



# The Eco-Environmental Changes in Typical Coastal Zones of Southern China From 1987 to 2020: A Case Study of Guangdong Coastal Counties

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Population growth, socioeconomic development, and rapid urbanization have exacerbated the deterioration of coastal ecosystems, particularly in the coastal region of southern China, which has experienced significant urbanization. A precise and timely insight into the ecological changes is indicative of economic and environmental harmonization in southern coast of China and other regions of the world. This study applied 731 Landsat images to assess quantitatively the spatial and temporal evolution of ecological environment quality in the coastal zone of South China during 1987–2020 based on the remote sensing ecological index (RSEI). The results show that 1) the correlation between the RSEI calculated using Landsat data and the parameters is more than 75%, and the results were significant when applied to assess the ecological environment of the coastal zone in South China. 2) The ecological quality of the coastal zone in South China as a whole showed a slight initial degradation during 1987–2020, followed by a gradual improvement trend and then a slight degradation; the area with good ecological quality decreased from 38.96 to 7.97%, and then gradually recovered to 56.61% in 2010. Subsequently, the regions with good ecological quality showed a significant decline, reducing to 1.72%, and then increasing to 38.46% until 2020. In addition, regional differences persisting during the study period are caused by the impact of human activities on the land use types of different landscapes. 3) Good and moderate ecological quality classes occupy most of the coastal zones in South China, but the pressure on the coastal zone is still not optimistic due to the sensitivity of the coastal zone and the accelerated urbanization in South China. As a large-scale, long time series of coastal zone ecological monitoring, this study can provide support for planning, ecological monitoring, environmental protection policy formulation, and integrated regional management of coastal zones and similar areas in South China.

**Keywords:** ecological quality, coastal zone of South China, RSEI, spatial and temporal, Landsat

## INTRODUCTION

Coastal zones are the transitional areas between land and water, where the inherent vulnerability of the zone, coupled with the interactions between land, ocean, and human activities, predominantly makes these areas most vulnerable to environmental change (Melet et al., 2020). The rich resources and the concentration of the global population drive the ecological and environmental changes in the coastal zones that are closely related to the survival and development of human beings (Piracha 2015; Kummur et al., 2016; Wang et al., 2021). Rapid urban expansion and population growth in coastal zones have placed enormous pressure on natural ecosystems, resulting in severe environmental degradation such as the heat island effect (Kuang et al., 2015), biodiversity loss (Lin and Yu 2018), desertification (Salvati 2014), and even insignificant anthropogenic disturbances such as agricultural activities, which may lead to severe ecological degradation (Tian et al., 2016) and associated economic decline, which have become increasingly prominent and serious threats to the survival and development of the coastal communities (L. Xu et al., 2021).

Ecological environmental quality is defined as the degree of suitability for human survival and socioeconomic development in a certain spatial and temporal context. Ecological protection and restoration work needs to be based on quantitative ecological monitoring results to give targeted and scientific implementation plans so that ecological restoration and protection work can be truly effective. Therefore, ecological monitoring and assessment has attracted extensive research attention from scholars (Ye and Liu 2000; Hansen et al., 2013; Petrie et al., 2015). Studies conducted on evaluation approaches show that researchers have produced some commonalities. For example, some scholars have evaluated changes in ecosystem quality based on land use and land cover changes (LUCC) (Lambin and Meyfroidt 2011; Locher-Krause et al., 2017). LUCC are considered to be a reflection of the quality of the ecological environment at a certain temporal and spatial scale under human influence. Others have focused on the application of landscape models to analyze and assess the ecological environment quality, and a large number of researchers have also chosen modeling methods to evaluate the ecological simulation, such as the ecological index (EI) and sampling. However, these methods, which use more statistics for ecological evaluation, are subject to human influence, and it is difficult to assess a district with sufficient accuracy by only vague assessment (Chase and Knight 2013; Zhong et al., 2020).

In addition to ecological monitoring methods, this study also discusses the disparities in ecological monitoring methods for different land covers. For example, net primary productivity (NPP), normalized difference vegetation index (NDVI), fractional vegetation cover (FVC), and leaf area index (LAI) are mostly used to describe the ecological condition of vegetation in an area. A large number of studies have used urban green space, urban heat islands, and rates of urban sprawl to assess the ecological condition of urban habitats (Xu et al., 2016; Jin et al., 2019; Liang et al., 2019; Aram et al., 2019). The ecological quality of agricultural land is evaluated by monitoring of heavy metals and soil erosion (Weihong et al.,

