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The evaluation of forestry ecological security in China: Developing a decision support system

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ABSTRACT

The development of modern science and technology tends to accompany environmental crisis and ecological degradation. And the evaluation of the security condition of the forestry ecosystem has become an urgent task. This paper details the development of a decision support system (the FESEDSS), which was built to provide a range of actors with an effective tool for the evaluation and governance of forestry ecological security in China. The FESEDSS considers multiple factors through a general decision-support framework, making possible the calculation of ecological security indexes and relative indexes for the forestry ecosystem and its three subsystems (forest, wetlands and desert) at both the national and provincial level. The system integrates econometric models, mathematical methods, geographic information systems and a dynamic database, providing users with an understanding of spatiotemporal patterns and regional differences in the ecological security of the forestry ecosystem and its three subsystems in China's 31 provinces. Results generated using the FESEDSS and addressing the period 1999–2012 demonstrate a positive change in forest ecological security condition and a negative change in wetland and desert ecological security. Spatially, the ecological security of the forest subsystem was shown to have improved significantly in eastern and central China, while in the western region it experienced degradation. The ecological security of wetland ecosystems performed well in the southwest region and the middle and lower reaches of the Yangtze River; and desert ecological security was shown to be of a higher standard in south of Qinling-Huaihe Line than in the northern regions of the country. The overall forestry ecological security condition (which integrates the three subsystems) demonstrated an upward trend with some fluctuations, with high values generally being located in the south and low values in the north of the country. Finally, the paper also discusses performance, uncertainty, and implementation challenges, as well as detailing potential extensions of the FESEDSS. The paper lays a foundation to the national forestry ecological security evaluation and monitoring.

1. Introduction

China is a populous country with a vast territory and a tremendous diversity of biological resources. In recent years, however, its forest ecosystems have begun to suffer severe degradation as a result of human disturbances of differing durations, intensities, frequencies and types (Dai et al., 2006). A large proportion of the country's wetlands have been converted to industrial, agricultural and construction land uses; this, in combination with environmental pollution and an excessive utilisation of resources, has in turn led to reductions in the quality of wetlands and a marked decrease in biodiversity. Human activities such as the overexploitation made possible by land reclamation, practices of overgrazing and the degradation of water resources have all further contributed to advancing land degradation and soil erosion, a trend ultimately linked to a soaring rate of desertification. In order to resolve the ecological problems addressed above, China's central government has put forward a series of policies and schemes to improve ecological security. Environmental protection forms one of the

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country's basic national policies, and the government has also mapped out a number of important strategies to realise sustainable economic development.

Ecological security is one of the most important aspects of environmental protection. Maintaining ecological security has become a critical task for human societies, in our attempt to achieve sustainable development in the 21st century (Wang et al., 2014; Li et al., 2014). The "forestry ecosystem" – a term put forward here to describe the management of not only forest ecosystems but also wetland and desert ecosystems – guarantees the biological function and terrestrial eco-environment of the earth (Lu et al., 2002). The higher the level of stability and security within the forestry ecosystem, the greater the level of protection it in turn can offer in relation to the environment as a whole. The evaluation of the security condition of the forestry ecosystem has thus become a hot topic in the research community. An urgent task exists in establishing a decision support system to effectively evaluate the ecological security of forests, wetlands and deserts and scientifically extends the results of such evaluations via practical applications.

A Decision Support System (DSS) is a technology for assisting users' decision making through identifying problems, collecting and analysing data, obtaining solutions and providing information (Antunes and Costa, 2012). A DSS often consists of various environmental models, databases and assessment tools, which are integrated through a graphical user interface (GUI) (He et al., 2006; Matthies et al., 2007). Current studies that use DSS technologies suffer from a number of deficiencies. Firstly, in terms of method, a DSS often comprehensively integrates the functions of geographic information systems (GIS) (Bouroushaki and Malczewski, 2010; Karnatak et al., 2007; Malczewski, 2006), multi-objective programming models (Chang et al., 2008; Chen et al., 2010; Papadopoulou-Vrynioti et al., 2013; Rahman et al., 2012; Zucca et al., 2008) and system optimization models (Huang et al., 2010). Whilst this capacity for integration allows for the effective synthesis of different types of information through scientific approaches to development planning, few current studies have integrated different types of methods into a DSS framework. Secondly, in terms of its practical applications, DSSs have been widely used in the study of industrial water pollution and treatment (Zhang et al., 2013), watershed pollution and management (Maksimović and Makropoulos, 2002), the sustainable use of energy (Santoyo-Castelazo and Azapagic, 2014), urban traffic planning (Ortega et al., 2014), water saving measures in agriculture (Massei et al., 2014), the planning and development of rural electrification (Agalgaonkar et al., 2006) and the construction of ecological modes of agricultural development (Scott et al., 2014). Such systems have, however, rarely been used in studies of forestry ecosystem, or the evaluation and governance of forestry ecological security. Thirdly, most current studies have focused on specific, smaller-scale areas. For example, a DSS was used in relation to the protection of pine forests in Michigan's Northern Peninsula (Maclean et al., 1992), decisions about reasonable irrigation on India's plains (Sharma and Pathak, 2002), pollution control in the Black Sea (Maksimović and Makropoulos, 2002), the use of rural land and water in northern Thailand (Merritt et al., 2004) and the comprehensive planning of socioeconomic development and eco-environmental protection in Yongxin County, Jiangxi Province, China (Huang et al., 2010). Current research has thus largely ignored macro scales; only a few of them have focused on the national and provincial level (Hof et al., 1999; Hof et al., 2004).

Responding to these deficiencies, through the present study we set out to establish a more comprehensive and systematic research framework, which would use a DSS to integrate multi-disciplinary knowledge in order to obtain the scientific results needed to support more rigorous decision making in relation to the forestry ecosystem. The study thus addressed the evaluation and management of "forestry ecological security" (which included the ecological security of three subsystems: forest, wetlands and desert ecosystems) in China's 31 provinces (municipalities). First, we constructed an evaluation index system for the ecological security of forest, wetland and desert subsystems. In this way, we were able to not only evaluate the ecological security of the forestry ecosystem as a whole, but also to separately assess that of the three ecological subsystems. Secondly, we produced an integrated index evaluation system, which combined econometric models, mathematical methods, geographic information systems (GIS) and dynamic databases for ecological security evaluation. Third, we designed a user-friendly interface (called the FESEDSS), which makes it convenient for forest managers and decision makers to update data and conduct real-time monitoring of the ecological security condition of forests, wetlands and deserts. Fourth, we applied the FESEDSS to a real study case in order to demonstrate its feasibility in the evaluation of forestry ecological security for China's 31 provinces (municipalities), and the country as a whole.

2. Research method

2.1. Forestry ecological security evaluation index system

The FESEDSS – the forestry ecological security evaluation index system described in this paper – was constructed to serve the managers and decision makers of the State Forestry Administration of China (SFAC), the authority responsible for the forestry ecosystem and its forest, wetland and desert subsystems in China.

