Assessment and prediction of land ecological environment quality change based on remote sensing-a case study of the Dongting lake area in China

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Abstract. Multi-source remote sensing data is rarely used for the comprehensive assessment of land ecologic environment quality. In this study, a digital environmental model was proposed with the inversion algorithm of land and environmental factors based on the multi-source remote sensing data, and a comprehensive index (Ecoindex) was applied to reconstruct and predict the land environment quality of the Dongting Lake Area to assess the effect of human activities on the environment. The main finding was that with the decrease of Grade I and Grade II quality had a decreasing tendency in the lake area, mostly in suburbs and wetlands. Atmospheric water vapour, land use intensity, surface temperature, vegetation coverage, and soil water content were the main driving factors. The cause of degradation was the interference of multi-factor combinations, which led to positive and negative environmental agglomeration effects. Positive agglomeration, such as increased rainfall and vegetation coverage and reduced land use intensity, could increase environmental quality, while negative agglomeration resulted in the opposite. Therefore, reasonable ecological restoration measures should be beneficial to limit the negative effects and decreasing tendency, improve the land ecological environment quality and provide references for macroscopic planning by the government.

1. Introduction

The use of multi-source remote sensing data to assess the ecological environmental quality has been increasing in recent years [1]. Such data are usually applied to reconstruct and evaluate the ecological environment quality background, such as soil [2], ecological climate [3], land use [4], and water [5]. For example, MODIS data were used to invert the land surface temperature, land evapotranspiration, soil water content, plant coverage, chlorophyll content in plants, and aerosol [6-8]. The global land use / vegetation cover situations were analysed with TM and ETM data [9-11]. DEM and the hydrological digital model were established using STRM and ASTER data [12,13]. These models are frequently applied for the evaluation of ecological environmental suitability, sustainability, risk and frangibility [14,15]. However, it is difficult to carry out research on the regional comprehensive quality of land ecology. This may be because it is difficult to obtain accurate data using previous research techniques due to the restriction of large-scale space information [16], the complexity of the environmental process, and the temporal and spatial responses of multi-dimensions.

The purpose of this study was to use the multi-source remote sensing data inversion algorithm for the reconstruction of land ecological environment quality background and apply it to the Dongting Lake Area in China, thus revealing the development and evolution rules and characteristics of the environment. Thus, a digital land environment quality model was proposed for the analysis of GIS (geographic information system) and RS (remote sensing) methods based on multi-source remote sensing data. The advantage of this approach is that the spatial and temporal change information of land environment quality can be obtained accurately on a regional scale. According to the study results, some basic references can be provided, such as the main effect of environmental change, the changing trends of the regional land environment and remote sensing for the assessment of land environment quality. Based on the findings, general recommendations were also presented for the development of the ecological economy, macro-ecological planning and ecological protection in the study area.

2. Research area and data

2.1. Research area

Dongting Lake (28º03′-30º20′N, 110º40′-113º30′E) is located in central China (figure 1) and possesses a humid subtropical climate. It is the second largest freshwater lake in China and is connected to the Yangtze River to the north, Xiangjiang to the south, and Zishui, Yuanshui and Lishui to the west. This area is approximately 2100 km^2 and covers 12 counties and cities in total. The annual average temperature is 16.6℃-17.6℃, and the average sunshine duration is 1,686 h. The annual average precipitation is 1,303 mm, and the precipitation from April to September represents 64.5% of total precipitation throughout the year. The current population is 16.63 million, accounting for about one quarter of the total population in Hunan Province. The area is rich in natural resources. Most of the area is covered by plains and lakes. It has been praised as "a land of fish and rice" since ancient times and was the main economic region in Hunan Province. The economy has developed rapidly in recent years. The GDP increased from 3.9 billion Yuan in 2000 to S10.3 billion Yuan in 2009, and the proportion of primary, secondary and tertiary industries was 19, 45, and 36, respectively, in 2009. In recent years, the urbanization of the area has rapidly increased.

