecological risk assessment model for validation, and through using the Phnom Penh-Sihanoukville Expressway as a case study. The ecological risk of the landscape in some sections of the Phnom Penh-Sihanoukville Expressway was also assessed based on the model.

Table 8
Land use ecological risk levels area transfer matrix during 2018–2021 (km^2).

Year	Ecological Risk levels	2018 Low Ecological Risk area	Lower Ecological Risk area	Medium Ecological Risk area	Higher Ecological Risk area	High Ecological Risk area	Total
2021	Low Ecological Risk area	1.32	0.32	2.09	0.42	2.79	6.94
	Lower Ecological Risk area	2.76	0.38	1.27	0.45	0.82	5.68
	Medium Ecological Risk area	1.49	0.32	3.94	1.81	3.28	10.84
	Higher Ecological Risk area	3.87	1.11	2.34	1.32	1.03	9.67
	High Ecological Risk area	2.54	0.67	3.15	3.5	4.36	14.22
	Total	11.98	2.80	12.79	7.50	12.28	47.35
Transition to a lower risk level than itself		0	0.32	3.36	2.68	7.92	14.28
Transition to a higher risk level than itself		10.66	2.1	5.49	3.5	0	21.75

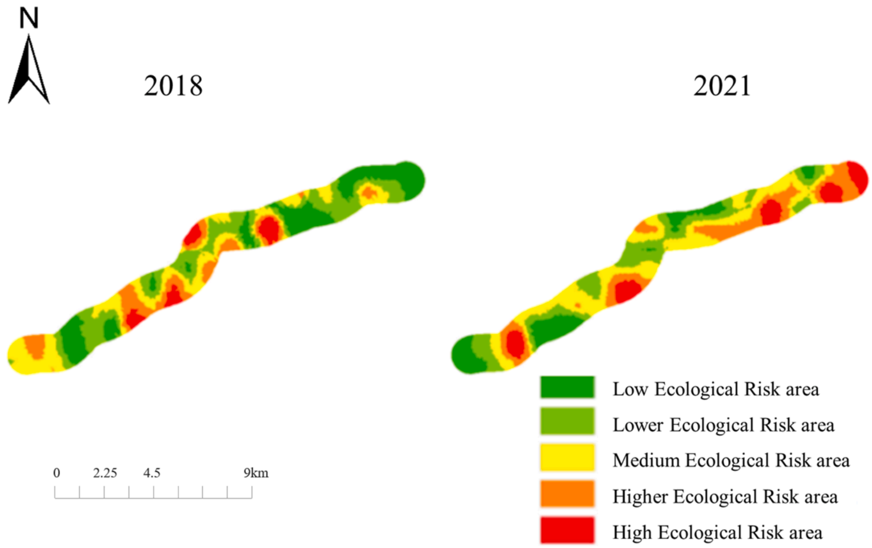

Fig. 7. Changes of landscape ecological risk during 2018–2021.

4.1. Spatial and temporal assessment of the landscape pattern

The formation and change of the landscape is the result of a combination of natural factors and human activity, and this can be viewed according to the interaction of matter and energy between humans and the Earth's environment (Zhang et al., 2019). The various landscape types along the construction of the Phnom Penh-Sihanoukville Expressway are mainly grassland, cultivated land and construction land. During the period 2018–2021, there is a clear trend towards an increase of grassland and construction land, and a decrease of other land types. Furthermore, water bodies and construction land are both more disturbed by human activities; the spatial structure of the landscape is complex; cultivated land and grassland are less resistant to external disturbances; and woodland and unused land are more geographically fragmented. This also indirectly confirms existing research that human activity on smaller time scales is a major driver of landscape dynamics and poses a potential ecological risk to regional landscapes (Zhu and Kasimu, 2020). Overall, the distribution of landscape types in the study area tends to be more complex during 2018–2021, with an increase in landscape diversity and a decrease in the stability of the landscape pattern. However, this result differs from some previous studies, which concluded that roads not only impede ecological processes, but also lead to a decrease in landscape diversity (Hersperger and Forman, 2003).

4.2. Spatial and temporal assessment of ecological risk in the landscape

During the construction of the Phnom Penh-Sihanoukville Expressway, the spatial variation of ecological risks in the study area was evident, with a general trend of decreasing from the central area to the south-west and north-east, and with high and higher ecological risk areas gradually concentrating towards the central area. As landscape separation increases and fragmentation intensifies, this will affect the flow of ecosystem materials, energy and information; ultimately causing changes in ecosystem service functions and triggering higher ecological risks (Duarte et al., 2018). During 2018–2021, the mean ecological risk value increases from 0.0158 to 0.024, and the transition between ecological risk levels is complex, and with the overall risk level showing a slight upward trend. Moreover, the cultivated land and grassland distributed in the study area are weakly resistant to anthropogenic disturbance and contribute significantly to the ecological risk values of the landscape. The reduction in their area due to human activities and their greater fragmentation and separation are the main reasons for the increase in ecological risk values. This is consistent with existing studies that show that the increased vulnerability and fragmentation of woodland, grassland and cultivated land have led to a decrease in the low ecological risk areas and an increase in the high ecological risk areas (Gong et al., 2015; Hosseini Vardei et al., 2014).