The forestry ecosystem is a significant part of the broader ecosystem, acting as an invaluable ecological, economic, aesthetic and cultural resource on which the earth's homeostasis relies. The forestry ecosystem (Bakuzis, 1969) in FESEDSS includes forests (Hao et al., 1999), but also wetland (Mitsch et al., 2009) and desert ecosystems (Havstad et al., 2006). In China, forest, wetland and desert ecosystems account for more than 70% of the total territorial area. The future of the world's forests is of considerable interest from a variety of perspectives, including global change and biodiversity conservation, and forest ecosystems provide services that are essential to maintaining life support systems across all scales, from the local level to the global level (Liebhold et al., 2017). Greenhouse gas regulation, water supply and regulation, nutrient cycling, genetic and species diversity, and recreation are only some examples of the services provided by forests (Ferretti, 1997). Wetland ecosystems are also extremely crucial natural resources, which perform functions such as seashore protection, flood regulation, underground water replenishment, fish and shellfish propagation, water purification, climate adjustment, and ecotourism destination development (Moreno-Mateos et al., 2012). Desert ecosystems have comparable capabilities in absorbing CO_2 and modulating global atmospheric CO_2 levels, and thus play an important role in the hydrological and biogeochemical cycles of the earth's ecosystem (Li et al., 2011).

Ecological security is a relatively new concept. Released in 1948, "Social Scientists Call for Peace" is considered the forerunner of modern international environmental safety research, and it was shortly followed by the United Nations Conference on the Conservation and Utilization of Resources in 1949, the first United Nations conference on natural resources (Trzyna, 1989). In 1989, the International Institute for Applied Systems Analysis (IIASA) put forward the concept of "ecological security". In a broader sense, ecological security refers to human life and the safeguarding of essential rights to live free from threat—it thus includes natural, economic and social ecological security. In a narrower sense, ecological security refers to the security of natural and quasi-natural ecological systems, thereby linking ecological systems to notions of environment security. Building on these notions, in this paper, we put forward the concept of "forestry ecological security" in order to describe the way in which, in a certain time and space, the forestry ecosystem itself can provide effective ecological, social and economic functions for human beings, and at the same time, in the case of external interference conditions such as natural disasters and human activity, continue to self-regulate and self-repair, maintaining its sustainability, complexity, recovery and serviceability (Bakuzis, 1969).

Through this study, we developed an evaluation index system for forestry ecological security, which follows the principles of scientificity, systematicity, comparability, pertinence, representativeness and practical applicability. This evaluation index system was constructed based on the Pressure-State-Response (PSR) model, a model advanced by the OECD for the analysis of the pressure, situation and response of a given system (Yin et al., 2002). The PSR model used here maintains some differences from traditional PSR models. The evaluation index system comprises of a State evaluation index system and a Pressure evaluation index system. The State evaluation index describes the material resources of the forestry ecosystem, including system structure, species diversity, system self-recovery (or anti-damage ability) and diversity of ecological service functions. It measures the capacity for self-regulation and self-repair—the stronger these factors are, the more secure the ecosystem is. The Pressure evaluation index is related to the influence of human behaviour on the forestry ecosystem. This layer reflects human behaviour and the intensity of human consumption, occupation and destruction of forestry resources – the more pressure placed on the forestry ecosystem, the less safe it becomes. In addition, the Response function that is part of traditional PSR models is here understood in terms of relief in relation to external pressures, whereby human beings become aware of the importance of forestry ecosystems and take measures to maintain and improve them. Response is made up of the inverse indicators of the Pressure evaluation index in this paper (Table 1).

Through the calculation of detailed index data, the FESEDSS facilitates the thorough and scientific evaluation of the forestry ecosystem, as well as its three subsystems, at national and provincial levels. The original data were predominantly sourced from the *Chinese Statistical Yearbook*, the *Chinese Forestry Statistical Yearbook* and the *China Environmental Statistical Yearbook*. The *Chinese Forestry Statistical Yearbook* is published annually and comprises of the "Forestry Statistics Annual Report" and other relevant information of the corresponding year that has been reported by the forestry management departments of the provinces, autonomous regions and municipalities. The *Chinese Statistical Yearbook* is also published annually, and the data is compiled by the relevant departments of the National Bureau of Statistics, including meteorological, mineral resources, water resources, land use and arable land changes, forest resources, agriculture, etc. The *Chinese Environmental Statistical Yearbook*, which is jointly edited by the National Bureau of Statistics, the Ministry of Environmental Protection and other relevant ministries, reflects the comprehensive situation of the environment in China, and bridges a range of fields. The time span of the data used is from 1999 to 2012–in total, a period of 14 years.

2.2. Evaluation method

The forestry ecological security evaluation model put forward in this paper was based on the evaluation index system described above. The evaluation model has two components. Firstly, it comprises of a comprehensive evaluation value model, which measures the security condition of the forestry ecosystem and its subsystems at the national and the provincial level from 1999 to 2012 – in total, a period of 14 years. The other component is a relative index model, which reflects changes in the security condition of the forestry ecosystem and its subsystems during the same period. The specific calculation steps were as follows:

2.2.1. Comprehensive evaluation value model

2.2.1.1. Steps for calculating state evaluation values for the ecological security of forest, wetland and desert subsystems. (1) Steps for calculating state evaluation values for the ecological security of forest, wetland and desert subsystems at the provincial level

First of all, the original data of the state index was standardised. When standardising these data, we first identified a maximum value (selected as the "satisfied value") from the regional and annual statistics data, and the minimum value (selected as the "non-permitting value") (Wang et al., 2012). The original data were then standardised using the following formula:

$$z_{eij}=\frac{x_{eij}-x_{bj}}{x_{dj}-x_{bj}} \qquad \text{(Formula 1)}$$

In Formula 1, z_{eij} and x_{eij} refer to the standardised data and the original data for area e, in year i and at state index j; meanwhile, x_{dj} and x_{bj} refer to the satisfied value and the non-permitting value of state index j.

The information utility value and the index weight were then determined. The concept of information utility value comes from entropy weight method—a kind of objective weight method, which uses entropy to express the size of the information. Generally, the greater the difference between attribute values, the greater the amount of information it contains, so the smaller the entropy value, the greater the entropy weight is. And entropy can reflect utility value (He et al., 2016; Wang and Li, 2010). An information utility value is calculated as follows:

$$h_j=1+\frac{\sum_{e=1}^{m}\sum_{i=1}^{n}Z_{eij}\ln Z_{eij}}{\ln mn} \qquad \text{(Formula 2)}$$

In Formula 2, h_j ($j = 1, 2, \ldots, s$) refers to the information utility value of state index j. $Z_{eij}=\frac{z_{eij}}{\sum_{e=1}^{m}\sum_{i=1}^{n}z_{eij}}$, where $e = 1, 2, \ldots, m$, m is the total number of statistical areas; $i = 1, 2, \ldots, n$, n is the total number of years; $j = 1, 2, \ldots, s$, s is the number of state indexes.

Having identified the information utility value of each index, we were able to calculate the weight u_j of each state index, whereby $j = 1, 2, \ldots, s$, s is the number of state indexes. The weight of each index can be obtained by calculating the ratio of the information utility value of each index to the sum of the information utility values of all of the state indexes.