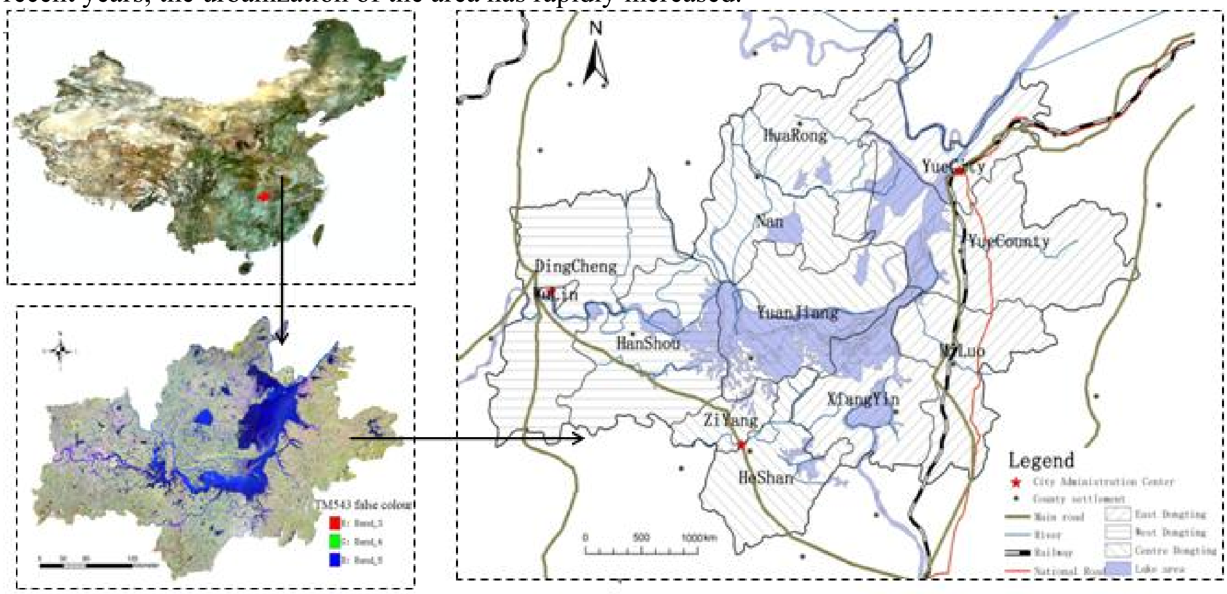

Figure 1. Study area of Dongting lake.

2.2. Data sources and pre-processing

The land ecological environment quality background was reconstructed using multiple sources of remote sensing data in the surrounding area of Dongting Lake. Several data sources were used.

MODIS data came from the USGS, TM/ETM data came from International Scientific Data Service Center of China, and DEM data came from NASA. Further data pre-processing was carried out. ENVI-IDL and MRT programming were utilized to project all data onto WGS_84_UTM_Zone_49, with the central meridian of 111 degrees, as MODIS is a sine surface projection. Multiple cutting and inversion algorithms were compiled under IDL, and the Grid TIFF data map was generated. The landscape pattern index was calculated via Fragstat 4.1 and a vector layer was entered. The hierarchical decision tree method was adopted for land classifications.

A soil taxon was expressed by conceptual functions as the base of a soil group, mainly covering red earth, Flovo-aquic soil and paddy soil. Gradient and slope length factor (LS) were calculated with the LS equation in American soil erosion equations (USLE). Soil water content was replaced by TVDI index [17], and its expression was as follows:

TVDI=(TS-TSmin)/(TSmax - TSmin)

Where TSmin is the minimum surface temperature, corresponding to moisture side; TS is the surface temperature of any pixel; TSmax is the corresponding maximum temperature of a certain NDVI, which is the dry side:

TSmax =a+b*NDVI

where a and b are the simulation coefficients. NDVI is the normalized difference vegetation index.

SHDI and CONTAG were calculated via the landscape pattern index method, and all remote sensing data consisted of images of summers (July, August and September) from 2001 to 2007.

3. Methodology

3.1. Design of land environment quality assessment model

The comprehensive index of the land ecological environment background (Ecoindex) was designed. The Ecoindex reflects the fitness of human activities for the environment or environment quality under natural state factors, including water, atmosphere, soil, geography and organisms, without considering the direct interference of human activities. These factors are summarized in table 1, and all the factors were in the form of a digital grid. The weight of the factors was referenced from 《Environmental Quality Assessment Standards》 in China and Hunan province, as follows:

Table 1. Relevant indexes and indicators of environment quality reconstruction.

Element weight	Factor weight	Data Source	Method and Model	Format	Resolution	Accuracy Control
Moisture and energy 0.282	LST 0.511	MOD11	Split-window algorithm	HDF	500 m	0.2℃
	PWV 0.489	MOD05	Infrared algorithm	HDF	500 m	0.5 mm
Geography 0.213	DEM 0.423	AsterV1/V2	DEM model	GeoTiff	30 m /15 m	—
	LS 0.577	AsterV1/V2	USLE model	Tiff	30 m	—
Soil 0.149	Soil Class 0.379	Soil map	Soil investigation	Grid	500 m	Subclass
	SWC 0.621	MOD11/TM5	TVDI index	HDF	500 m	0.05
Land Use/Land Cover 0.356	Diversity 0.097	TM/ETM+	SHDI index	Grid	100 m	—
	Contagion 0.113	TM/ETM+	CONTAG index	Grid	100 m	—
	LandClass 0.322	TM/ETM+	Decision tree	Tiff	30 m/15 m	85%
	NDVI 0.468	MOD13	Maximum value composite	HDF	250 m	—

Moisture and energy conditions, Land Surface Temperature (LST) and Atmospheric Precipitable Water Vapour (PWV);

Geographical environment, landform, gradient and slope length index (LS) adopted by the Universal Soil Loss Equation (USLE);Soil conditions, soil class, temperature vegetation/soil dryness index (TVDI);

Land use/cover conditions, land use intensity index and NDVI [18].

The land use intensity index was expressed by the method of land use intensity classifications. The construction land was given value 4, agricultural land was given value 3, forest land, grassland and water body were both given value 2, and unused land was given value 1.

The NDVI expression [18] was:

NDVI= (p(nir)-p(red))/(p(nir)+p(red)

where p(nir) is the flection ratio of the near infrared band and p(red) is that of the infrared band. CONTAG and Diversity Index were calculated from Landscape index model (table 1). The reconstructed model is as follows:

$$\text{Ecoindex} = \sum_{i=1}^{n} b f(x) = b_1 f(x_1) + b_2 f(x_2) + b_3 f(x_3) + \cdots + b_n f(x_n) \quad (1)$$

f(x) is the index system of influencing factors, and it was normalized. *b* refers to the weight, m is the number of environmental influencing factors, and x_1, x_2, x_3, and x_n are the digital matrix of the corresponding environmental influencing factors, respectively. Figure 2 shows the matrix grid form of the digital model. Ecoindex represents the land ecological environment background value. The higher the Ecoindex value, the more suitable the environment quality; its value ranged from 0-1.