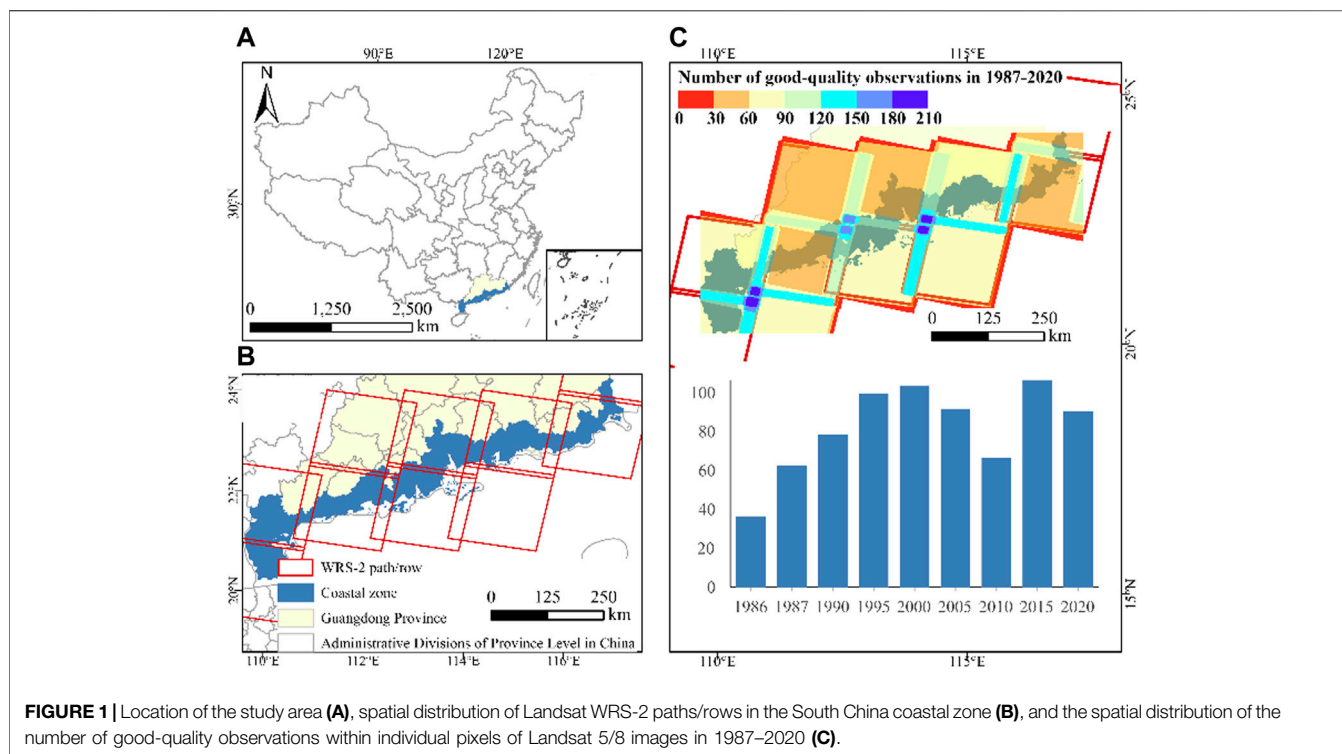
2017; Tong et al., 2021). Similarly, a large number of studies have applied remote sensing images or water transparency monitoring devices to assess the ecological environment of water (Chang et al., 2009; Houlei et al., 2018). However, it is difficult for any one of them to achieve an accurate and comprehensive assessment of land cover on a large scale. In contrast, RSEI reduces the impact of multiple types of land cover in large scale ecological assessments. In recent years, many studies have applied the RSEI to assess the ecological indicators of land cover and demonstrated the usefulness and credibility of the index. For example, ecological assessments in various regions in China such as the part of the Yellow River Basin in Inner Mongolia, the middle reaches of the Yangtze River region, Tibet, and Xiongan, have yielded objective and accurate results (Xu H. et al., 2018; Gao et al., 2021; Huang et al., 2021; Yang et al., 2021). However, current research mainly focuses on inland area, watersheds, and less on coastal zones (Li et al., 2016). Most coastal studies focus on shoreline change detection (Bouchahma and Yan 2014; Liu et al., 2017), only Zheng's research has applied MODIS data combined with comprehensive nighttime light index (CNLI) to conduct ecological assessments of the national coastal zone and reached an accurate conclusion (Zheng et al., 2020). However, the low spatial resolution of MODIS data compared to 30 m Landsat imagery prevented observation of many fine-grained processes to the ecological changes and cannot adequately reflect the actual local ecological differences or provide a targeted study of South China's rapidly growing economic coastal zone (Kennedy et al., 2014).

In this regard, China has been experiencing rapid economic development over the past 40 years, especially in the southern coastal belt, where the fragility of the ecological environment in tropical and subtropical areas has inevitably led to the degradation and loss of surrounding natural habitats, including ecological zones such as forests, peat swamps, planted forests, and wetlands (Lin and Yu 2018), as well as long-term international and national interests in the coastal zone. Therefore, this study employs the RSEI to describe in detail the ecological evolution of the land portion of South China's coastal counties during 1987–2020, to gain experience from the past ecological evolution of the coastal zone in South China, and to lay the foundation for the future development of the coastal zone as well as the ecological planning and management of coastal zones in other regions.

## MATERIALS AND METHODS

### Study Area

The South China coastal zone is located (20°08'–24°14'N, 109°24'–117°31'E) in the coastal region of southern China, with a land area of about  $4.93 \times 10^4 \text{ km}^2$  (Figure 1A). The entire South China coastal zone has a humid subtropical climate, with an average annual temperature of 22°C, and a rainy season mainly from April to September. Typical vegetation types are subtropical evergreen broad-leaved forest and conifer-broadleaved mixed forest. Since 1978, with the development of the socioeconomic and tourism industries, there has been a



**FIGURE 1** | Location of the study area (A), spatial distribution of Landsat WRS-2 paths/rows in the South China coastal zone (B), and the spatial distribution of the number of good-quality observations within individual pixels of Landsat 5/8 images in 1987–2020 (C).

general increase in the exploitation of land resources, most notably in the coastal areas of Guangdong Province, and it is widely believed that the rapid expansion of the impervious surface has seriously affected the ecological patterns and processes of the coastal zone (Zhai et al., 2020). In addition, as the economic development of China's coastal zone is constrained by administrative divisions, the nearest county-level administrative districts along the Guangdong coast are selected as the study area in this study (Brenner et al., 2006; Zhi-bing and Zhang, 2021).