According to the standardised data z_{eij} and the weight u_j of each state index, we could then obtain the corresponding annual forest, wetland and desert ecosystem state evaluation value, I_{iz}, using the following formula:

$$I_{iz}=\sum_{j=1}^{s}u_j z_{eij} \qquad \text{(Formula 3)}$$

In Formula 3, s is the number of state indexes, u_j is the weight of state index j and z_{eij} is the standardised state index data.

(2) Steps for calculating state evaluation values for the ecological security of forest, wetland and desert subsystems at the national level

Providing that $q_1, q_2, \ldots q_k$ are ecological locational coefficients in different regions, and taking $q = q_1 + q_2 + \ldots\ldots q_k$, the national forest, wetland and desert ecological security state evaluation value can be calculated as follows:

$$I_{cz}^{*}=\frac{\sum_{i=1}^{k}q_i I_{iz}}{q} \qquad \text{(Formula 4)}$$

In Formula 4, I_{iz} refers to the state evaluation values of area i in the same year, and k is number of areas involved in the statistical calculation. Differences in provincial location conditions (q) exert different influences on the evaluation of the national forest ecological security. Acknowledging this, we introduced an ecological locational coefficient as a weight in order to calculate the national state evaluation value, ensuring that our assessment of national forest ecological security exceeded a simple combination of data in each province. In this way, the ecological locational index system put forward here was able to scientifically measure differences in locational conditions. The ecological locational index system took into account three main types of factors – those relating to terrain (T), to climate (C) and to soil (S). The terrain factor was further divided into three determinants – average elevation, slope and exposure. Further, the climate factor was comprised of five determinants – annual precipitation, annual sunshine hours, annual

Table 1
Forestry ecological security evaluation index system.

Criterion Layer	First Class Index	Second Class Index	Direction	Weight
Forest Ecological Security State Index	Index of Stock Number	Forest Stock Volume Per Unit Land Area (ten thousands m^3/ha)	+	0.18301
		Forest Coverage Ratio (%)	+	0.14907
		Forest Stock Volume Per Unit Forestland Area (ten thousands m^3/ha)	+	0.16803
	Index of Complexity	Forest Species Richness Index (%)	+	0.12463
		Proportion of Forestland Area (ten thousands m^3/ha)	+	0.15424
		Proportion of Natural Forest (%)	+	0.11732
		Proportion of Public Welfare Forest (%)	+	0.08171
	Index of Catastrophe	Forest Fire Disaster Rate (%)	−	0.00272
		Forest Disease Pest and Rodent Disaster Rate (%)	−	0.00790
		Forest Drought Disaster Rate (%)	−	0.00505
		Forest Flood Disaster Rate (%)	−	0.00632
Forest Ecological Security Pressure Index	General Pressure Index	Population Density (People/ha)	−	0.22281
		Energy Consumption Per Unit Forestland Area (tons of standard coal/ha)	−	0.12105
	Pressure of Human Behavior on Forest Resources	Forest Harvesting Intensity Index (%)	−	0.15993
		Sulfur Dioxide Emission Index (t/ha)	−	0.10689
	Human Maintenance of Forest Resources	New Afforestation Area Per Unit Land Area (ten thousands m^3/ha)	+	0.20696
		Forest Construction and Protection Investment Per Unit Forestland Area (ten thousands Yuan/ha)	+	0.18236
Wetland Ecological Security State Index	Index of Stock Number	Wetland Coverage Ratio (%)	+	0.41869
	Index of Complexity	Wetland Species Richness Index (%)	+	0.20956
		Proportion of Natural Wetland (%)	+	0.04119
		Proportion of Permanent Wetland (%)	+	0.31154
	Index of Catastrophe	Wetland Drought Disaster Rate (%)	−	0.01147
		Wetland Flood Disaster Rate (%)	−	0.00755
Wetland Ecological Security Pressure Index	General Pressure Index	Population Density (People/ha)	−	0.17193
		Industrial Output Per Unit Wetland Area (ten thousands Yuan/ha)	−	0.24127
		Water Resource Consumption Per Unit GDP (m^3/Yuan)	−	0.16856
	Pressure of Human Behavior on Wetland Resources	Intensity of Human Engineering Occupation of Wetland (%)	−	0.12496
		Sewage Discharge Intensity Index (ten thousands m^3/Ha)	−	0.08262
		Fertilizer load intensity Index (t/ha)	−	0.09171
		Pesticide load intensity Index (t/ha)	−	0.06580
		COD Emissions Intensity Index (t/ha)	−	0.04943
	Human Maintenance of Wetland Resources	Attainment Rate of the Industrial Sewage Discharge (%)	+	0.00341
		Wetland Recovery and Protection Investment Per Unit Wetland Area (ten thousands Yuan/ha)	+	0.00031
Desert Ecological Security State Index	Index of Stock Number	Land Desertification Rate Per Unit Area (%)	−	0.62552
	Index of Catastrophe	Sandstorm Occurrence Rate (%)	−	0.37448
Desert Ecological Security Pressure Index	General Pressure Index	Population Density (People/ha)	−	0.13855
		Primary Industry output Per Unit Desert Area (ten thousands Yuan/ha)	−	0.01908
		Water Resource Consumption Per Unit GDP (m^3/Yuan)	−	0.21389
		Energy Consumption Per Unit GDP (Tons of standard coal/Yuan)	−	0.15669
	Pressure of Human Behavior on Desert Resources	Land Reclamation Rate (%)	−	0.02167
		Livestock per unit Desert Area (/ha)	−	0.03173
		Sewage Discharge Intensity Index (ten thousands m^3/ha)	−	0.14710
		Fertilizer load intensity Index (t/ha)	−	0.15726
		Pesticide load intensity Index (t/ha)	−	0.10120
	Human Maintenance of Desert Resources	Desertification Control Investment Per Unit Desert Area (ten thousands Yuan/ha)	+	0.01283

temperature, annual accumulated temperature and wind velocity. Finally, the soil factor was divided into a soil organic matter factor and a soil erosion intensity factor. Through the calculation of ecological locational index data using the FESEDSS, we were able to obtain ecological locational coefficients in specific provinces which thoroughly reflected the differences among provinces in terms of their locational conditions.

2.2.1.2. Steps for calculating pressure evaluation values for the ecological security of forest, wetland and desert subsystems. (1) Steps for calculating pressure evaluation values for the ecological security of forest, wetland and desert subsystems at the provincial level

First of all, the original data of the pressure index was standardised. In order to do this, we choose a maximum value and a minimum value from the regional and annual statistics data and then standardised the original data using Formulas 5 and 6 (below). Formulas for inverse index and positive index are as follows, respectively:

$$y_{eij} = \frac{x_{eij} - x_{j\min}}{x_{j\max} - x_{j\min}} \quad \text{(Formula 5)}$$

$$y_{eij} = \frac{x_{j\max} - x_{eij}}{x_{j\max} - x_{j\min}} \quad \text{(Formula 6)}$$

In the formula, y_{eij} and x_{eij} refer to the standardised data and the original data of pressure index j, for area e, in year i. $x_{j\max}$ and $x_{j\min}$ refer to the maximum value and minimum value of pressure index j.