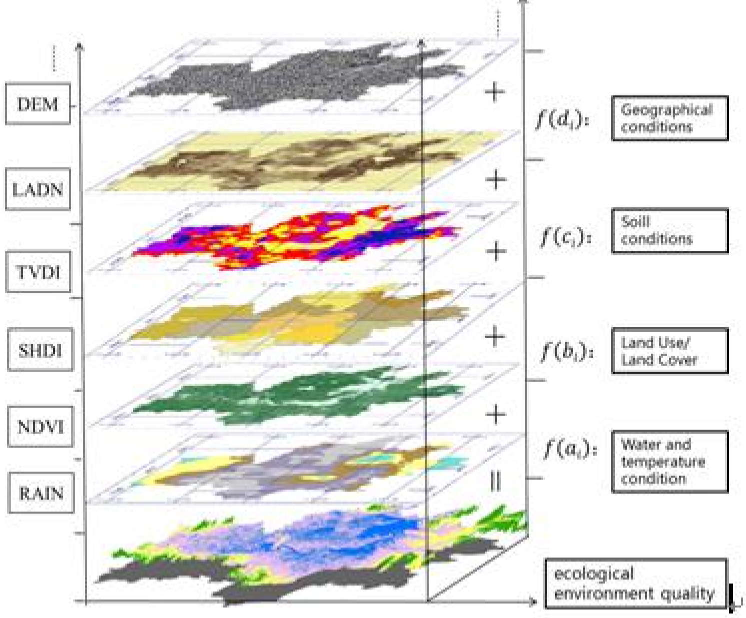

Figure 2. The land ecological environment quality background to reconstruct the digital model.

3.2. Environmental change prediction model

The grey multiple regression prediction method was used to establish grey models for the original sequence of different independent variables of the multiple regression model, and multiple regression analysis was performed by setting the predicted values of the model as a new independent variable and dependent variable. In other words, the grey multiple regression model series was produced. The limitations of some influencing factors could be eliminated, while the regularity of the data was enhanced. The independent variables of the regression model were reprocessed and regenerated via the grey model [19] (figure 3).

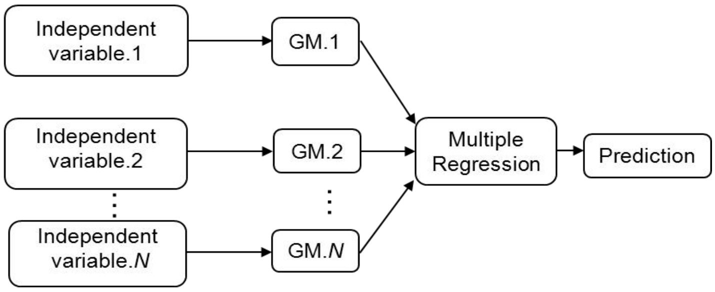

Figure 3. The grey multiple regression model for environment quality prediction.

4. Results and analysis

4.1. Ecological environment quality changes

The Ecoindex was calculated using the Ecological environment background reconstruction digital model in the Dongting Lake region in 2001 and 2007. The specific factors and weights are listed in table 1, and the Ecoindex results are shown in figure 4. The following changes were observed:

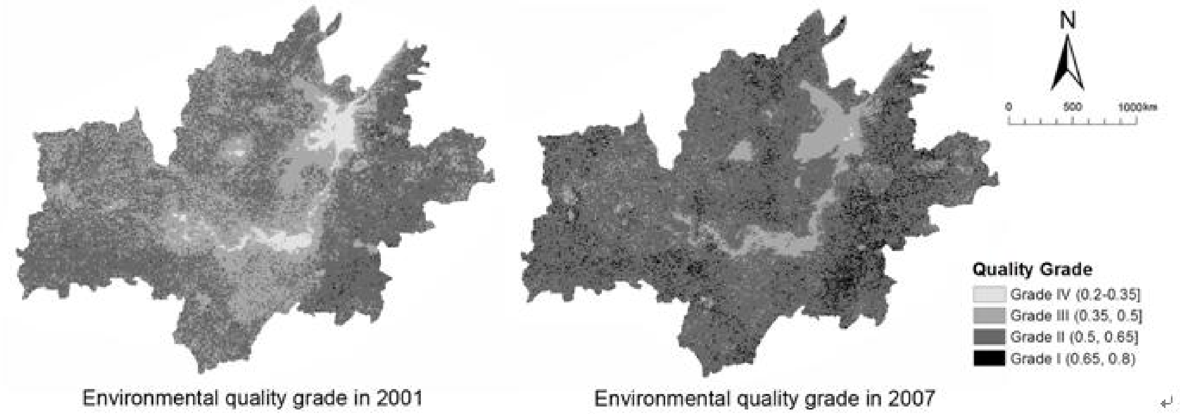

Figure 4. The ecological environment quality background value (Ecoindex) grade.