## Materials

In this study, the surface reflectance of Landsat was collected from the USGS. The Landsat imageries of South China coastal zone is covered by five Worldwide Reference System (WRS-2) paths/rows (123/44, 123/45, 121/44, 121/45, 124/45, 124/46, 122/44, 122/45, 120/43, 120/44). From 1986 to 2020, there were 731 Landsat images available for the study area, 535 of which were Landsat-5 images for 1986, 1987, 1990, 1995, 2000, 2005, and 2010, and 196 were Landsat-8 images for 2015 and 2020 (Figure 1C). The area covered by good observations and the year distribution are shown in Figure 1C to generate a coastal zone dataset for the period 1987–2020. In particular, it is noted that the 1987 remote sensing image data cannot provide complete coverage of the study area, and the uncovered portion consists of high-quality Landsat observation data from 1986. In addition, the quality assessment (QA) band flags poor observations (e.g., clouds and cloud shadows) for each image and uses the QA band to remove poor observations. In addition, the DEM, the solar azimuth, and zenith angle of each image are used to identify

and remove topographic shadows (Farr et al., 2007; Zou et al., 2018).

## Human and Natural Data

Anthropogenic and natural factors have a profound impact on changes in ecological quality, and based on scholarly research (Ward et al., 2016; Xie et al., 2017; Ma et al., 2018; Zheng et al., 2020), eight factors have been selected for this study (Table 1) to detect its impact on the changes in ecological and environmental quality in the coastal zone of South China during 1987–2020.

Geodetector was used to assess the impact of driving factors. Since Geodetector can only handle categorical variables, this study therefore used the method of natural breaks (Jenks) discrete and categorized the elevation, slope, aspect, precipitation, and night light remote sensing data into six types of stratification based on the intrinsic properties of the data and previous research (Shi et al., 2019; Sun et al., 2020; Zhu et al., 2020).

## Methods

### Construction of RSEI

The rapid changes in land cover in the study area are manifested in the transition from ecological land to construction land, especially vegetation to construction land; on the other hand, the current state of the environment, the quality and quantity of resources, and their change over time are accompanied by rapid changes in the regional climate, a process that can be felt between heat and wetness as well as dryness. The RSEI is a description of ecological quality by integrating four parameters (greenness, dryness, wetness, and heat) and the principal component

**TABLE 1 |** Driving factors of eco-environment change.

Factor type	Code	Index	References
Natural factors	X1	Elevation	JPLNASA (2013)
	X2	Slope	Calculated from elevation
	X3	Aspect	Calculated from elevation
	X4	Landforms	Jijun (2009)
	X5	Annual mean precipitation	Peng et al. (2019)
Socioeconomic factors	X6	Land use type	Xu et al. (2018b)
	X7	Population	Guangdong Statistical Yearbook
	X8	Nighttime light index	Zhang et al. (2021a)

analysis (PCA) (H. Xu 2013). These parameters are based entirely on remote sensing technology; indicators are easily available, without human involvement, and the results can be visualized, and it can quickly and objectively evaluate the quality of the regional ecological environment. At the same time, the application of the PCA can bring together the main information of the four indicators to achieve a quantitative evaluation of the regional ecological environment. Therefore, it is considered that RSEI can efficiently complete the ecological environmental assessment of the coastal zone. In addition, the first band of PCA has the most information of the four parameters, so we choose the first band as the RSEI for evaluation, which is calculated using the following equation:

$$RSEI_0 = 1 - PC1[f(NDVI, Wet, LST, NDBSI)]. \quad (1)$$

The normalized difference vegetation index (NDVI) is the most frequently used vegetation index and is directly related to biomass, leaf area index, and vegetation cover, so NDVI is chosen to represent the greenness (Song et al., 2018).

$$NDVI = (\rho_{nir} - \rho_{red}) + (\rho_{nir} + \rho_{red}). \quad (2)$$

In the regional context, the main causes of surface cover drying are construction land and bare ground, so the dryness index can be calculated using the bare soil index (BI) and the index-based built-up index (IBI) given as follows:

$$SI = \frac{(\rho_{swir1} + \rho_{red}) - (\rho_{nir} + \rho_{blue})}{(\rho_{swir1} + \rho_{red}) + (\rho_{nir} + \rho_{blue})} \text{ and} \quad (3)$$

$$IBI = \frac{2\rho_{swir1}/(\rho_{swir1} + \rho_{nir}) - [\rho_{nir}/(\rho_{nir} + \rho_{red}) + \rho_{green}/(\rho_{green} + \rho_{swir1})]}{2\rho_{swir1}/(\rho_{swir1} + \rho_{nir}) + [\rho_{nir}/(\rho_{nir} + \rho_{red}) + \rho_{green}/(\rho_{green} + \rho_{swir1})]} \quad (4)$$

$$NDBSI = \frac{SI + IBI}{2}. \quad (5)$$

The brightness, greenness, and wetness components obtained from Kauth–Thomas (K-T) transformation have been widely used in ecological environment monitoring, and their wetness components reflect the wetness of soil and vegetation, which are closely related to the ecological environment. Therefore, the wetness index is represented by the wetness component of K-T transformation. The wetness calculation used in this study is as follows (E. P. Crist 1985; E. Crist and Kauth 1986):

$$WET = \beta_1 B_{blue} + \beta_2 B_{green} + \beta_3 B_{red} + \beta_4 B_{nir} + \beta_5 B_{swir1} + \beta_6 B_{swir2}. \quad (6)$$

Here,  $B_i$  represents the bands of Landsat-5 TM and Landsat-8 OLI/TIRS, and  $\beta_i$  represents the band parameters of Landsat-5 TM and Landsat-8 OLI/TIRS, respectively.