The information utility value was then identified, after which the index weight could be determined. The information utility value of the pressure index calculation formula is as follows:

$$l_k = 1 + \frac{\sum_{e=1}^{m} \sum_{i=1}^{n} Y_{eik} \ln Y_{eik}}{\ln mn} \quad \text{(Formula 7)}$$

In Formula 7, l_k refers to the information utility value of pressure index k. $k = 1, 2, \ldots, t$, t is the number of pressure indexes. Y_{eik} refers to the standardised data of pressure index j, for area e, in year i.

$Y_{eik} = \frac{y_{eik}}{\sum_{e=1}^{m}\sum_{i=1}^{n} y_{eik}}$, where $e = 1, 2, \ldots, m$, m is the total number of statistical areas; $i = 1, 2, \ldots, n$, n is the total number of years; $k = 1, 2, \ldots, t$, t is the number of pressure indexes.

After gaining the information utility value of each index, we can determine the weight w_k of each pressure index, wherein $k = 1, 2, \ldots, t$, t is the number of pressure indexes. The weight of each index was obtained by calculating the ratio of the information utility value of each index to the sum of the information utility values of all the pressure indexes.

According to the standardised data, y_{eik} and the weight of each pressure index w_k, we were able to obtain the corresponding annual forest, wetland and desert pressure evaluation value I_{iy}:

$$I_{iy} = \sum_{j=1}^{t} w_k y_{eik} \qquad \text{(Formula 8)}$$

In Formula 8, w_k is the weight of pressure index k, and $k = 1, 2, \ldots, t$, t is the number of pressure index. y_{eik} is the standardised pressure index data.

(2) Steps for calculating pressure evaluation values for the ecological security of forest, wetland and desert subsystems at the national level.

The national annual pressure evaluation value I^*_{cfy} is obtained through the weighted calculation of annual pressure evaluation in each region I_{iy}, which is marked as I_{ify}. The weight can be obtained through calculating the ratio of the regional forest stock volume to the national forest stock volume. The larger the ratio is, the smaller the weight will be. The formula of national annual pressure evaluation value I^*_{cfy} is as follows:

$$I^*_{cfy} = \prod_{i=1}^{k} (I_{ify})^{\frac{p_i}{p}} \qquad \text{(Formula 9)}$$

In Formula 9, I_{ify} is the pressure evaluation value of region i; k is the number of areas involved in statistical calculation; p_i is the forest stock volume of region i; and $p = \sum_{i=1}^{k} p_i$ is the sum of the forest stock volume in the statistical region.

The calculation of the national wetland pressure evaluation value I^*_{CWY} was similar to that performed in relation to the forest pressure evaluation value. This value was obtained through the weighted calculation of annual pressure evaluation in each region I_{iWY}. The weight was obtained by calculating the ratio of the regional wetland area to the national wetland area. The larger the ratio is, the smaller the weight will be. The formula for calculating national wetland pressure evaluation value I^*_{CWY} is as follows:

$$I^*_{CWY} = \prod_{i=1}^{k} (I_{iWY})^{\frac{p_i}{p}} \qquad \text{(Formula 10)}$$

In Formula 10, I_{iWY} is the wetland pressure evaluation value of region i and k is the number of areas involved in the statistical calculation. p_i is the wetland area of region i, and $p = \sum_{i=1}^{k} p_i$ is the sum of the wetland areas in the statistical region.

The national desert pressure evaluation value I^*_{CDY} was obtained through the weighted calculation of annual pressure evaluation in each region I_{iDY}. The weight resulted from calculating the ratio of the regional desert area to the national desert area. The larger the ratio is, the larger the weight will be. The formula for the calculation of national desert pressure evaluation value I^*_{CDY} is as follows:

$$I^*_{CDY} = \frac{1}{p}\sum_{i=1}^{n} (I_{iDY} \times p_i) \qquad \text{(Formula 11)}$$

In Formula 11, I_{iDY} is the desert pressure evaluation value of region i; k is the total of area involved in statistical calculation. p_i is the desert area of region i, $p = \sum_{i=1}^{k} p_i$ is the sum of the desert area in statistical region.

2.2.1.3. Steps for calculating comprehensive evaluation values for the ecological security of forest, wetland and desert subsystems.

(1) The comprehensive evaluation value for the ecological security of forest, wetland and desert subsystems at the provincial level can be calculated for a given year as follows:

$$I_i = \sqrt{(1-I_{iy}) \times I_{iz}} \qquad \text{(Formula 12)}$$

In Formula 12, I_{iz} and I_{iy} are the state evaluation value and pressure evaluation values for the ecological security of forest, wetland and desert subsystems of year i in a given province.

(2) The comprehensive evaluation value of the ecological security of forest, wetland and desert subsystems at the national level can be calculated for a given year as follows:

$$I_C = \sqrt{(1-I^*_{cy}) \times I^*_{cz}} \qquad \text{(Formula 13)}$$

In Formula 13, I^*_{cz} and I^*_{cy} are the national state assessment value and national pressure evaluation value for a given year.

2.2.1.4. Steps for calculating the comprehensive evaluation value for forestry ecological security.

(1) The forestry ecosystem security evaluation value for a given year can be calculated at the provincial level as follows:

$$I_{iI} = d_1 I_{1i} + d_2 I_{2i} + d_3 I_{3i} \qquad \text{(Formula 14)}$$

In the formula, weight d_1, d_2 and d_3 respectively represent the ratio of provincial forest, wetland and desert area to the total sum of the area of these three subsystems. I_{1i} is the forest ecosystem comprehensive evaluation value for different provinces. I_{2i} is the wetland ecosystem comprehensive evaluation value for different provinces. I_{3i} is the desert ecosystem comprehensive evaluation value for different provinces.

(2) The forestry ecosystem comprehensive evaluation value can be calculated at the national level as follows:

$$I_C = d_1 I^*_{1c} + d_2 I^*_{2c} + d_3 I^*_{3c} \qquad \text{(Formula 15)}$$

In Formula 15, weight d_1, d_2, and d_3 respectively represent the ratio of the national forest, wetland and desert areas to the total sum of the area of these three subsystems. I^*_{1c} is the national forest ecosystem comprehensive evaluation value; I^*_{2c} is the national wetland ecosystem comprehensive evaluation value; and I^*_{3c} is the national desert ecosystem comprehensive evaluation value.

2.2.2. Relative index model

The relative index for ecological security, which enables the comparison of the forestry ecological security conditions of two different years, was calculated in this study as the ratio of the comprehensive evaluation value of the report period to the base period. In contrast to the ecological security comprehensive evaluation value, the relative index can more directly reflect the fluctuating trends and degree of forestry ecological security at national and provincial levels. As such, the index has great importance in forestry ecological security evaluation. The formula for calculating the forestry ecological security relative index is as follows:

$$y_c = \frac{100}{I_C^0} I_C \qquad \text{(Formula 16)}$$

In Formula 16, y_c is the ecological security relative index; I_C^0 is the ecological security comprehensive evaluation value of the base year; and I_c is the ecological security comprehensive evaluation value of the report year. By putting the comprehensive evaluation values of the forestry ecosystem and its subsystems into the formula, we were thus able to obtain the corresponding relative index.

