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Research Article

Regional Ecological Security Evolution and Green Economy: An Empirical Study

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How to maintain and improve ecological security in the process of green economy development is of great significance in terms of both theory and practice. Hence, in this paper, based on the framework of DPESAR (driving force-pressure-exposure-sensitivity-adaptation-response), we establish a structural model using SPASS and Eviews6 software to identify the contributing factors for green economy development. We use panel data of Liaoning Province, China, from 1995 to 2017 to analyze the relationships among these factors and their indicators. Furthermore, we simulate and identify the ideal evolution status of the ecological security and green economy development up to the year of 2022. Our results show that first, those adjusted indicators of ecological security can greatly promote green economy development. Second, specific regulation indicators and scope can be obtained by identifying the evolutionary state of ecological security. Third, the interactions among the government, firms, and the public should be considered to further develop regional ecological security and green economy.

1. Introduction

In recent years, how to promote green economy development while maintaining ecological security has become a hot topic for academics, industry practitioners, and policymakers. At present, much research has been done from different perspectives.

Wang and Wu [1] explore the regional ecological security gradual-change process and explain the gradual positive phase transition process from the "Rheology-Mutation" theory of safety science. Wu et al. [2] discuss the selection and weighting methods of regional ecological security evaluation indicators based on the principal component projection evaluation model. They establish an evaluation model of regional ecological security and apply this model for Anhui Province, China. Li et al. [3] build the "Human Green Development Indicator," assuming equal importance of the two dimensions of social and economic sustainable development and sustainable development of ecological resources and environment. They measure the green development indicator values of 123 countries and their rankings based on 12 element indicators. Zhou et al. [4] summarize the key economic development indicators and predicted the future green economy development for 2016–2020 in Liaoning Province of China. Wang and Liu [5] employ the Biennial Weight Modified Russell Model to study the effects and mechanisms of energy conservation and emission reduction on China's Green Total Factor Productivity under resource and environmental constraints. They analyze whether energy conservation and emission reduction could achieve a win-win situation between environmental protection and China's economic development. Wang et al. [6] adopt the PSR framework to build a land ecological security evaluation indicator system of Yongzhou City from the perspectives of nature, society, and economy. They adopt the range method and the entropy weight method to evaluate the land ecological security of Yongzhou City from 2003 to 2012. Peng et al. [7] reveal the driving mechanism behind the vulnerability of the ecological environment and the spatial clustering characteristics of the vulnerability of urban agglomerations. They determine the Moran Index (MI) with spatial autocorrelation model and estimate the ecological environment vulnerability in 2005, 2011, and 2017. They show that the driving forces of ecological environment vulnerability of Yangtze River city group have changed from natural factors to social-economic factors and then to policy factors. Their results show that the environmental protection investment has the greatest impact on ecological carrying elastic force, followed by the proportion of the tertiary industry.

Although the above-mentioned research has laid an important foundation for building and refining the relevant theories of ecological security, the research on the relationship between the evolutionary state of regional ecological security and the development of green economy has not attracted the attention of scholars, especially from the perspective of the dynamic evolution of ecological security. To fill this research gap, Liaoning Province, China, is taken as the research object in this paper, and the panel data comprising environmental economy and ecological security factors are obtained to establish a model on the relationship between ecological security evolution and green economy development. It is based on the ecological safety status indicator system with the DPESAR (driving force-pressure-exposure-sensitivity-adaptation-response) framework from 1995 to 2017. The optimal control model for developing the green economy is identified through the adjustment of the control variables. In short, this paper makes a major contribution by providing managerial and policy insights for green economy development. The optimal control model of green economy constructed in this paper can also be used as a reference for the development of green economy in other countries and regions.

The rest of this paper is organized as follows. Section 2 details the indicator selection and data processing in this research. In Section 3, we build a measurement model so that the evolution trend of the different levels of indicators can be identified. In Section 4, we build a structural equation model to study the mutual evolution among the indicators. After that, we set up an optimal control model and use it to identify the optimal state equations in Section 5. Finally, we summarize our conclusions and managerial insights in Section 6.

2. Indicator Selection and Data Processing

2.1. Original Indicator System and Data Normalization. PSR [8], DPSIR [9], DPSER [10], and other ecological security evaluation indicator systems commonly used in the literature have several common shortcomings such as ambiguity of specific classification and application context differences. Hence, in this research, the area method is adopted in view of the actual situation in Liaoning Province in particular and China in general. Specifically, the economic, social, and environmental aspects are classified according to the main research directions of sustainable development, and then the specific goals are determined by the layered approach [11–17]. Therefore, based on the framework of DPESAR, a total of 64 indicators are selected including resource and environment indicator, natural resources indicator, and environmental policies and investment. Following Ge et al. [18], to measure Level-1 comprehensive economic and environmental indicators, we adopt the six indicators of DPESAR for Level-2 indicators. The indicators are defined as follows: $A(k)$ driving indicator, $B(k)$ presser indicator, $C(k)$ exposure indicator, $D(k)$ sensitivity indicator, $E(k)$ adaptation indicator, and $F(k)$ response indicator. All data are based on the National Statistical Yearbook 1995–2017, the information provided by the local authorities, and Beijing EPS Data Company. The entropy evaluation method [19] is adopted to normalize the six secondary indicators (see Table 1).