The study uses the surface temperature as the thermal component. Based on the statistical mono-window (SMW) algorithm, the empirical relationship between the apparent brightness of the atmosphere and the surface temperature obtained from the single thermal infrared band is implemented to obtain the surface temperature, and thus, the surface temperature is calculated using the following equation (Kalnay et al., 1996; Duguay-Tetzlaff et al., 2015; Hulley et al., 2015; Ermida et al., 2020):

$$LST = A_i \frac{Tb}{\epsilon} + B_i \frac{1}{\epsilon} + C_i. \quad (7)$$

In this formula,  $Tb$  is the brightness temperature data of the apparent reflectance of the atmosphere (TOA) and  $\epsilon$  is the apparent emissivity of the corresponding waveband. The algorithm coefficients  $A_i$ ,  $B_i$ , and  $C_i$  are determined by linear regression of the radiative transfer simulations for 10 classes of TCWV ( $I = 1, \dots, 10$ ).

In addition, due to the non-uniformity of the magnitudes of the four calculated indices, in this study, the four indices were normalized separately to ensure that they are comparable with each other.

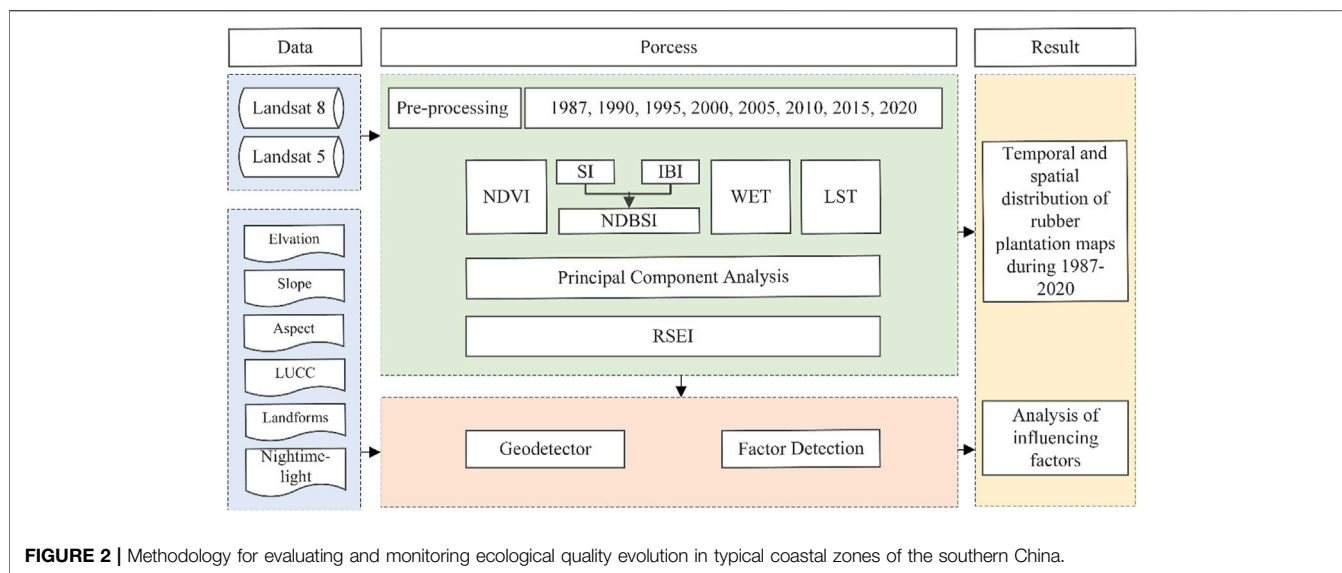
$$NI_i = \frac{(I_i - I_{min})}{(I_{max} - I_{min})}. \quad (8)$$

In this formula,  $NI_i$  is the standardized indicator value,  $I_i$  represents the indicator value, and  $I_{max}$  and  $I_{min}$  are the maximum and minimum values of each indicator, respectively.

To compare the RSEI of different years, the RSEI is normalized to a value between [0,1], with higher values indicating better ecological quality.

$$RSEI = \frac{(RSEI_0 - RSEI_{0\ min})}{(RSEI_{0\ max} - RSEI_{0\ min})}. \quad (9)$$

In this formula,  $RSEI_0$  is the initial value of RSEI;  $RSEI_{0\ max}$  and  $RSEI_{0\ min}$  are the maximum and minimum values of  $RSEI_0$ , respectively; and RSEI is the result of normalization.



**FIGURE 2 |** Methodology for evaluating and monitoring ecological quality evolution in typical coastal zones of the southern China.

### GeoDetector

The GeoDetector is a spatial heterogeneity detection method that is commonly used to quantify the influence of dependent variables. We use Excel GeoDetector software developed by Wang et al. to achieve impact factor detection (J. Wang and Chengdong, 2017). GeoDetector includes factor detectors, risk detectors, ecological detectors, and interactive detectors. Specifically, it detects whether the independent variable  $x$  is an impact factor of variable  $y$  (RSEI) and explains, to some degree, the spatial heterogeneity mechanism of variable  $y$ . The degree of impact can be measured by the value of  $q$ ; the value of  $q$  is calculated by the following formula:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} \quad q \in [0, 1], \tag{10}$$

where  $q$  is an indicator of the explanatory power of ecological influences. The larger the value of  $q$ , the greater the influence of the variable  $x$  on ecological heterogeneity.  $N_h$  is the number of samples in the subregion  $h$ ;  $N$  is the total sample size; and  $\sigma$  and  $\sigma^2$  denote the overall variance and variance of samples in the subregion  $h$ , respectively.

The technical route of ecological environment quality monitoring and impact factor detection of the coast in this study is shown in **Figure 2**, and the aforementioned method is done using Google Earth engine, ENVI 5.3, and ArcGIS 10.2. Furthermore, to avoid water information to influence the PCA, the NDWI was applied to the images of each year for water rejection during data pre-processing.