- Generally, the Ecoindex change ranged from 0.276 to 0.776 in 2001 and from 0.243 to 0.696 in 2007. The Ecoindex of water bodies and the city centre was relatively low, while the Ecoindex of mountainous regions was high in both 2001 and 2007. This indicated that the urbanization process profoundly affected the ecological environment quality. In recent years, the urbanization level has obviously increased, from 15.7% in 1996 to 35.6% in 2011 in the lake region.
- The Ecoindex of plain areas was moderate. As the agricultural economy played an important role in the lake area and most agricultural land was distributed in flat terrain or plain areas, the Ecoindex decreased over time. The agricultural output value had sustained growth. The GDP of agriculture was 3.82 billion Yuan in 2010, almost 3 times that observed in 2000. However,

the agroecological environment has been protected, while the environmental quality has exacerbated the developmental process.

- In addition, the Ecoindex increased gradually with the transition of land use from water bodies to grassland. This showed that wetlands could promote the land ecological environmental quality in the lake region [20]. However, the wetland area of the lake region has been decreasing yearly [21], and the biodiversity and water regulation and storage capacity of the wetland have declined. Due to the development of the forestry and paper industries in the lake region, the protection of wetlands has become weak.

4.2. Changes in land ecological environmental quality

The temporal and spatial level changes in the land ecologic environmental quality were shown by the change area calculated in various grid cells. The statistical formula is S=N*(0.5 km*0.5 km), where N is the number of grid cells, 0.5 km is the unit size of the grid, and S is the grade area.

According to the research results, the Ecoindex was graded via the equal interval classification method, and the grading rules were as follows: Grade IV (0.2-0.35] is poor quality, Grade III (0.35, 0.5] is common quality, Grade II (0.5, 0.65] is better quality and Grade I (0.65, 0.8) is the best quality.

Table 2 and figure 5 (a) show the change and transfer situations of the Ecoindex from 2001 to 2007. The research results showed that Grade I changed to Grade II, so the area of Grade I decreased from 29.8% to 5.15%, mainly distributed in the middle and surrounding areas of the lake. The area of Grade III increased from 10.96% to 35.09% due to Grade II conversion to Grade III with a scattered distribution in surrounding areas. Obvious changes in area were not observed in Grade II and Grade IV, and the major change characteristics are described below.

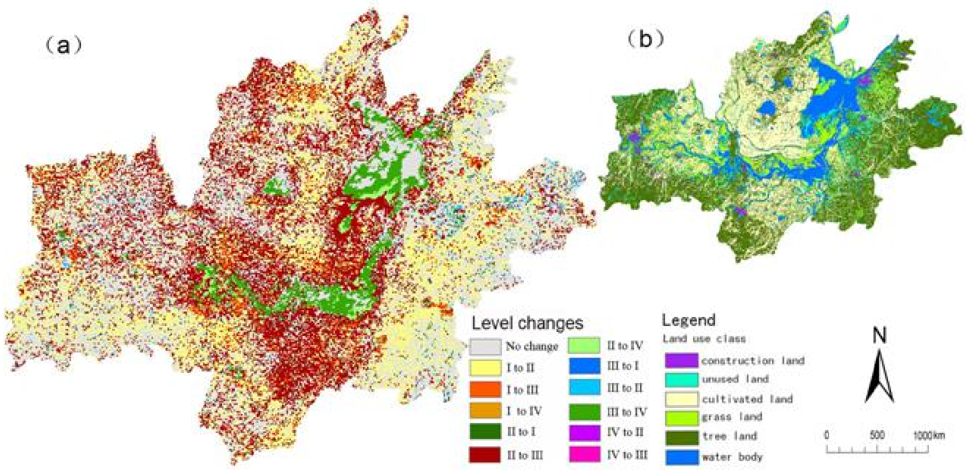

Figure 5. The level changes in land environment quality between 2001 and 2007.

Table 2. 2001-2007 Transfer matrix of environment quality area changes (unit, km^2).

Year	2007				Total	Proportion	Change %
2001	I	II	III	IV		%	ratio
I	854.3	4173.0	630.5	10.00	5667.8	29.80	-24.65
II	122.3	5561.5	5002.0	239.8	10925.5	57.44	-5.36
III	2.3	171.0	1036.8	875.5	2085.5	10.96	24.13
IV	0.00	0.25	5.0	337.8	343.0	1.80	5.89
Total	978.8	9905.8	6674.3	1463.0	19021.8	100	
Proportion	5.15	52.08	35.09	7.69	100		

- A sudden change was found in some parts. The change mode was Grade I towards Grade III and Grade IV, and Grade IV towards Grade II. This showed that great differences were mainly caused by different social and economic environments and different policies in different regions.
- A slight reduction of grades was recorded in surrounding areas around the lake, especially Grade II conversion towards Grade III and Grade III towards Grade IV. The decreasing trend in environment quality was present in the hills and mountainous areas, although some policies have demanded the return of arable land for forestry and some farmland to the lake region.The actual effect is not obvious. The economic benefit was considered a priority, while the environmental benefit was ignored due to industry upgrades in some local counties and cities.The phenomenon of Grade II conversion towards Grade I mainly occurred in water bodies as shown in figure 5 (b), while the phenomenon of Grade III towards Grade I was sporadically distributed in plain areas or farmland. The main cause was that the control of the water resource environment led to great improvement in the water body environment. Meanwhile, some advantages of ecological agricultural policies, such as ecological-functional zone division (EFZF) and the protection of water resources, were achieved [22].