2.2. Reliability Analysis. The Spass17 statistical software is used to perform reliability analysis on the Level-3 indicators corresponding to each Level-2 indicator. The test results are shown in Table 2.

It can be seen from Table 2 that, in addition to the standardization-based Cronbach's alpha for the adaptation indicator E which is less than 0.050, the reliability of the remaining Level-2 indicators is above 0.7, which basically meets the reliability requirements. The lower reliability of the adaptation index E is because the main factors governing the regional climate are affected by global climate change. The last row in Table 2 is the reliability analysis for the five Level-2 indicators except the pressure indicator B. The pressure indicator B is excluded because it belongs to the control index, and the man-made interference factor is very strong. In recent years, it is basically not affected by other factors.

Excluding the unreasonable items marked in Table 2, the original indicator system is modified, then the new indicator is weighted by the entropy evaluation method, the new Level-2 indicator relative weight is obtained, and the normalized data processing is performed (see Table 3).

3. The Measurement Model

3.1. Establishment of the Measurement Model. In order to clearly identify the evolution trend of the Level-2 indicators to the Level-3 indicators, it is necessary to build a measurement model. The Eviews6 software is used to perform regression analysis on the data shown in Table 3. Under the condition that the regression coefficient meets the significance level, it is maximized as much as possible. The driving force $A(k)$ is firstly selected to analyze the influence of the Level-3 indicator $A3(k)$ under the control of it (see Table 4) in this paper.

At the same time, the regression residual is detected by the stable test. For the same reason, other measurement models are also available. Therefore, the autoregression model with the optimal value of more than 80% is established as follows:

Table 1: Results of the normalized Level-2 indicators.

Year	Indicators					
	Driving force $A(k)$	Pressure $B(k)$	Exposure $C(k)$	Sensitivity $D(k)$	Adaptation $E(k)$	Response $F(k)$
1995	0.062515279	0.554008256	0.170396237	0.299288603	0.478851639	0.338847808
1996	0.079761957	0.550948637	0.130446872	0.478374506	0.538525099	0.426467514
1997	0.103784324	0.573532237	0.120333465	0.496376063	0.584590071	0.31230814
1998	0.159314346	0.612556851	0.145198523	0.409126508	0.569717204	0.323568583
1999	0.171555202	0.731633643	0.149487769	0.240158058	0.558088313	0.323725194
2000	0.117896377	0.722537486	0.211500799	0.251745624	0.453673551	0.30047401
2001	0.176112462	0.758234341	0.138905639	0.257331683	0.50634672	0.35169011
2002	0.249795582	0.770750275	0.16026194	0.35181978	0.599533125	0.537412353
2003	0.276901581	0.633325512	0.179665904	0.389412742	0.605954178	0.661452739
2004	0.306615453	0.621869147	0.331337733	0.493904663	0.646167515	0.520039655
2005	0.317217797	0.618704131	0.415880593	0.649177649	0.657882041	0.57287592
2006	0.378745275	0.613395057	0.465656738	0.588295084	0.635852849	0.41732973
2007	0.413868808	0.585522534	0.406153937	0.603292328	0.738934244	0.431047789
2008	0.473513813	0.577595292	0.404717536	0.624369666	0.454874014	0.465758895
2009	0.501527729	0.60234923	0.408873809	0.55099052	0.457230192	0.535970383
2010	0.594543468	0.45383938	0.595231705	0.740063333	0.478117393	0.559654168
2011	0.698071288	0.350319444	0.603114891	0.601875745	0.384523358	0.536559697
2012	0.776066983	0.339548947	0.583509956	0.690841737	0.570898895	0.581865815
2013	0.828731687	0.262698718	0.615840786	0.651202316	0.683711182	0.529667742
2014	0.870258716	0.216689291	0.704755113	0.563865747	0.536881738	0.437334201
2015	0.780059732	0.158424842	0.673207491	0.526042039	0.541477922	0.333518245
2016	0.747573198	0.205292335	0.672157152	0.647591665	0.553753782	0.222746235
2017	0.821217159	0.203897471	0.697909594	0.627739579	0.610668478	0.240741813

Table 2: Results of reliability analysis.