4.3. Ecological risk prevention based on landscape patterns

As road intensity increases, not only do they alter ecosystem function through the landscape scale, but roads and accompanying traffic, noise and accumulation of pollutants on both sides of the road may further cause an ecological separation effect of the road. This has the effect of blocking the migration and gene flow of species with weak dispersal capabilities, such as herbaceous plants and amphibian reptiles (Trombulak and Frissell, 2000). The study area has been designed to be an ecologically sensitive area. Therefore, combining the analysis of the ecological risk of the landscape in the study area, the following recommendations are made for the land use of the area around the construction of the Phnom Penh-Sihanoukville Expressway. Firstly, for the medium and high ecological risk areas, special attention should be paid to the impact of the increase in construction land on the ecological risk of the areas along the road, and a buffer zone should be reasonably planned and implemented. This can be achieved through elevated woodlands and underpass culverts across the expressway, while achieving three-dimensional communication of habitat connectivity, continuity of ecological processes and ecosystem integrity on both sides of the road (Jones et al., 2013). Secondly, for areas with low ecological risk values, road runoff can be purified through plant absorption, substrate adsorption and microbial degradation in artificial wetlands (Zhou et al., 2019). At the same time, the intensity of development should be controlled and the size of the buffer zone expanded, so that ecological construction and economic construction proceed in parallel to realizing the goals of sustainable development. Thirdly, the construction of expressways often leads to a rapid increase in the ecological risk level in locations close to cities or the start and end of expressways, and targeted ecological protection measures should be adopted for similar locations.

5. Conclusions

This empirical research conducts an ecological risk assessment based on the landscape pattern and proposes the generic road construction area landscape ecological risk assessment model. Using part of the study