4.3. Analysis of the main effect factors
Person correlations between different indexes and the Ecoindex are shown in figure 6. The correlation of PWV was the greatest, up to 0.83. This meant that rainfall played the greatest role in environmental effects. Dongting Lake lies in a humid subtropical region, and rainfall often exhibits radical changes, while drought and flood are common in some places under the influence of subtropical high pressure in the summer. The distinct correlations between the Ecoindex and LST, NDVI, degree of land use and DEM were observed. The results suggested that the environment temperature, vegetation, and geographical locations suitable for human activities were all important effect factors. The importance not only responded to the stable influence on regional climate, soil and vegetable environment but also provided the carrying space for production activities. The land ecological environment quality could be effectively promoted by improving environmental conditions, such as rainfall, temperature and vegetation, in the lake region. A weak correlation between the Ecoindex and Contag, SHDI, LS, and soil taxon was present. The results implied that geographical and landscape patterns did not obviously influence the environment quality in the lake region. The reason might be that effects of the landscape pattern and geography on the environment are not obvious in the short term. Therefore, the main effects that influence the Ecoindex can be explained by PWV, LST, NDVI, land use degree, and DEM.

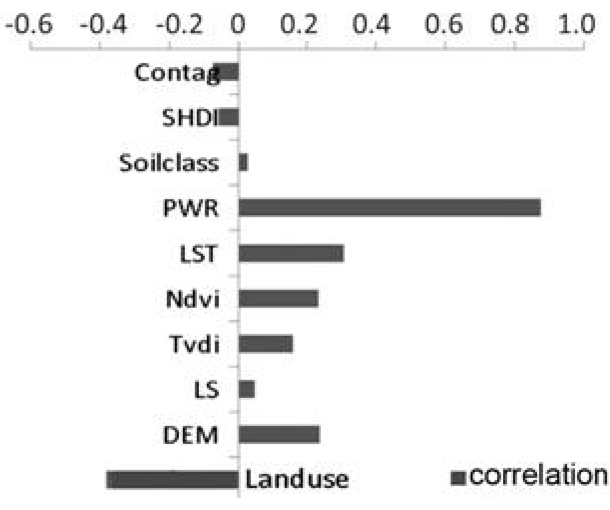

Figure 6. Correlation analysis.

4.4. The change characteristics of effect factors

Figure 7 shows the dynamic changes of various main effect factors from 2001 to 2007. The ranges of change in effect factors were as follows: TVDI (-0.996， 0.998), PWV (-1.31， -0.64), NDVI (-0.64， 0.52), LST (0.295， 0.21), and land use intensity changes (-3， 3). The following characteristics were observed:

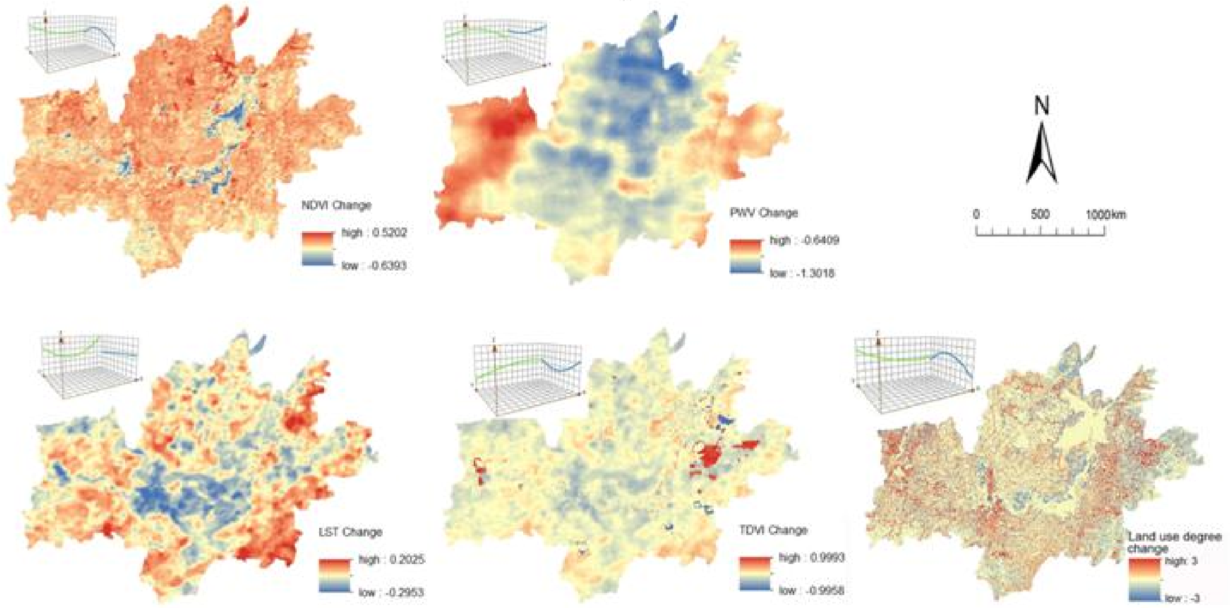

Figure 7. The main factor to effect change and tendency between 2001 and 2007.