Test indicators	Cronbach's alpha	The standardization-based Cronbach's alpha	Number
Reliability analysis of driving-force indicators $A1$–$A9$	0.846	0.807	9
Reliability analysis of pressure indicator except for $B6$ and $B9$	0.772	0.736	10
Reliability analysis of exposure indicator except for $C2$, $C3$, $C8$, and $C9$	0.838	0.814	5
Reliability analysis of sensitivity indicator D except for $D5$, $D11$, and $D12$	0.828	0.817	9
Reliability analysis of adaptation indicator E except for $E4$ and $E8$	−0.168	−0.036	7
Reliability analysis of response indicators $F1$–$F13$, except for $F10$, $F11$, $F12$, and $F13$	0.785	0.761	9
Reliability analysis without the pressure indicator	0.794	0.742	5

$$A3(k) = 1.271321A(k) - 0.153368, \tag{1}$$

$$A7(k+1) = 1.109224A(k) - 0.462559B(k) * F(k), \tag{2}$$

$$A8(k) = 1.177841A(k) - 0.405501B(k) * F(k), \tag{3}$$

$$A9(k) = 1.178331A(k) - 0.614137B(k) * F(k), \tag{4}$$

$$B1(k) = 0.742291B(k)^{1/2} - 0.949691A(k) - 0.692429\,D(k)^{1/4}, \tag{5}$$

$$B5(k) = 1.267020B(k) - 0.379112A(k), \tag{6}$$

$$B8(k) = -0.457302B(k)^3 - 1.227039A(k) + 1.097400, \tag{7}$$

$$C1(k) = 0.508405C(k) + 0.913359A(k)^2, \tag{8}$$

Table 3: Normalized results of newly obtained Level-2 indicators.

Time	Criterion layer					
	Driving force $A(k)$	Pressure $B(k)$	Exposure $C(k)$	Sensitivity $D(k)$	Adaptation $E(k)$	Response $F(k)$
1995	0.062515279	0.554008256	0.080304781	0.221676968	0.478851639	0.250342784
1996	0.079761957	0.550948637	0.061899025	0.398488261	0.538525099	0.329769889
1997	0.103784324	0.573532237	0.059619658	0.418430243	0.584590071	0.229999561
1998	0.159314346	0.612556851	0.084484716	0.331067497	0.569717204	0.254885971
1999	0.171555202	0.731633643	0.104442041	0.161231245	0.558088313	0.227464781
2000	0.117896377	0.722537486	0.181143896	0.183421081	0.453673551	0.25633122
2001	0.176112462	0.758234341	0.116382775	0.194424161	0.50634672	0.254875767
2002	0.249795582	0.770750275	0.122070997	0.294706585	0.599533125	0.320016834
2003	0.276901581	0.633325512	0.16497708	0.336988909	0.605954178	0.286491388
2004	0.306615453	0.621869147	0.263769141	0.419801964	0.646167515	0.277399012
2005	0.317217797	0.618704131	0.363000825	0.563545587	0.657882041	0.34784701
2006	0.378745275	0.613395057	0.42844505	0.507514087	0.635852849	0.384687032
2007	0.413868808	0.585522534	0.308228441	0.520490054	0.738934244	0.418927723
2008	0.473513813	0.577595292	0.30679204	0.546488528	0.454874014	0.448007493
2009	0.501527729	0.60234923	0.340325962	0.55099052	0.457230192	0.494587689
2010	0.594543468	0.45383938	0.559978527	0.730663048	0.478117393	0.521349684
2011	0.698071288	0.350319444	0.505189395	0.577916879	0.384523358	0.425751915
2012	0.776066983	0.339548947	0.583509956	0.664996345	0.570898895	0.458516591
2013	0.828731687	0.262698718	0.593242595	0.618613945	0.683711182	0.443254801
2014	0.870258716	0.216689291	0.621895078	0.555085321	0.536881738	0.345105884
2015	0.780059732	0.158424842	0.658142031	0.503861896	0.541477922	0.252292119
2016	0.747573198	0.205292335	0.6344935	0.620123862	0.553753782	0.127747234
2017	0.821217159	0.203897471	0.652713211	0.59832596	0.610668478	0.160363254

Table 4: Regression results of driving force $A(k)$ to the Level-3 indicator $A3(k)$.

Dependent variable: SER01
Method: least squares
Date: 05/16/20; time: 23 : 24
Sample: 1995 2017
Included observations: 23

Variable	Coefficient	Std. error	t-statistic	Prob
SER02	1.271321	0.047795	26.59968	0.0000
C	−0.153368	0.024358	−6.296369	0.0000