## RESULTS

### Performance of RSEI

The results of the PCA for each year from 1987 to 2020 show the good adaptability of the RSEI. The percentage of the first

**TABLE 2 |** Principal component analysis of five factors.

Year	PC1	PC2	PC3	PC4
1987	98.58	1.16	0.23	0.03
1990	97.10	2.30	0.52	0.08
1995	97.72	1.76	0.43	0.09
2000	99.22	0.63	0.11	0.04
2005	98.48	0.98	0.46	0.08
2010	99.66	0.23	0.09	0.02
2015	93.03	6.96	0.01	0
2020	75.10	24.58	0.28	0.04

eigenvalue for each year is greater than 75%, which indicates that the characteristics of all variables are mainly integrated in the first feature (**Table 2**), where the largest percentage of eigenvalues is 99.66% for 2010 and the smallest is 75.10% for 2020.

The correlation between RSEI and the four parameters was high for each year from 1987 to 2020 (**Table 3**). The mean absolute values of the RSEI correlation coefficients for each year were 0.652, 0.751, 0.747, 0.867, 0.914, 0.828, 0.822, and 0.904. The correlation between RSEI and each parameter was good, which indicates that compared with individual parameters, the RSEI index is more representative and universal than any single indicator used independently. Hence, it can be used to adequately reflect the quality of the ecological environment in the coastal zone of South China.

### Temporal Evolution of the Quality of the Ecological Environment

To observe changes in ecological quality, spatial analysis and equal interval classification were used to create the RSEI ecological values into five ecological quality classes. To clearly describe the flow, distribution, and changes of ecological quality between time intervals, the form of Sankey diagram was used to describe the transfer of ecological quality from 1987 to 2020



**TABLE 3** | Correlation matrix among RSEI, NDVI, WET, DRY, and LST in 1987–2020.

Year	Factor	NDVI	WET	DRY	LST	RSEI
1987	NDVI	1	0.695	-0.825	-0.35	0.659
	WET	—	1	-0.933	-0.65	0.879
	DRY	—	—	1	0.798	-0.843
	LST	—	—	—	1	-0.227
1990	NDVI	1	0.838	-0.565	-0.4	0.908
	WET	—	1	-0.704	-0.54	0.543
	DRY	—	—	1	0.567	-0.968
	LST	—	—	—	1	-0.586
1995	NDVI	1	0.473	-0.723	0.244	0.888
	WET	—	1	-0.856	-0.68	0.725
	DRY	—	—	1	0.535	-0.89
	LST	—	—	—	1	-0.486
2000	NDVI	1	0.545	-0.856	-0.78	0.972
	WET	—	1	-0.869	-0.68	0.711
	DRY	—	—	1	0.797	-0.949
	LST	—	—	—	1	-0.835
2005	NDVI	1	0.725	-0.963	-0.89	0.995
	WET	—	1	-0.839	-0.69	0.769
	DRY	—	—	1	0.886	-0.982
	LST	—	—	—	1	-0.911
2010	NDVI	1	0.735	-0.874	-0.59	0.993
	WET	—	1	-0.911	-0.58	0.775
	DRY	—	—	1	0.616	-0.903
	LST	—	—	—	1	-0.641
2015	NDVI	1	0.805	-0.937	-0.69	0.831
	WET	—	1	-0.889	-0.66	0.81
	DRY	—	—	1	0.68	-0.83
	LST	—	—	—	1	0.815
2020	NDVI	1	0.684	-0.924	-0.76	0.95
	WET	—	1	-0.839	-0.72	0.812
	DRY	—	—	1	0.807	-0.969
	LST	—	—	—	1	-0.884

(Figure 3). From 1987 to 2020, in general, the distribution of ecological quality classes in the coastal zone of South China was dominated by good, moderate, and fair, with all reaching over 95%, and the major change in ecological classes was mainly the mutual flow between these three classes.

From 1987 to 2010, the area with good ecological quality grade decreased and then increased from 38.96 to 7.97% in 1995, and then gradually rebounded until 2010, when the area with good ecological grade accounted for 56.61% of the entire area. The area with moderate ecological class showed the opposite trend, gradually increased from 53.31 to 71.47%, and then decreased to 31.78% of the total area. Overall, the ecological quality of the coastal zone, dominated by good and moderate, showed a decreasing and then an increasing trend between 1987 and 2010. Similarly, it showed a clear trend of decreasing and then rebounding between 2010 and 2020. The area with good ecological quality accounted for 56.61% of the total area during 2010 and then decreased to 1.72%; the area with moderate ecological quality gradually increased from 31.78 to 77.69% during this period, and then the overall ecological quality rebounded to a certain degree mainly because the area with moderate ecological quality gradually returned to good, and the total area also increased from 1.72 to 38.46%. The overall ecological quality exhibited a gradually improving trend.

## Spatial Evolution of the Quality of the Ecological Environment

To determine whether the spatial distribution of different classes of ecological environmental quality has specific spatial characteristics, based on spatial differences, the study area is divided into three parts: eastern, middle, and western, which can reflect the inter-regional differences more intuitively when combined with the spatial distribution of RSEI. From Figure 4, we can clearly find the RSEI has a significant tendency to aggregate, with low values mainly distributed in Zhanjiang in the west, the middle Zhujiang delta, and the eastern offshore side, and high values are mainly distributed in Jiangmen in the central region, Huidong in the east, Maoming in the west, and a part of Yangjiang.