3. Introduction to the FESEDSS

3.1. Purpose of constructing the FESEDSS

The FESEDSS, which is described in this paper, was constructed in order to serve the policy makers of the State Forestry Administration. One of their responsibilities is to supervise and manage "forestry ecological construction" throughout the country, a task which includes organising surveys, dynamic detection and the evaluation of forest, wetland and desert resources. We constructed the FESEDSS in order to help the public to better understand the development of the forestry ecological system in the country and thus get involved in questions around it. The FESEDSS provides a comprehensive evaluation value and relative index for forestry ecological security, releasing relevant information based on the forestry information platform. The system makes possible the processing, calculation and integration of data about forest, wetland and desert ecosystems, making evaluation simpler and more efficient.

3.2. Structure and function of the FESEDSS

The FESEDSS was established in order to comprehensively evaluate the forestry ecological security condition at national and provincial levels. The system is a visualisation software running on a Microsoft Windows operating system, and it is developed using Microsoft Visual Studio 2010 by applying MS ACCESS to realise the background data storage. Fig. 1 schematically illustrates the overall structure of the FESEDSS, which has three modules: a man-machine interaction module, a data management module and a model module.

The man-machine interaction module provides input windows, which display original data input, index management, evaluation result display and export options. The data management module includes original data, the formula of the evaluation index, data for the state and pressure evaluation indexes, the ecological security comprehensive evaluation value and its relative index. The model module is used to access and query large quantities of data and information and it consists of three sub-modules: the comprehensive evaluation value model, the relative index model and the GIS-based spatial analysis model, a module used for calculating the ecological security comprehensive evaluation value, the relative index and the ecological locational coefficient of the forestry ecosystem in the background. Fig. 2 shows the structure of the forestry ecological security evaluation model. The man-machine interaction and model modules communicate with the data management module directly and with each other indirectly through the data management module (Huang et al., 2010).

In terms of its function, the FESEDSS comprises of data management, index analysis, data review and background management. Fig. 3 illustrates the functional layout of the model. 1) Data management is used to effectively collect, store and process data such as original data and formulas. 2) In index analysis, this system uses the mathematical methods and models introduced in 2.2 to calculate and analyse ecological locational coefficients, state and pressure evaluation values, ecological security comprehensive evaluation values and the ecological security relative index. 3) Through the data review function, users can review ecological security comprehensive evaluation results for the forestry ecosystem and its subsystems in different periods and regions. 4) In the background management, the user management function is used to manage the information and permissions of user. The index management function is used to add and edit the index. The model management function was established to manage the comprehensive evaluation model, the relative index model and the GIS-based spatial analysis model, as well as their formulas. All in all, the FESEDSS can help forest managers and decision makers to understand in depth the evolution rules and the spatiotemporal patterns of ecological security in the forestry system and its subsystems.

The FESEDSS is a highly intuitive, visually based, user-friendly system. All interfaces conform with a normal Windows style. Most operations can be activated by using a mouse or keyboard in order to select corresponding buttons, menus or items. The background can undertake the analysis and calculation automatically, based on the ecological security evaluation index. With these different types of interfaces, evaluation and decision-making processes become relatively easy to implement, and the decision maker can obtain more valuable data that enables them to concentrate on the evaluation and decision

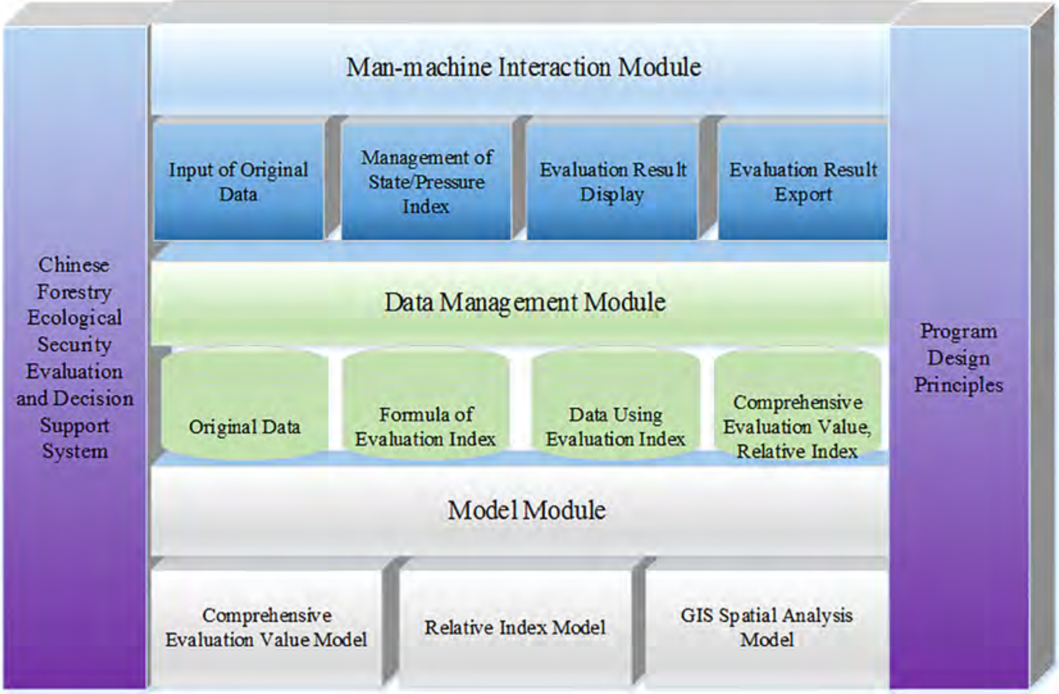


Fig. 1. Structure drawing of Chinese forestry ecological security evaluation and decision support system.