R-squared	0.971175	Mean dependent var	0.394165
Adjusted R-squared	0.969803	SD dependent var	0.359425
SE of regression	0.062459	Akaike info criterion	−2.625683
Sum squared residuals	0.081923	Schwarz criterion	−2.526945
Log likelihood	32.19536	Hannan-Quinn criterion	−2.600851
F-statistic	707.5429	Durbin-Watson stat	1.072855
Prob (F-statistic)	0.000000		

$$C4(k) = 0.318150C(k) + 1.031150A(k)^2, \tag{9}$$

$$D1(k) = 1.013354\,D(k)^2 + 0.825936A(k) + 0.512665B(k)^2 + 0.529585F(k)^{1.2} - 0.339622, \tag{10}$$

$$D2(k) = -1.435704C(k)^3 + 0.608169D(k)^2 + 1.312289A(k), \tag{11}$$

$$D4(k) = 1.756984D(k)^{1/10} + 2.066999A(k)^{0.3} + 0.964715B(k)^2 - 2.650451, \tag{12}$$

$$D9(k) = 3.023137\,D(k)^2 - 3.294728A(k) * B(k)^{2/3} - 0.431347, \tag{13}$$

$$F3(k) = 3.030753F(k) - 1.264241A(k)^{2/3} * B(k), \tag{14}$$

$$F4(k) = 2.641657F(k)^{1.1} - 0.219171A(k)^{1.1}. \tag{15}$$

The maximum significance level and the optimum can be obtained after the regression analysis of (1)–(15) is conducted (see Table 5).

Since most of the data obtained are from the National Statistical Yearbooks and related regional organizations, there are errors in the data, and the randomness by various industries is strong. Hence, it is satisfactory that the adjusted optimum can reach 80% or more.

3.2. Explanations of the Measurement Model. When discussing the measurement model, we need to understand why the Level-2 indicators may have a negative impact on the Level-3 indicators. It can be seen from the regression results of the measurement model that $A3(k)$ can be completely affected by $A(k)$ without the influence of other Level-2 indicators. In addition to being affected by $A(k)$, $A7(k)$, $A8(k)$, and $A9(k)$ are also negatively affected by the interaction of $B(k)$ and $F(k)$. This is because the proportion of tourism output to GDP is affected by the number of people employed in tourism, which is also restricted due to environmental protection. At the same time, the total export-import volume and the throughput of coastal ports are also affected by the government's investment policy and local economic protection.

$B2(k)$ is positively affected by $B(k)$ and $A(k)$ because the improvement of industrial sewage discharge is related to the reduction of total solid waste production; the gradual decrease of the impact speed is related to the improvement of science and technology; $B2(k)$ is negatively affected by $C(k)$ because the pollution is increasing with the increase in environmental governance investment.

$B1(k)$ and $B5(k)$ are positively affected by $B(k)$ and are negatively affected by $A(k)$; this is because the total solid waste reduction should be positively affected by the reduction of industrial sewage discharge and industrial waste gas emissions and negatively related to the increase in per capita GDP and the throughput of coastal ports.

Both $C1(k)$ and $C4(k)$ are positively affected by the square of $A(k)$ because the urban green area and the growth of domestic tourists in Liaoning Province are driven by the per capita GDP, the annual growth rate of tourists, and the tourism output value, and the speed of the green industry development is increasing year by year.

$D2(k)$ is negatively affected by $C(k)$ because the reduction in dust fall quantity is related to the increase in the number of domestic tourists in Liaoning Province. $D9(k)$ is negatively affected by the interaction between $A(k)$ and $B(k)$ because the increase in per capita water resources and per capita GDP is negative correlation to the acceleration of "three wastes" emissions.

$F4(k)$ is positively affected by $A(k)$, because the planned fixed-asset investment growth will increase with the natural population growth rate, the proportion of the population of urban and town, per capita GDP, investment, and other indicators; $F4(k)$ is directly affected by $F3(k)$, which is indirectly affecting $F5(k)$. In recent years, $F4(k)$ has been affected by $F8(k)$ and $F9(k)$ due to the economic policy of "One Belt and One Road."

Therefore, our results indicate that, in the process of institutional reform, it is necessary to focus on measuring the negative effect of the Level-2 indicators on the Level-3 indicators. The elimination or reduction of this negative effect will greatly promote the ecological security of Liaoning Province and the development of a green economy.

4. Establishment of the Structural Equation Model

In order to study the mutual evolution among the Level-2 indicators, it is necessary to establish a structural equation model. The Eviews6 software is used to perform regression analysis on the data of the Level-2 indicators. Under the condition that the regression coefficient meets the significance level, it is maximized as much as possible. The nonlinear structural equations are obtained as follows:

$$A(k) = 1.109737C(k)^{1/2} - 0.481420F(k), \tag{16}$$

$$B(k) = -0.469607C(k) * F(k) + 1.495583B(k) * D(k)^{1/3}, \tag{17}$$

$$C(k) = 0.401778D(k) + 0.596833A(k)^{2}, \tag{18}$$

$$D(k) = 0.279918A(k) + 0.973383B(k)^{1/3} * D(k), \tag{19}$$

$$F(k) = -0.237758A(k)^{2} + 0.239984C(k)^{1/2} + 1.118338D(k)^{1/2} * F(k). \tag{20}$$

Firstly, after the cointegration test, it can be seen that the adaptation indicator $E(k)$ is stable, so the role of the adaptation indicator is neglected when studying the relationship among the Level-2 indicators. Secondly, in order to establish the Level-2 indicators' optimal state equation of the system, the Eviews6 software is employed. After repeated tests, it is maximized as much as possible under the condition that the regression coefficient satisfies the significance level. The autoregression structural equations for $A(k)$, $C(k)$, and $D(k)$ are obtained as follows:

Table 5: The maximum significance level and the optimum after regression.