- Changes were not distributed evenly; rather, they formed an aggregate state, e.g., the heat island effect of LST. To show the indicative characteristics of the aggregation effect for Ecoindex, these changes were divided into positive aggregation, which referred to an increase of the Ecoindex, and negative aggregation, which referred to a decrease of the Ecoindex. The increase of PWV and NDVI could lead to an increased Ecoindex value, while an increase of land use intensity could promote Ecoindex reduction.
- The changes were characteristic of spatial heterogeneity. The extent of changes in the effect factors was sharper in cities surrounding the lake and slower in grassland and the lake body. This implied that the wetland could play an important role in the improvement of the ecological environment. Under the influence of social and economic activities, the aggregated degree of effect factors was higher in suburbs and farmland than other regions, which was mainly caused by population aggregation, land development and urbanization.
- The transfer of substances or energy of various factors tended to aggregate in the surrounding areas of the lake. This showed that the deteriorating trend of environment quality was present in the above areas (thumbnail of figure 7). The spatial change of various factors showed that NDVI increased gradually from the south to the north, as the vegetation degradation was more severe in the south. LST and TVDI increased gradually from the east to the west, which indicated that the increased tendency of temperature spread towards the east. However, PWV was the reverse of LST; in other words, PWR was higher in the west and lower in the east. The degree of land use tended to be higher in the west and lower in the east, while little visible difference was observed in the north-south direction of Dongting Lake.

4.5. Prediction of changes of the main environmental factors

Figure 8 shows the factor predictions fitted via the GM (1.1) model. The model evaluation process indicated that the C values of PWV, TVDI and NDVI were more than 0.35, and their P values were equal to 0.83. This demonstrated that the prediction models of PWV, TVDI and NDVI were reasonable. However, the C values of LST and land use were less than 0.35 and their P values were equal to 0.9, which revealed that the model could satisfy the general prediction accuracy.

To predict the changing situations of the general environmental background values in the future, the prediction model for the land ecological environment background in Dongting Lake was determined through factor change analysis and stepwise regression. The model is expressed as follows:

$$y= -2.383+0.065x_1+0.102x_2+0.139x_3-0.035x_4+0.098x_5 \quad (2)$$

where y is the land ecological environment background value Ecoindex, and x_1, x_2, x_3, x_4, and x_5 represent the factors PWV, TVDI, NDVI, land use intensity and LST, respectively, after stepwise regression. The correlation coefficient of the model fitting degree R^2 was 0.941, which showed that the independent variable Ecoindex could explain the degree of change in dependent variables. The Std. Error of the estimate is 0.036. According to variance analysis of the stepwise regression model, the value of F is 72.93, the significance probability is 0.001, and the regression model is significant.