Analyzing the overall evolution trend of the RSEI from 1987 to 2020, it was found that the spatial heterogeneity of the RSEI in the study area was obvious, and the ecological quality in the western region gradually improved between 1987 and 2010, and then declined until it began to improve again in 2020. The RSEI of the middle region gradually declined from 1987 to 1995, then maintained relatively moderate until 2010, and then the ecological quality of the central region gradually improved to fair. In the eastern part of the study area, there was less variation, especially near the coastline, which has maintained a fair ecological quality during 1987–2020, indicating that the ecological quality in this area is relatively poor and has not improved significantly.

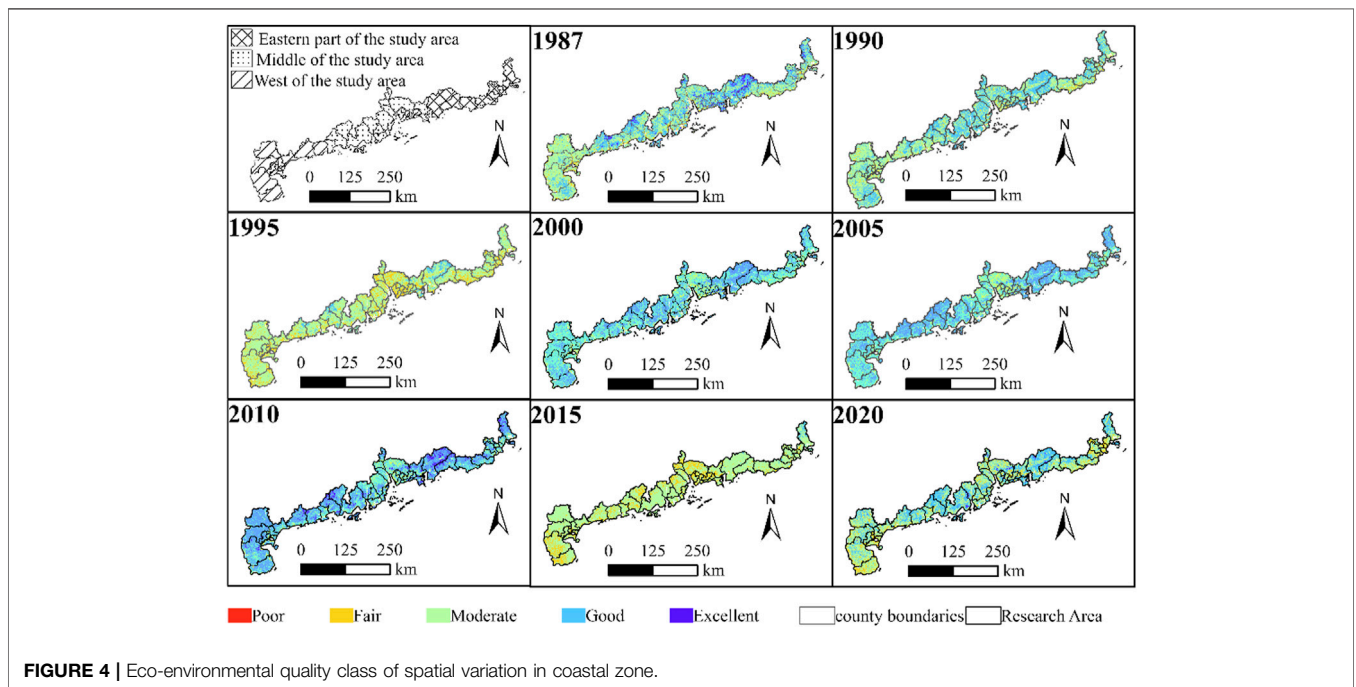
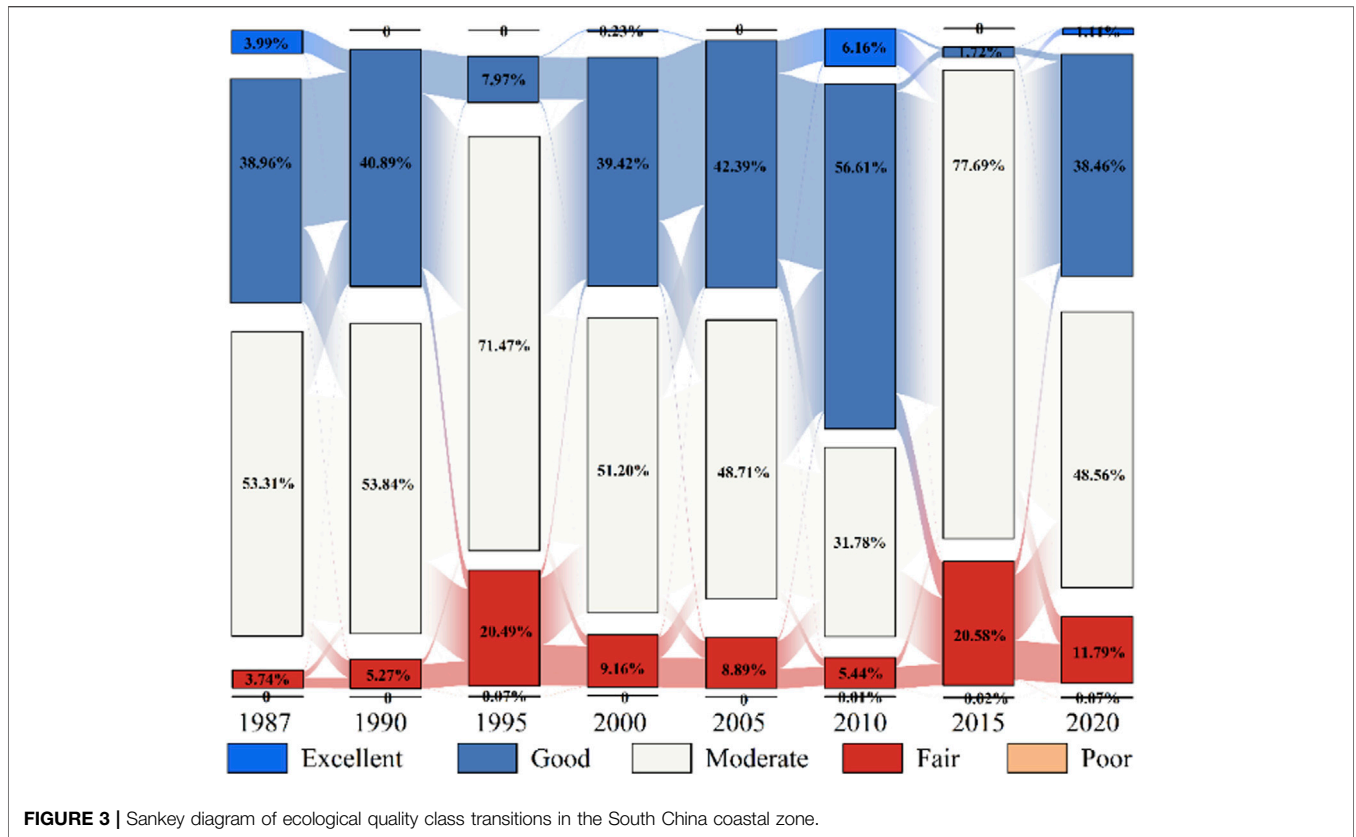
## Driving Factors for the Evolution of Ecological Environment