Explained variable	Description of the maximum significance level probability	Optimum	Adjusted optimum
$A3(k)$	0.0000	0.9712	0.9698
$A7(k+1)$	0.0000	0.8975	0.8924
$A8(k)$	0.0000	0.9592	0.9572
$A9(k)$	0.0000	0.9826	0.9817
$B1(k)$	0.0001	0.9033	0.8937
$B5(k)$	0.0000	0.8630	0.8565
$B8(k)$	0.0000	0.9267	0.9194
$C1(k)$	0.0000	0.9622	0.9604
$C4(k)$	0.0000	0.9725	0.9712
$D1(k)$	0.0030	0.8375	0.8014
$D2(k)$	0.0000	0.9466	0.9412
$D4(k)$	0.0000	0.8342	0.8080
$D9(k)$	0.0000	0.8192	0.8011
$F3(k)$	0.0000	0.8292	0.8211
$F4(k)$	0.0000	0.8139	0.8051

$$C(k+1) = 0.864968C(k)^{1.5} + 0.357649\,D(k), \tag{21}$$

$$D(k+1) = 0.932583C(k)^{0.3} * D(k)^{0.5} + 0.556664A(k)^{0.2} * B(k)^{2/3} * F(k) - 0.582002C(k-1) * B(k). \tag{22}$$

When computing $D(k+1)$, an autoregressive structural equation of $A(k)$ needs to be established in case that the normalized data of $A(k)$ is needed:

$$A(k+1) = 0.959433A(k) + 0.156981F(k). \tag{23}$$

Hence, the data of $A(k)$ can be calculated from the response indicator $F(k)$. Regression results of (16)–(23) are shown in Table 6.

It can be seen from the structural equation (16) that $A(k)$ is negatively affected by $F(k)$, indicating that, under the past or existing system, the government decision-making has a negative impact on the driving-force indicators, so institutional reform shall be carried out. Moreover, it can be calculated based on the structural equation (17) that when $D(k) > 0.2989$, the government decision-making can play a positive role on the pressure indicator through the exposure indicator. This is because if the government's response indicator is biased towards economic development, it will result in a decline in investment in pollution control, which will inevitably lead to increasing emissions of "three wastes." It can be seen from structural equations (16) and (17) that the effect of increasing the driving-force indicator is beneficial to the indicators of exposure and sensitivity. It can be seen from the calculation of structural equation (18) that the driving-force indicator $A(k)$ has a negative effect on the government's response indicator. This is because the increase in the import and export volume of $A(k)$ (including the tourism industry in $B(k)$) and the throughput of coastal ports (with the consumption of large-scale enterprises in the province) is difficult for the government to determine the economic growth rate in the province, especially under the premise that the system is not transformed. And when the resources are exhausted, the growth rate of GDP can only be reduced. It can be seen from the autoregressive structural equation of $A(k)$ that the driving-force indicator can be completely controlled by the response indicator, which is an abnormal phenomenon. From the perspective of economic development, government intervention can only play an auxiliary rather than dominant role in the development of the natural environment.

5. Establishment and Prediction of Optimal Control Model

5.1. The Optimal Control Model and Preliminary Prediction. Since the adaptation status indicator is mainly determined by climatic factors in the natural environment, the climatic environment status of a region is affected by the global climate environment and geographic location. In the measurement model analysis earlier, the effect of the region on adaptation indicator only accounted for more than 20%. Therefore, as the state variable, the adaptation indicator E is not affected by the local environmental control, so it is ignored in this paper. At the same time, since the sensitivity indicator $C(k)$ is affected by the one-phase lag of the pressure indicator, the lagged item $C(k-1)$ is placed in the control vector when the objective function is established. According to the specific meaning of the Level-3 indicators, it is determined that the vector function $x(k) = [C(k), C(k-1), D(k)]^T$ represents the indicator system state variable, $u(k) = [A(k), B(k), F(k)]^T$ represents the control variable of the indicator system, and the correlation matrix of the state indicator and the control indicator is

Table 6: The maximum significance probability and optimality of structural equation coefficient regression.