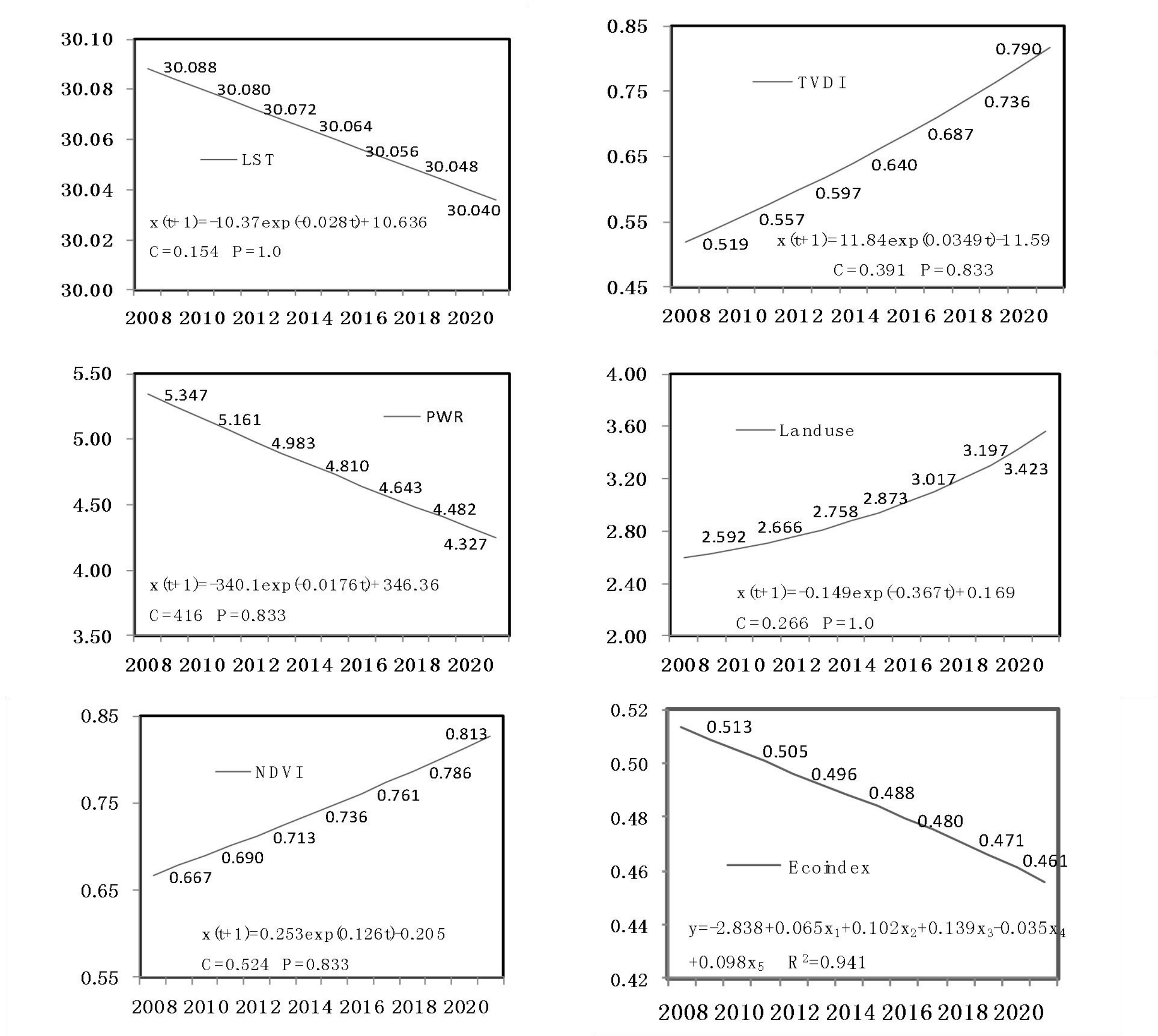

Figure 8. The predictions of land ecological environmental changes in the Grey Multiple Regression Model (Note, x was factors, t was years, and C, P was the index of model evaluation)

The prediction results showed that the range of change in the general temperature was only 0.048℃; therefore, the LST changes were not significant in the Dongting Lake area from 2008 to 2012. The reason may be that the climatic effect on the region was not apparent in the short term.

However, PWV decreased from 5.35 cm to 4.33 cm, and the average rainfall decreased by 1.02 cm. Compared with the value in 2007, PWV decreased by almost 20% in 15 years. Furthermore, the TVDI index increased significantly and had increased by 0.26 within 15 years. Its increase was nearly 50% compared with 2007. These results implied that water environment problems could be severe in the Dongting Lake region in the future. According to global water circulation and atmospheric circulation, due to the influence of the global greenhouse effect, the regional temperature will increase; on the other hand, because of the expansion of regional cities and populations, the consumption of water resources will increase sharply. This could lead to a decrease in the soil moisture content and accelerate the deterioration of the water environment.

Additionally, NDVI increased from 0.67 to 0.81, which means that the vegetation cover will increase in the future. This may have been mainly caused by the increase of carbon emission and temperatures in the lake area.

Land use intensity increased from 2.59 to 3.42, showing that urban development in the future, especially construction land and farmland areas, may further increase. With the increase of population density and urban demand, the climate would deteriorate, and some point source pollutions and non-point source pollutions [23] would further speed up the degradation of land ecological environment quality.

The prediction of the Ecoindex suggested that the land ecological environment quality would decrease in the lake region in the future. By 2021, the Ecoindex will reach as low as 0.461, or by 0.105 compared with 0.566 in 2001 or by 18.55% compared with 2007. The change tendency analysis of the factors indicated that main influencing factors were the decrease of soil moisture content, vegetation cover and rainfall as well as the increase of land use intensity. The change extent of TVDI index and land use intensity index were more obvious. This suggested that the environment quality was severely restricted by soil moisture contents and types of land use in the lake region. Soil moisture content played an important role in water and soil conservation and water reservation [22], so these factors would be of great concern in eco-developmental planning in the future to slow down environmental degradation. Surface temperature and rainfall did not show obvious changes in the short term, but the main effect analysis indicated that a local sudden change of the temperature occurred, especially in cities. Therefore, the relationship between population, urban development and ecological environment must be harmonized under the construction of the ecological economy.

5. Discussion

This study showed that the main reason for the change in ecological environment quality was the aggregation of environmental factors rather than the simple increase or decrease of sunlight, rainfall or temperature. Due to such aggregation, sudden changes in the local environment would occur [24-26]. According to the main effect change of factors and spatial distribution, temperature, rainfall, soil moisture, land use intensity, atmospheric circulation, and water circulation lead to aggregate matter and energy in the regional ecological environment. The aggregation of rainfall and land use intensity was the main factor behind the effect on the ecological background in the lake region. Such an aggregation effect was also closely related to the development of urbanization. As shown in figure 9, with the development of urbanization, industrial and agricultural production, the ecological environment was directly threatened. For example, an increase in population density, land development and energy consumption intensified the aggregation effect [27]. Thus, a negative aggregation would exist, and a local sudden change would occur in the climatic environment, such as heavy rainfall, excessive temperature and drought. However, some activities caused a positive aggregation effect on the ecological environment. These could relieve the environmental degradation and protect the ecological environment. For example, ecological gardens and ecological planting could boost the effective land use, biodiversity protection and regional development [20]. Land use intensity is currently increasing rapidly in the Dongting Lake area, especially in the plain area. A reasonable land use arrangement will effectively promote the protection and sustainability of the ecological environment.