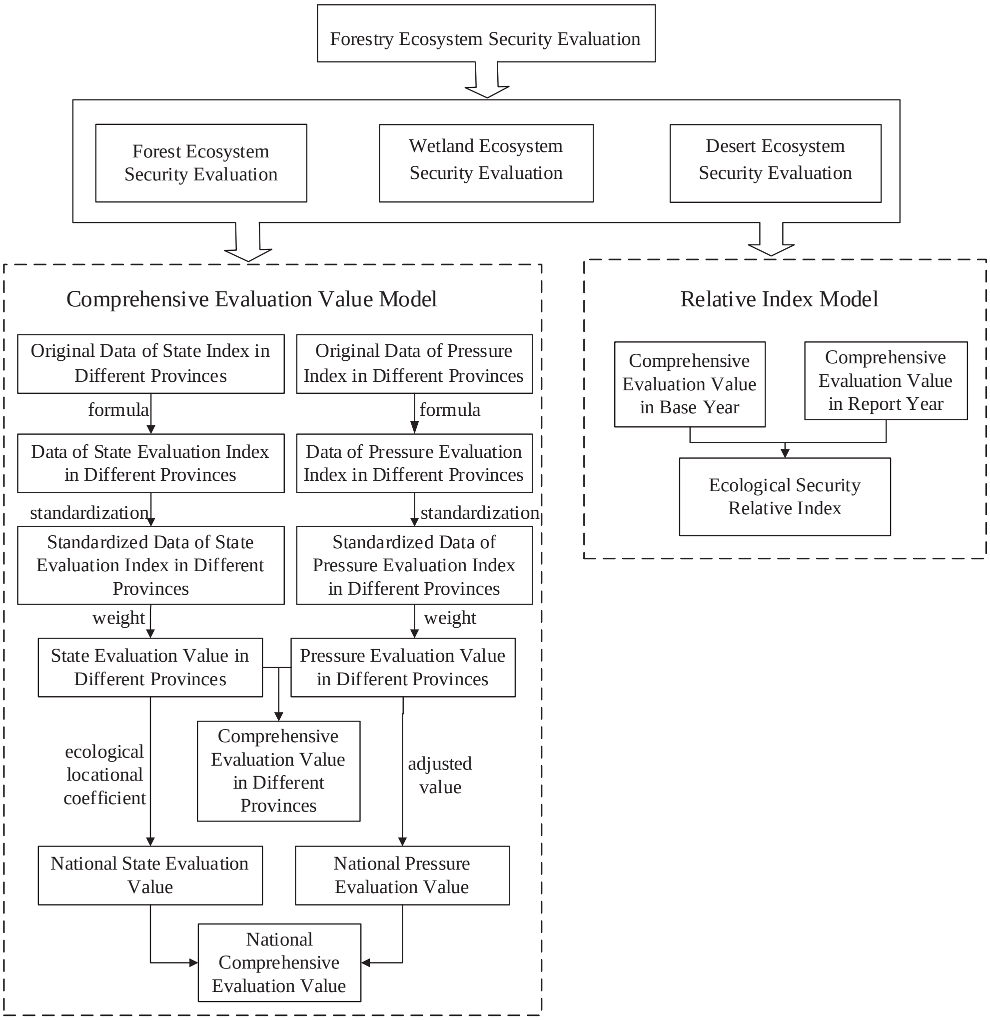


Fig. 2. Structure drawing of security evaluation model.

making itself, rather than on the use of the FESEDSS, a feature that makes this tool accessible to users who have no knowledge of computer programming or system modelling (Huang et al., 2010).

3.3. FESEDSS operation

The operation processes of the FESEDSS are as follows:

i) Data Input: Users can start the FESEDSS by double-clicking its shortcut and they can enter the main interface after they input a correct user name and password. By simply clicking the "data management" button, users can activate all the items (forestry ecosystem, forest ecosystem, desert ecosystem, wetland ecosystem and ecological locational coefficient) in the dialogue board, which is located on the right-hand side of the interface (Fig. 4). Besides, users can refer to it at any stage by simply clicking this button. Users can then input corresponding original data into the database by selecting one of these items. This original data includes state data and pressure data for each subsystem, as well as ecological locational data. The FESEDSS already contains original data from 1999 to 2012, and users can add new data at any time according to their own needs.

ii) Index Management: Users can manage corresponding state and pressure evaluation indexes in accordance with their practical needs. After filling in the related items (index name, index unit, index type and formula) on the left-hand side of the interface, users can click the "create index" button in order to finish creating the new index. Modifications can be easily made by selecting a particular evaluation index and editing the relevant items (Fig. 5a-b). Based on the established formula for the evaluation index, the FESEDSS transforms original data into data using the evaluation index, which can be reviewed by selecting the corresponding region and year (Fig. 5c-d). In addition, based on geographic grid data such as annual precipitation, annual accumulated temperature, annual temperature etc., the ecological locational coefficient and its classification maps, at both the national and provincial levels, can be obtained through the GIS spatial analysis model. Results in different regions and years can be reviewed (Fig. 5e-f).

iii) Model calculation: Based on the evaluation method introduced at 2.2, the FESEDSS calculates the ecological security comprehensive evaluation value and relative index of the forestry ecosystem and its subsystems.

iv) Results Display and Results Export: The FESEDSS can display the ecological security comprehensive evaluation value for different subsystems in the forms of both bar charts and GIS maps – the bar chart shows the sequential variation of a particular subsystem at national and provincial levels (Fig. 6a-d), while the GIS map shows the spatial distribution (Fig. 7a-d). The ecological security relative index can be illustrated in the forms of a line chart and a table. Users can export the results and store them in their personal computers according to their own needs, which is convenient for performing follow-up analysis and undertaking decision making.

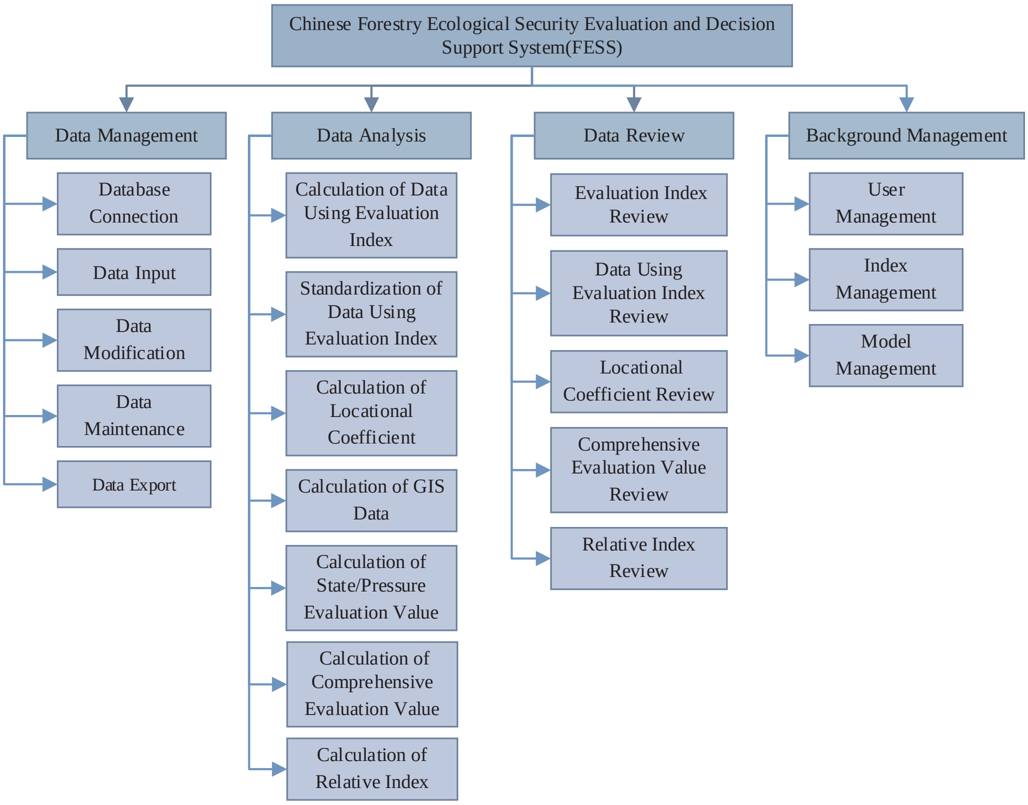


Fig. 3. Function drawing of FESEDSS.