Explained variable	$A(k)$	$B(k)$	$C(k)$	$D(k)$	$F(k)$	$A(k+1)$	$C(k+1)$	$D(k+1)$
Maximum significance level	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Optimality	0.8336	0.8876	0.9134	0.9687	0.8669	0.9755	0.8837	0.9059
Adjusted optimality	0.8257	0.8823	0.9093	0.9672	0.8535	0.9743	0.8779	0.8960

$$Q = \begin{bmatrix} 1 & 0.948859 & 0.819449 \\ 0.948859 & 1 & 0.747501 \\ 0.819449 & 0.747501 & 1 \end{bmatrix},$$
$$R = \begin{bmatrix} 1 & -0.869593 & 0.262762 \\ -0.869593 & 1 & 0.020812 \\ 0.262762 & 0.020812 & 1 \end{bmatrix}. \tag{24}$$

The objective function of building an ecological security indicator system is

$$J = \max \frac{1}{2} x(5)^T Q x(5) + \sum_{k=0}^{4} \frac{1}{2} \left[x(k)^T Q x(k) + u(k)^T R u(k) \right]. \tag{25}$$

The constraint equation of equation (24) is determined by equations (21)–(23) as

$$A(k+1) = 0.959433 A(k) + 0.156981 F(k), \tag{26}$$

$$C(k+1) = 0.864968 C(k)^{1.5} + 0.357649\, D(k), \tag{27}$$

$$D(k+1) = 0.932583 C(k)^{0.3} * D(k)^{0.5} + 0.556664 A(k)^{0.2} * B(k)^{2/3} * F(k) - 0.582002 C(k-1) * B(k), \tag{28}$$

where the regularity conditions need to be met:

$$\begin{aligned} &0 \le A(k), \\ &B(k), \\ &C(k), \\ &D(k), \\ &E(k), \\ &F(k) \le 1. \end{aligned} \tag{29}$$

Considering that Q,R are both the positive definite matrix, the larger $x(k)_2$ and $u(k)_2$, the larger the objective function. Under the premise that the control vector is given in the theoretical model, it is important to find out whether the maximum value can be obtained in the objective function and how to obtain the maximum value. According to the relevant regulations of China and Liaoning Province during 2016–2020, this paper obtains the control variable data for the next five years. That is, $u(k) = [A(k), B(k), F(k)]^T$ is obtained. Then the state equation is used to predict the trend in the next five years to determine whether it can achieve the desired result.

According to the official plan for 2016–2020, the three-waste emission shall be reduced by 20% each year. Specifically, the amount of agricultural fertilizers used reached the highest level. It shall be reduced by 20% per year. The increase in the number of employees in the tourism industry can drive the domestic and overseas market demand, expand green industries, and reduce dependence on industrial output. According to the national requirements and industry requirements for 2016–2020, the number of employees in the tourism industry should increase by more than 15% per year (20% is used in this paper). As a result, the main indicators of pressure growth from 2018 to 2023 can be obtained, which is listed in Table 7.

According to the calculation of the pressure indicator $B(k)$, the data of the control indicator $B(k)$ from 2018 to 2023 is obtained as shown in Table 8 under the assumption that the other Level-3 indicators remain unchanged.

According to the official targets for the five-year period of 2016–2020, the industrial removal rate of sulfur dioxide can be increased by 20% per year, and the regional GDP growth rate is set according to the national minimum standard of 6%. The growth rate of fixed assets investment is 20%, and other response control data are given according to the targets for the years of 2016–2020 and combined with the data of Liaoning Province in previous years. In this way, the $F(k)$ indicators are obtained (see Table 9).

From Table 9, the normalized data is obtained according to the indicator system, and then the weights of the response indicators in Table 3 are combined to obtain the control indicator of $F(k)$:

$$F(k) = 0.2530, k = 2018, \ldots, 2023. \tag{30}$$

Taking the data of 2015, 2016, and 2017 as the initial data, a numerical study was carried out using MATLAB, and the state change curve of Figure 1 was obtained. The results showed that it was very unsatisfactory. The indicator $D(k)$ has been in a state of decline, indicating that the existing system must be changed. Otherwise, the ecological security

Table 7: Expected data of the pressure $B(k)$ indicator for 2018–2023.

	2018	2019	2020	2021	2022	2023
Total production of solid waste	0.5746	0.6895	0.8274	0.9928	1.1914	1.4297
Drainage of industrial wastewater	0.7429	0.8915	1.0698	1.2837	1.5405	1.8486
Discharge of industrial waste gas	0.9719	1.1663	1.3996	1.6795	2.0154	2.4184
Application amount of agricultural fertilizer	0.0759	0.0911	0.1093	0.1312	0.1574	0.1889
Number of employees in the tourism industry	0.1700	0.2040	0.2447	0.2937	0.3524	0.4229

Table 8: Prediction results of control indicator $B(k)$.

	2018	2019	2020	2021	2022	2023
$B(k)$	0.2447	0.2936	0.3523	0.4228	0.5074	0.6088

Table 9: F(k) indicators during the years of 2016–2020.