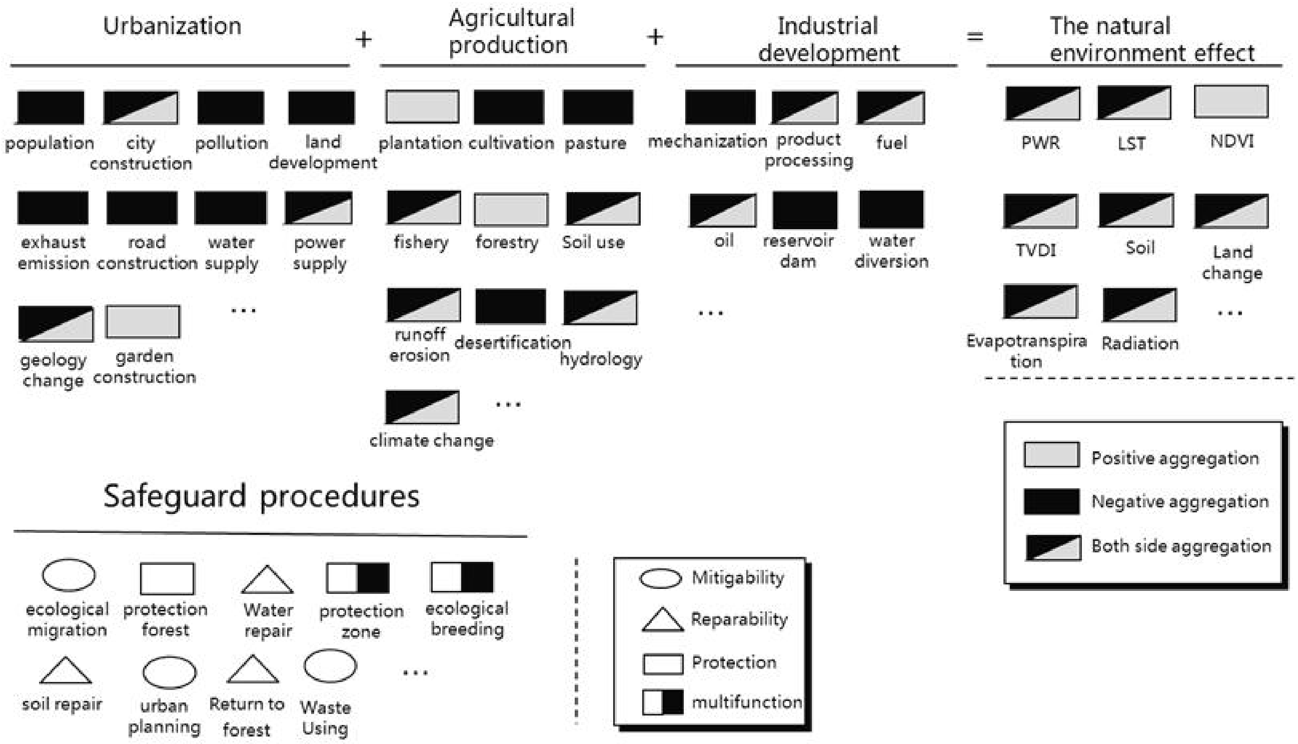

Figure 9. The cumulative effect of human activities on the environment.

The results of multi-source remote sensing data analysis and grey multiple regression prediction showed that the degradation trend of the environment would be obvious in the next 14 years, and the Ecoindex would decrease to 4/5 of that in 2007. The study revealed that the decrease of land use intensity as well as an increase of vegetation cover rate and rainfall would improve the environment quality. Furthermore, the proper soil moisture content and surface temperature could also improve the environment quality. According to the development history in the lake area, the main policy reasons for ecological environment degradation included:

- Large-scale urbanization. The urbanization rate was increased, and most regional plans focused on central towns, which surpassed the degree of tolerance of ecology.
- Reduced attention to environmental protection. The government advocated returning the arable land to forestry and the transformation of the industrial economy in 1998, but the government has placed emphasis on cultivated land protection and food safety since 2006 in the Dongting Lake region. Such policies have directly weakened forest land and wetland protection.
- Adjusted industrial structure. After industrial restructuring, the industrial proportion has increased greatly since the 1990s. The ratio of the industrial GDP to the total GDP was 21% in 1996, but it reached 41% in 2012. Furthermore, in order to promote the paper industry, people started to grow aspens on a large scale, and the cultivated area reached 400,000 hm^2 in 2010, up to 1/8 of the wetland area; thus, the wetland has been seriously damaged. Meanwhile, some point source and non-point source pollutions (such as lead, cadmium and phosphorus) have also accelerated environmental pollution.

- Effect of hydraulic engineering. The construction of Three Gorges Dam (the largest power station in the world) and the South-to-North Water Diversion Project [28] had a knock-on effect. Due to these massive engineering projects, people have begun to build dams. Compared with that in 2006, the quantity (including projects under planning) increased by 60% in the lake area in 2012. The regional water circulation has been seriously obstructed in the region.

Therefore, the ecological tolerance capacity will face severe challenges in the future. A reasonable density of layout and ecological restoration measures should be established to limit the degradation and improve the environmental quality.

6. Conclusions

The space interpretation accuracy has improved greatly due to the full use of remote sensing data such as MODIS, TM, ETM and Aster data, and it is feasible to assess environment quality with the reconstruction of the land ecological environment background (Ecoindex) that can reflect the suitable degree of human activities for the land ecological environment. Over the 7 years studied, the land ecological environment quality decreased overall, and this state was especially obvious in suburban areas and wetland in the lake area. The results revealed that the main factor causing environmental change was the environment aggregation effect; in other words, the superimposed interference of multiple elements leads to changes in the environmental suitability. Evaluating the aggregation effect of the environment could provide effective references for the government's macroscopic planning, intensive land use and the relief of ecological degradation. In the next 14 years (2008-2021), the degeneration tendency of land environment quality will be obvious in the Dongting Lake region according to the predictions made with grey multiple regression. When making economic development plans, the positive aggregation effect of main effect factors should be fully considered. It is beneficial to slow down the environmental degradation and improve the environmental quality, and the measures of ecological economy must be implemented under the integration of ecological planning, ecological early warnings and protection strategies under land development. The environmental effect process is complex, and a large number of factors must be considered. With the acquisition of new data and new algorithms, particularly in remote sensing inversion, further studies should be performed in the Dongting Lake Area.

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