4. Evaluation results of forestry ecological security

In our experiment, by calculating the comprehensive evaluation value and relative index of forestry ecosystem and its three subsystems with the help of the FESEDSS, we analysed changes trends in the national forestry ecological security from 1999 to 2012. We also managed to gain a good working knowledge of the spatiotemporal evolution pattern and the regional differentiation characteristics of the ecological security of the forestry ecosystem and its three subsystems, for 31 provinces (municipalities) using the FESEDSS. The results can be detailed as follows:

4.1. Results of the comprehensive evaluation of the ecological security of the forest subsystem

Fig. 6a shows that the comprehensive evaluation value for the ecological security of the forest subsystem increased continuously during the research period. Taking the initial year 1999 as the base year

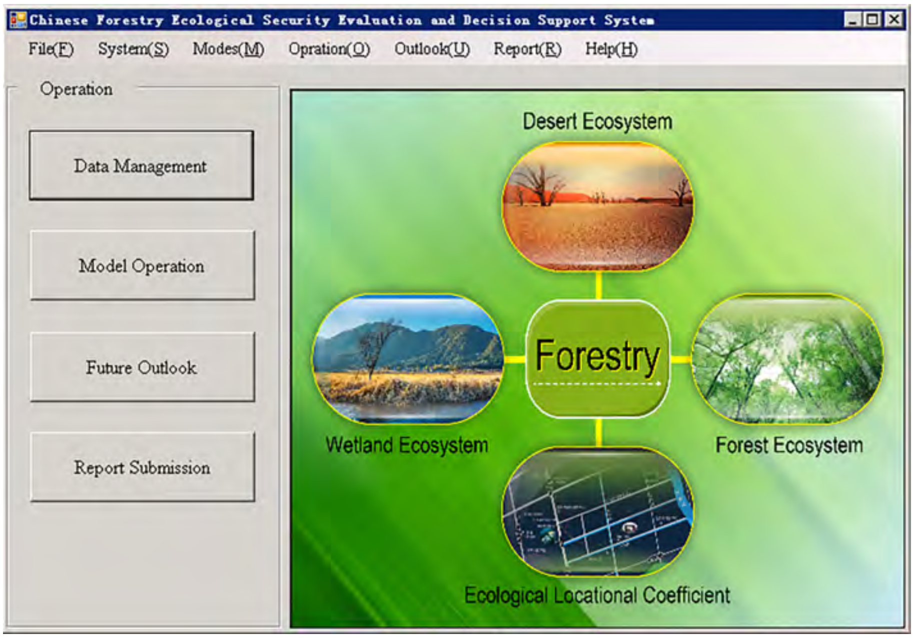
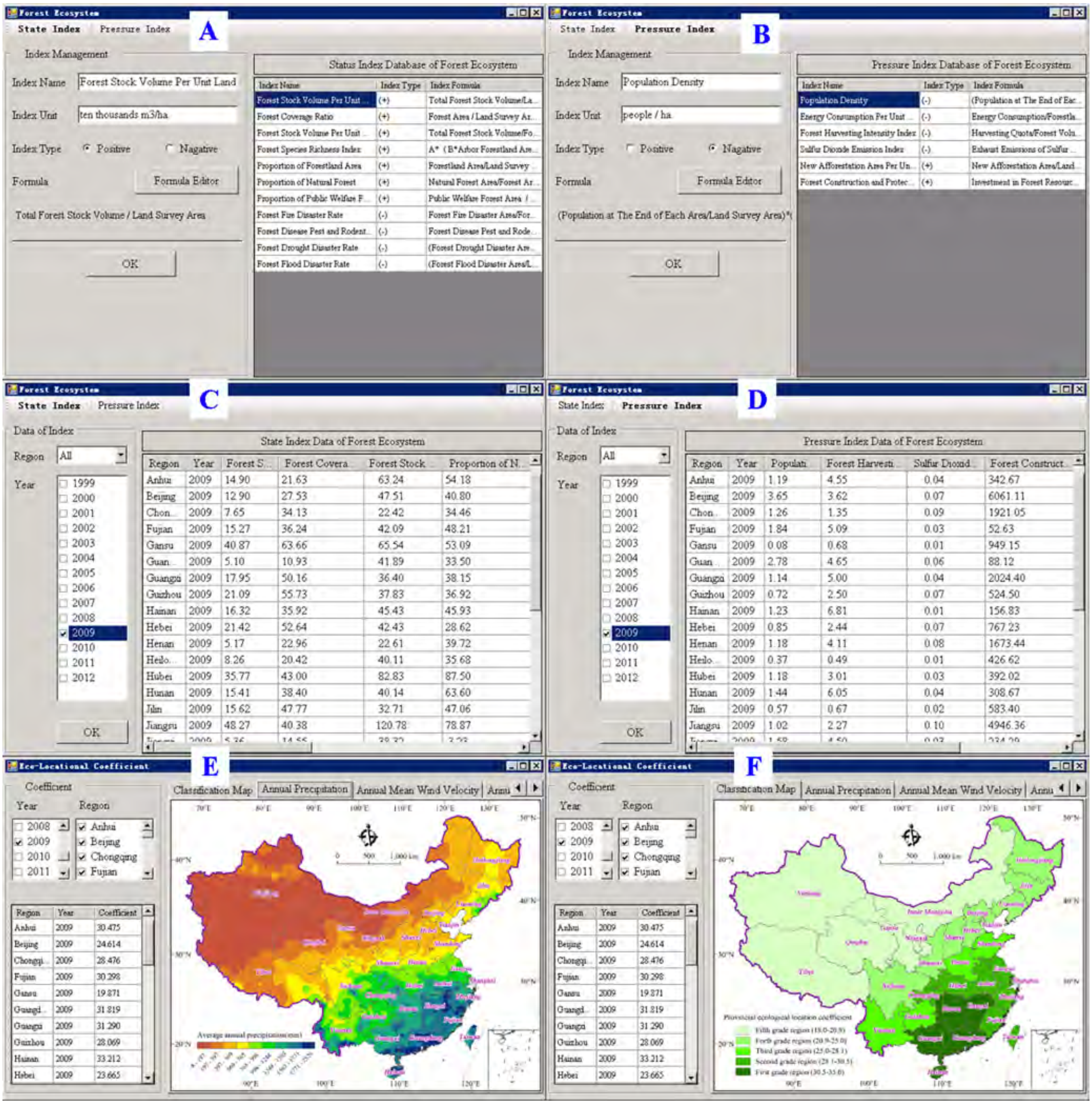


Fig. 4. Main interface of the system.