Industrial removal rate of sulfur dioxide (%)	$F1$	0.728
Planned regional GDP growth rate (%)	$F3$	6.5
Planned fixed-asset investment growth rate (%)	$F4$	20
Planned public budget revenue growth (%)	$F5$	6.5
Planned total revenue growth of tourism of more than (%)	$F6$	11.18
Planned total retail sales of consumer goods growth rate (%)	$F7$	15
Planned growth rate of gross foreign export value (%)	$F8$	15
Planned foreign direct investment growth rate (%)	$F9$	15

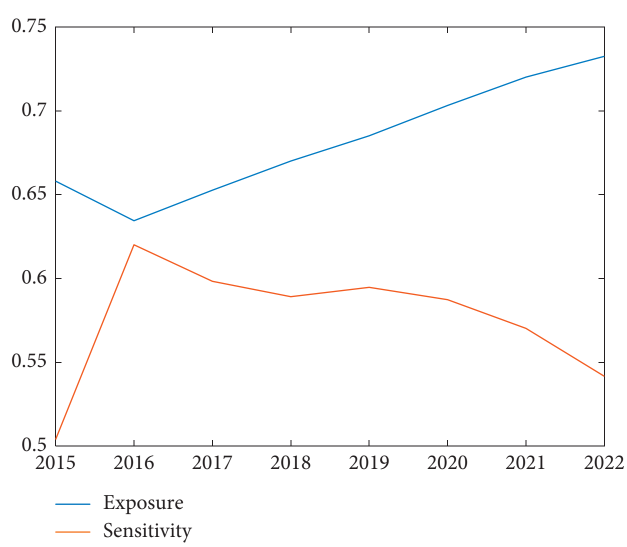

Figure 1: The state change curve.

will further deteriorate and directly affect the development of green economy.

It can be seen from the state equation of $D(k)$ that there is one item $(-0.582002C(k-1)B(k))$ for the decline. That is, there is a negative effect due to the interaction between the pressure indicator of the current year and the exposure indicator of the previous year. If the lagged effect of the exposure indicator $C(k)$ can be eliminated by institutional reform and the negative effect coefficient of 0.582002 is adjusted to be 0.1 or less, a better result illustrated in Figure 2 can be obtained. Therefore, this coefficient is very sensitive to the exposure and sensitivity indicators. However, indicator $D(k)$ is still unsatisfactory.

5.2. Correction and the Optimal State Equation. In order to achieve satisfactory results, the state equation needs to be corrected and optimized. This is because, in the process of economic development, the internal mechanism of the relevant indicators will not change greatly in a short time period. Moreover, the concept of a smooth transition of the green economy also requires the gradual reform of enterprises and governments. At the same time, the improvement of exposure indicator $C(k)$ and sensitivity indicator $D(k)$ shall meet the requirements of consistency. Therefore, the reforms outlined in the official plan (called the 13th Five-Year Plan in China) only reduce or eliminate the negative effects in the evolution of the ecological security state to varying degrees, that is, the changes in the degree of effect. Then, according to (21)–(23), the state equation containing the influence factor is obtained as follows:

$$A(k+1) = 0.980504A(k) + \alpha_1 F(k), \tag{31}$$

$$C(k+1) = 0.898542C(k) + \alpha_2 D(k), \tag{32}$$

$$D(k+1) = \alpha_3 C(k)^{0.3} * D(k) + \alpha_4 A(k) * B(k)^{1.5} * F(k)^2 + \alpha_5 C(k-1) * B(k) + 0.212647. \tag{33}$$

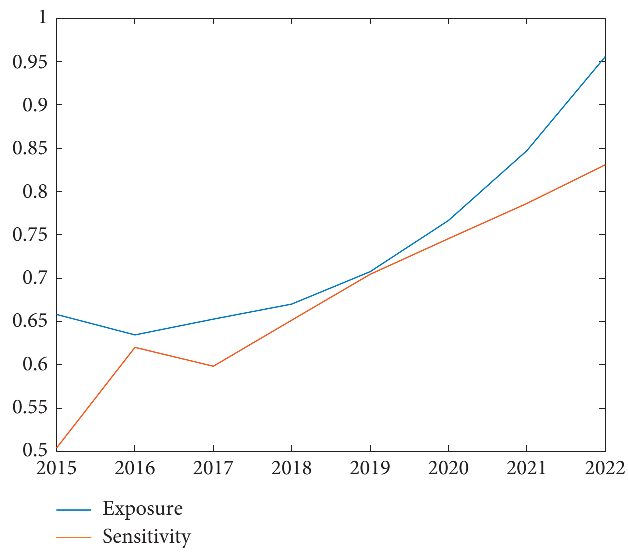

Figure 2: Prediction of interaction between lag of adjusted exposure indicator and pressure indicator.

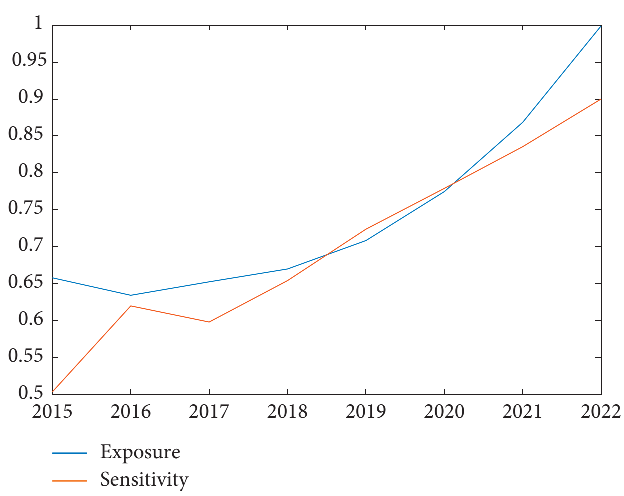

Figure 3: An ideal prediction result after adjustment of the state equation.