The impact of different driving factors on the ecological quality varied, and the strength of each factor and the significance level of each factor  $p$  were measured by the GeoDetector (Table 4). Overall, all the  $q$  values of LUCC and landform ranked high for land use intensity in each year, with the largest  $q$  values for LUCC, so LUCC were considered to be the factor with stronger explanatory power for ecological change in the coastal zone of South China. Then, the landform including elevation and slope demonstrates that landform is a significant factor in the variation of ecological change, and the population reached 0.157 only in 2015, with weak explanatory power in the rest of the years. In addition, the overall explanatory power of nighttime light, precipitation, and aspect on ecological quality was weak.

## DISCUSSION

### Possibility and Advantages of RSEI

The ecological environmental quality of the South China's coastal zone during 1987–2020 was obtained from four indexes calculated from an open-source, freely accessible remote sensing dataset, followed by the first principal component of the PCA as the RSEI. The results of PCA show that the contribution rate of the first principal component is more than 75%, and the average contribution rate is 94.86%. RSEI



has a high correlation with each index, which can well represent the overall information of the four indexes of greenness, dryness, wetness, and heat. On the other hand, the RSEI allows us to obtain

the real eco-environmental condition quickly and easily compared with the traditional eco-environmental quality assessment method. In addition, we can also conduct

**TABLE 4 |** Influence of anthropogenic and natural factors on ecological changes between 1987 and 2020.

Year	Natural factors						Socioeconomic factors		
	Factors	Elevation	Slope	Aspect	Landforms	Precipitation	Nighttime light	Population	Land use
1987	q	0.126	0.169	0.001	0.221	0.048	0.003	0.133	0.241
	p value	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00
1990	q	0.057	0.088	0.002	0.169	0.054	0.006	0.084	0.272
	p value	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
1995	q	0.114	0.118	0.002	0.199	0.057	0.046	0.093	0.281
	p value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000	q	0.082	0.130	0.002	0.203	0.064	0.053	0.113	0.306
	p value	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
2005	q	0.074	0.132	0.002	0.207	0.052	0.106	0.153	0.314
	p value	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
2010	q	0.095	0.135	0.002	0.218	0.060	0.091	0.130	0.302
	p value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2015	q	0.053	0.056	0.000	0.088	0.037	0.078	0.157	0.199
	p value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2020	q	0.118	0.216	0.001	0.242	0.073	0.046	0.164	0.289
	p value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: The q values indicate the explanatory power of each factor on ecological quality, within [0, 1]. p is the significance of the corresponding factor, if p is less than 0.05, the difference is significant.

large-scale ecological quality assessment and spatial and temporal visualization (S. Zhang et al., 2021b), and this will help scholars to further delineate the scope of the coastal zone ecological reserve precisely and further improve the efficiency of ecological protection (Lin et al., 2016). Simultaneously, it also avoids the inaccuracies caused by the use of statistics in the traditional ways of ecological environment quality evaluation. Therefore, the combined results of four ecological environment-related indicators used in this study will reflect the ecological environment quality of the coastal zone more comprehensively and accurately than the single-factor indicator method, avoiding the limitations of applying single-factor evaluation.

## Potential Driving Factors of Ecological Quality in the Coastal Zones of Southern China

The RSEI of the South China coastal zones between 1987 and 2020 is divided into five classes (H. Xu 2013). The results showed a trend of decreasing and then increasing ecological quality of the coastal zone dominated by good and moderate values between 1987 and 2010, and the same trend of decreasing and then rebounding ecological quality between 2010 and 2020. Further analysis of the spatial differences in the evolution of ecological and environmental quality in the coastal zone of South China during the study period showed that it formed a spatial distribution pattern of three parts with obvious evolutionary differences in the east, middle, and west. Combining the results of the GeoDetector's analysis of influencing factors, we can conclude that the hills, mountains, the areas with relatively high altitude, significant vegetation growth, and low levels of reclamation and utilization appear to have better ecological environment quality in the study area, and this is consistent with the findings of Qiu et al. (2013). In the eastern part of the study area, areas with poor ecological quality are concentrated in