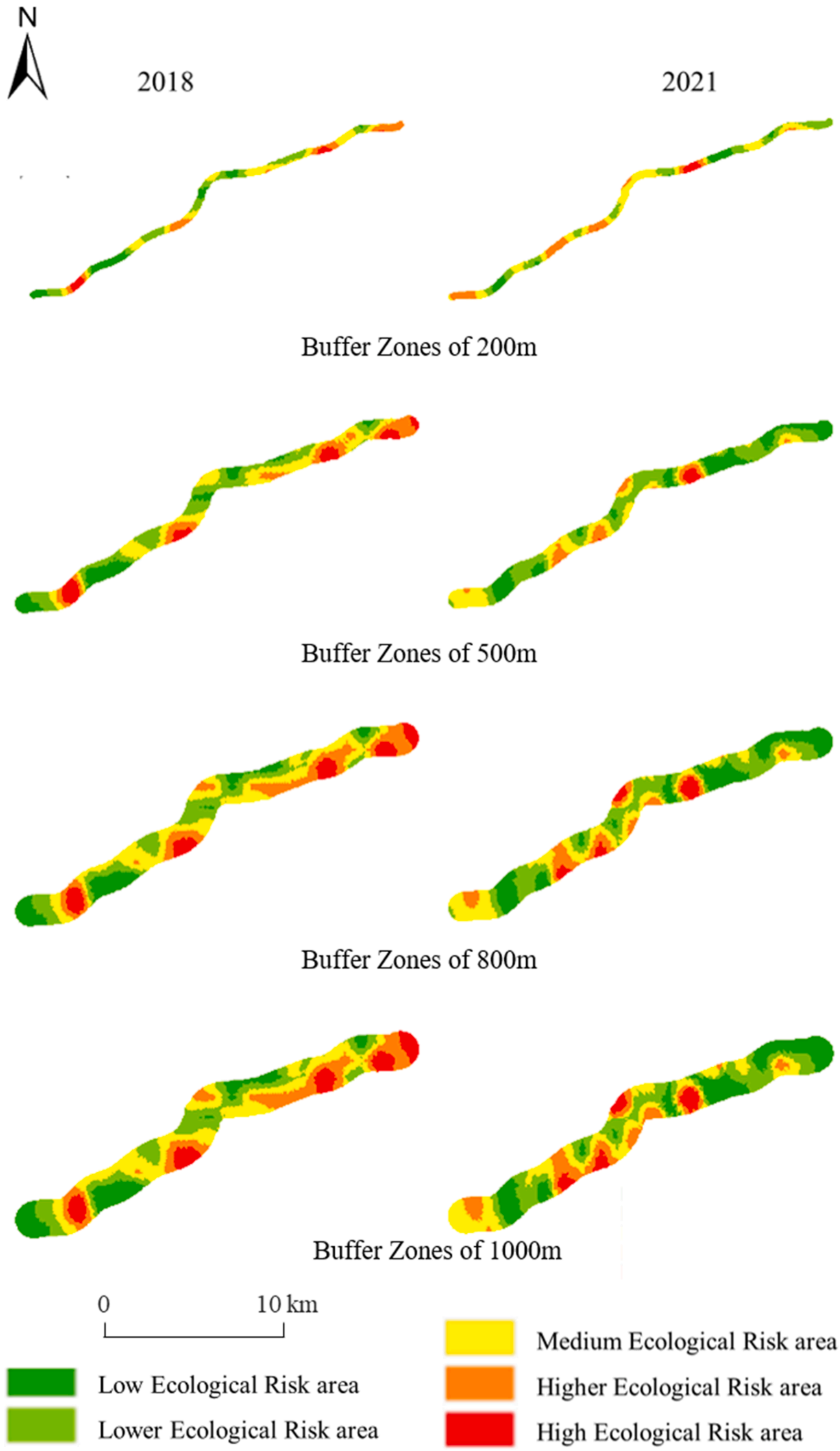

Fig. 8. Ecological risk values for each buffer zone during 2018–2021.

section of the Phnom Penh-Sihanoukville Expressway as the study area and the grid of the study area as the assessment unit to calculate the landscape pattern index and ecological risk index. The study assesses the ecological risk level caused by the construction of the Phnom Penh-Sihanoukville Expressway; analyses the spatial and temporal change characteristics of the ecological risk level of land use; and undertakes a quantitative assessment of the ecological risk of the landscape along the Phnom Penh-Sihanoukville Expressway. The study has a certain reference value for ecological environmental protection in the areas along the Phnom Penh-Sihanoukville Expressway. The research findings of this study are as follows:

(1) The expansion of the area of construction land has come at the expense of the occupation and reduction of grassland and

cultivated land. Only the area of grassland and construction land has increased in the study area, with the increase coming mainly from the reduction of cultivated land, grassland and woodland. The study area is dominated by the interconversion of cultivated, grassland and construction land during 2018–2021, as the proportion of woodland is relatively small.

(2) The expressway construction has led to a decline in the integrity of the landscape along the route and a more fragmented ecological landscape. Among them, water bodies and construction land are more disturbed by human activities, and the spatial structure of the landscape tends to be more complex; the resistance of cultivated land and grassland to external disturbance is less; and the ecological loss of woodland and unused land during the expressway construction is great. Therefore, the expressway construction makes the landscape distribution along the route more dispersed and complex, and the difference in ecological loss is relatively large when different landscape types receive disturbance.

(3) In terms of the evolution of the land use landscape pattern, the direction of the standard deviation ellipse changes and the gravity center migration consistent with the direction of expressway construction. The northeast direction of the study area is Phnom Penh, which is also the starting point of the whole expressway, and the construction direction is from northeast to southwest, and the gravity center of all land use types transitioned from the northeast to the southwest. In addition, the standard deviation ellipse of land use types remains consistent with the area change, and it is also possible to conclude that the expansion of the construction land area comes at the expense of the occupation and reduction of grassland and cultivated land.

(4) The expressway construction results in a transition to poorer overall ecological quality in the study area. In 2018 the study area is dominated by medium, high and low ecological risk areas. In 2021 the study area is dominated by medium, higher and high ecological risk areas. This indicates that the study area as a whole transitions to a higher ecological risk rating compared to the previous condition of the area.

(5) The expressway construction has led to gradual areas concentration of high ecological risk and higher areas towards the central area. The spatial variation of ecological risks in the study area is obvious, with a general trend of decreasing from the central area to the southwest and northeast. At the same time, close to the city or the start and end of the expressway, the ecological risk level grows and changes more rapidly, requiring targeted protection measures.

This study has some limitations, mainly stemming from the data processing step. The data used for the calculation of the indicators is obtained through image processing in the data cloud, however, the indicators required in the model are sensitive to particle size and extent (McGarigal and Marks, 1995). The clarity of the images can have a significant impact on the final ecological risk assessment. In addition, data based on data cloud images are calculated in a two-dimensional plane in terms of area and distance, which is a simplified way of processing (Hoechstetter et al., 2008). The topography can also have a significant impact on the landscape pattern. Further research studies are recommended to address these limitations. However, as a concluding comment, it should be noted that a road construction project represents a significant investment and should be assessed not only in economic terms, but also in environmental and societal dimensions (Ovezikoglou et al., 2020). Finally, ecological risk and landscape empirical studies are important aspects towards the holistic sustainability assessment of road construction projects.

CRediT authorship contribution statement

Jingxiao Zhang: Conceptualization, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Ruizhi Hu:** Conceptualization, Supervision, Methodology, Writing – original draft, Writing – review & editing. **Xiaolai Cheng:** Data curation, Funding acquisition, Validation, Writing – review & editing. **Vlachokostas Christos:** Conceptualization, Methodology. **Simon P. Philbin:** Conceptualization, Methodology. **Rui Zhao:** Project administration, Resources. **Xiwen Zhao:** Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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