In this research, ideally, both the exposure indicator $C(k)$ and the sensitivity indicator $D(k)$ can be steadily improved through changing the values of the influence factors, which help promote the development of green economy. However, it can be seen that the faster the state curve $x(k) = [C(k), C(k-1), D(k)]^T$ rises, the larger the optimal control target is. Since it is difficult to solve the theoretical optimal control model of (31), we turn to analyze the evolution of the state process brought about by the change of the influence factors $\alpha_i, i = 1, 2, 3, 4, 5$. The following results can be observed through simulations.

The increase or decrease of the influence factor α_1 does not change the evolution trend of the state process but consistently rises or lowers the curves of $C(k)$ and $D(k)$; the increase of the influence factor α_2 rapidly rises the curve of the exposure indicator $C(k)$ and rapidly lowers the curve of the sensitivity indicator, and the two curves become steeper. Conversely, the decrease of the influence factor α_2 results in the lower of the $C(k)$ curve and the rise of the curve of the sensitivity indicator $D(k)$, the distance between the two curves becomes shorter, and the shape of the curve tends to be straight; the increase of the influence factor α_3 will cause both curves to rise. However, as α_3 increases, the $D(k)$ curve rises rapidly. As $\alpha_3$decreases, the $C(k)$ curve lowers rapidly. The increase (decrease) of the influence factorα_4 will cause both curves to rise (lower) at the same time, but $D(k)$ curve changes faster and the factor is more sensitive. The increase (decrease) of the influence factor α_5 will cause the $C(k)$ curve and the $D(k)$ curve to lower (rise), while $D(k)$ curve changes faster and the factor is more sensitive.

Based on the nature of the change of the above influence factors α_i, $i = 1, 2, 3, 4, 5$, the following set of influence factor values was selected through simulations:

$$\begin{aligned} \alpha_1 &= 0.3, \\ \alpha_2 &= 0.357649, \\ \alpha_3 &= 0.9, \\ \alpha_4 &= 0.9, \\ \alpha_5 &= -0.048. \end{aligned} \tag{34}$$

The ideal simulation state evolution result is obtained as shown in Figure 3.

To ensure the realization of the expected goals, the value of the influence factor $\alpha_1$was increased by about 90% from its original value, which required the enforcement of government decision-making institutions to be strengthened; the value of the influence factor α_2 was increased by about 7% on the original basis, which required the mutual effort of enterprises and communities to reduce the effect of pollution. The value of the influence factor α_3 remains almost unchanged. The value of the influence factor α_4 was increased by about 62% on the original basis, which required the government to further develop tourism resources and increase the output value of the tourism industry. At the same time, the total amount of solid waste and the application amount of agricultural fertilizer shall be reduced. The value of the influence factor α_5 was also reduced by about 90% on the original basis, and it was necessary to eliminate the exposure indicator $C(k)$ by the lag effect brought about by the pressure indicator. The ecological security indicators and green economy development issues can be effectively solved through the above calculations.

6. Conclusions

In this paper, we adopt the DPESAR indicator framework which is combined with the ecological security status and development of the green economy of Liaoning Province, China. We propose and refine a total of 64 Level-3 indicators of the evolution relationship between the ecological security and green economy development. Furthermore, we use the data on the ecological security and green economy from 1995 to 2017 to build a state equation model for this evolutionary relationship. In addition, the evolution of different state equations is explored, and the development of state indicators is improved through the adjustment of the control variables. Furthermore, the optimal control model for the development of the green economy is obtained.

The main conclusions of this research are as follows. First, several Level-2 indicators have a negative effect on the Level-3 indicators. Hence, the interactions among the government, firms, and the public should be considered to identify the symptoms and eliminate or reduce such negative effects. Second, the driving-force indicator $A(k)$ has a negative effect on the government's response indicators. This is because the inconsistency between the government and the public and firms can cause the government to make relatively arbitrary plans. Lastly, it can be seen from the optimal control model that the current economic system has no significant promotional effect on the development of green economy, and under the current situation, the decline of the sensitivity indicator will result in the deterioration of the ecological security. However, the efforts of the government can prevent the deterioration of the ecological environment or even improve it, thereby promoting the development of the green economy.

Therefore, our research shows that the key factors for the development of the measurement model and the structural model can be identified directly or indirectly. Then the specific regulation indicators and scope can be obtained by studying the evolutionary state of ecological security. This can provide a theoretical basis for the ecological security and green economy development of different countries and regions.

Data Availability

The data used to support the study are available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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