the offshore part, and this area is mostly used for construction and agriculture. In the middle part of the study area, there are low-elevation plains and terraces that are easy to develop and transform. Consequently, it became an economic development center in the coastal region of southern China, where economic development promotes the artificial surface at an unprecedented scale. Gradually, this has led to a variety of urban ecological problems, including urban heat islands. In the western part of the study area, Google Earth's high-resolution image analysis revealed that the dominant land type in the area is agricultural land, abandoned land, and sharply reduced forest land. These findings indicate that urban expansion and encroachment of agricultural activities on forest land will contribute to a significant decline in ecological quality, which is consistent with the results of Chen's study (Cabecinha et al., 2007; Chen et al., 2009). Therefore, we conclude that with rapid economic development and urban expansion, impervious surfaces and the development of agricultural land took up an increasing amount of ecological land between 1987 and 2020. Therefore, we need to strictly limit urban expansion in the east and central parts of the country and strictly limit the use of land resources in the west to achieve a scientific and rational use of land and to protect the ecological environment of the bay area.

## Development of Ecological Quality Conservation Measures in Coastal Zones of Southern China

The South China coastal zone is an important area for China's economic development and contributes a major part of country's GDP (Z. Sun and Graham 2015). Although some studies have shown that the ecological quality of coastal areas as a whole is improving, non-urbanized areas are the major contributor to this improvement (Zheng et al., 2020). The quality of the ecological environment in the southern coastal region of China is not yet



optimistic. Poor quality is predominantly concentrated in densely populated urban areas, and the demand for economic development has fueled human-dominated land cover changes, resulting in a series of ecological challenges within urban environments, including the transition of ecological and vegetated land into impervious surfaces, which leads to an increase in the surface temperature (Zhou et al., 2016; Ouyang et al., 2021). On the other hand, the quality of the ecological environment in less populated areas is also degraded due to the illegal transformation of ecological land through agricultural and other anthropogenic activities.

Human development activities on the earth's surface will continue to have an adverse impact on the quality of the ecological environment in the future. Therefore, it is critical to rationally design the link between increasing impervious surfaces and ecology within urban environments (Ramadan et al., 2004). At present, the primary focus of governance and protection in southern coastal region of China is on macro-scale policy formulation, resulting in significant disparities between urban and rural areas, as well as between regions (Ling and Ping-Xiang 2016; Kuang 2020). Administrative districts are unreasonably divided, resulting in both overlapping and cross-cutting, or even void, scope of governance. In addition, due to differences in objectives and standards between specific functions, there is a lack of coordination and cross-departmental communication between relevant management departments, and relevant planning or management systems are formulated only from the perspective of their own business or industry development, lacking macro-general principles and objectives, resulting in a lack of effective management of the ecological environment (Hou et al., 2016). It is therefore necessary to focus on county-level planning and remediation in order to improve the quality of the local ecological environment and the well-being of local residents. The ecological quality can be improved through the reasonable configuration of urban green spaces, which not only reduces the density of impervious surface but also helps to achieve harmonious economic development.

### The Challenges for Future Study

Although this study obtained satisfactory results in the evolution of ecological quality from 1987 to 2020, there are still some challenges. First, only Landsat TM and OLI multispectral images were used in this study; however, the application of hyperspectral and high-resolution imagery may lead to better ecological quality assessment results. Second, because the South China coastal region is more sensitive to external changes, a shorter time interval for ecological evaluation of the coastal region may be needed to better understand the ecological quality of the coastal zone. Therefore, in the future work, we will adopt a six-month interval to assess the ecological quality and will also consider a rich collection of meteorological, physical, and socioeconomic driving factors for ecological quality assessment to provide meaningful insights for solving ecological challenges in the coastal zone of southern China.

## CONCLUSION

The qualitative trend of the ecological environment quality of the southern coastal zone of China from 1987 to 2020 was analyzed considering various driving factors. We found that the application of Landsat data to obtain the RSEI can provide more meaningful information for evaluating coastal ecology, and the RSEI can be considered as a feasible tool for rapid and high-precision assessment of ecological quality in broad spatial and temporal distributions. Similarly, the results revealed that the majority of the study area is of good to moderate ecological quality, indicating a considerable need for specific approaches to improve the ecological quality. Furthermore, the evolutionary process of ecological environment quality in South China's coastal zone over time and space exhibits frequent variations. Temporally, the overall change in the RSEI from 1987 to 2020 shows a trend of "first decreasing, then increasing, and then decreasing," and the highest RSEI value was obtained in 2010, leading to a decline of ecological environment quality. Spatially, this study found that the study area consists of three parts, each with significant differences. The western and central parts are ecologically worse, while the eastern part is more degraded on the seaside but relatively better on the other side. Based on GeoDetector results, we found that this is primarily due to variances in geomorphology and land use patterns, resulting in regional differences in ecological and environmental quality. In conclusion, the ecological environment quality in the southern coastal zone of China is still not satisfactory, and strong measures are required to create a balance between the rapid landscape changes and ecological environment; at the same time, authorities should use the ecological monitoring techniques of remote sensing to identify ecological reserves and to achieve inter-departmental and inter-regional cooperation and development in the management of ecologically of ecologically poor areas, as well as to achieve monitoring and quantitative assessment of regional ecology through remote sensing technology.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found at: <https://earthengine.google.com/> <https://earthexplorer.usgs.gov/>.

## AUTHOR CONTRIBUTIONS

YL had the original idea and designed this study. DC, ZZ, and HG were responsible for data processing and analysis. ZA contributed to the revision of the manuscript. YL and YZ contributed to writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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