A

Index Management

Index Name: Forest Stock Volume Per Unit Land

Index Unit: ten thousands m3/ha

Index Type: ● Positive ○ Nagative

Formula: Total Forest Stock Volume / Land Survey Area

Status Index Database of Forest Ecosystem

Index Name	Index Type	Index Formula
Forest Stock Volume Per Unit ...	(+)	Total Forest Stock Volume/La...
Forest Coverage Ratio	(+)	Forest Area / Land Survey Ar...
Forest Stock Volume Per Unit ...	(+)	Total Forest Stock Volume/Fo...
Forest Species Richness Index	(+)	A* (B*Arbor Forestland Are...
Proportion of Forestland Area	(+)	Forestland Area/Land Survey ...
Proportion of Natural Forest	(+)	Natural Forest Area/Forest Ar...
Proportion of Public Welfare F...	(+)	Public Welfare Forest Area / ...
Forest Fire Disaster Rate	(-)	Forest Fire Disaster Area/For...
Forest Disease Pest and Rodent...	(-)	Forest Disease Pest and Rode...
Forest Drought Disaster Rate	(-)	(Forest Drought Disaster Are...
Forest Flood Disaster Rate	(-)	(Forest Flood Disaster Area/L...

B

Index Management

Index Name: Population Density

Index Unit: people / ha

Index Type: ○ Positive ● Nagative

Formula: (Population at The End of Each Area/Land Survey Area)*(

Pressure Index Database of Forest Ecosystem

Index Name	Index Type	Index Formula
Population Density	(-)	(Population at The End of Eac...
Energy Consumption Per Unit ...	(-)	Energy Consumption/Forestla...
Forest Harvesting Intensity Index	(-)	Harvesting Quota/Forest Volu...
Sulfur Dioxide Emission Index	(-)	Exhaust Emissions of Sulfur ...
New Afforestation Area Per Un...	(+)	New Afforestation Area/Land...
Forest Construction and Protec...	(+)	Investment in Forest Resourc...

C

Data of Index

Region: All

Year: ☐ 1999 ☐ 2000 ☐ 2001 ☐ 2002 ☐ 2003 ☐ 2004 ☐ 2005 ☐ 2006 ☐ 2007 ☐ 2008 ☑ 2009 ☐ 2010 ☐ 2011 ☐ 2012

State Index Data of Forest Ecosystem

Region	Year	Forest S...	Forest Covera...	Forest Stock ...	Proportion of N...
Anhui	2009	14.90	21.63	63.24	54.18
Beijing	2009	12.90	27.53	47.51	40.80
Chon...	2009	7.65	34.13	22.42	34.46
Fujian	2009	15.27	36.24	42.09	48.21
Gansu	2009	40.87	63.66	65.54	53.09
Guan...	2009	5.10	10.93	41.89	33.50
Guangxi	2009	17.95	50.16	36.40	38.15
Guizhou	2009	21.09	55.73	37.83	36.92
Hainan	2009	16.32	35.92	45.43	45.93
Hebei	2009	21.42	52.64	42.43	28.62
Henan	2009	5.17	22.96	22.61	39.72
Heilo...	2009	8.26	20.42	40.11	35.68
Hubei	2009	35.77	43.00	82.83	87.50
Hunan	2009	15.41	38.40	40.14	63.60
Jilin	2009	15.62	47.77	32.71	47.06
Jiangsu	2009	48.27	40.38	120.78	78.87

D

Data of Index

Region: All

Year: ☐ 1999 ☐ 2000 ☐ 2001 ☐ 2002 ☐ 2003 ☐ 2004 ☐ 2005 ☐ 2006 ☐ 2007 ☐ 2008 ☑ 2009 ☐ 2010 ☐ 2011 ☐ 2012

Pressure Index Data of Forest Ecosystem

Region	Year	Populati...	Forest Harvesti...	Sulfur Dioxid...	Forest Construct...
Anhui	2009	1.19	4.55	0.04	342.67
Beijing	2009	3.65	3.62	0.07	6061.11
Chon...	2009	1.26	1.35	0.09	1921.05
Fujian	2009	1.84	5.09	0.03	52.63
Gansu	2009	0.08	0.68	0.01	949.15
Guan...	2009	2.78	4.65	0.06	88.12
Guangxi	2009	1.14	5.00	0.04	2024.40
Guizhou	2009	0.72	2.50	0.07	524.50
Hainan	2009	1.23	6.81	0.01	156.83
Hebei	2009	0.85	2.44	0.07	767.23
Henan	2009	1.18	4.11	0.08	1673.44
Heilo...	2009	0.37	0.49	0.01	426.62
Hubei	2009	1.18	3.01	0.03	392.02
Hunan	2009	1.44	6.05	0.04	308.67
Jilin	2009	0.57	0.67	0.02	583.40
Jiangsu	2009	1.02	2.27	0.10	4946.36

E

Coefficient

Year: ☐ 2008 ☑ 2009 ☐ 2010 ☐ 2011

Region: ☑ Anhui ☑ Beijing ☑ Chongqing ☑ Fujian

Region	Year	Coefficient
Anhui	2009	30.475
Beijing	2009	24.614
Chongqi...	2009	28.476
Fujian	2009	30.298
Gansu	2009	19.871
Guangd...	2009	31.819
Guangxi	2009	31.290
Guizhou	2009	28.069
Hainan	2009	33.212
Hebei	2009	23.665

F

Coefficient

Year: ☐ 2008 ☑ 2009 ☐ 2010 ☐ 2011

Region: ☑ Anhui ☑ Beijing ☑ Chongqing ☑ Fujian

Region	Year	Coefficient
Anhui	2009	30.475
Beijing	2009	24.614
Chongqi...	2009	28.476
Fujian	2009	30.298
Gansu	2009	19.871
Guangd...	2009	31.819
Guangxi	2009	31.290
Guizhou	2009	28.069
Hainan	2009	33.212
Hebei	2009	23.665

Fig. 5. Examples of input interfaces: (A) State index management, (B) Pressure index management, (C) State evaluation index data display, (D) Evaluation index data display, (E) Annual precipitation display, (F) Classification map of ecological coefficient.

and the remaining years as the report years, the relative index for the ecological security of the forest subsystem was able to be calculated (Table 2). The results of this calculation returned a peak value of 109.74 for 2012, with a valley value of 100.73 in 2000 (the base year = 100). Furthermore, when the last year was regarded as the base year, the maximum value was 100.94 in 2012 and the minimum value was 100.47 in 2006, with an average value that amounted to 100.72 (the last year = 100). In conclusion, we can confirm that the security condition has improved remarkably and that positive results have been achieved in the overall construction of ecological security in the forest ecosystem in China.

Using the natural break point method based on GIS, the comprehensive evaluation value for the ecological security of the forest subsystem for the 31 Chinese provinces was classified into the five zones of higher, high, medium, low, and lower (Fig. 7a). The results show that during 1999–2012, provinces with higher and high comprehensive evaluation values were mostly located in the China's three major forested areas (the northeast forest region, the southeast forest region and the southwest forest region) and their security improved continually. By contrast, provinces with low and lower comprehensive evaluation value were predominantly distributed within the northwest regions (including Xinjiang, Ningxia and Qinghai) and in northern China (including Beijing, Tianjin, Hebei, Henan, Shandong, Jiangsu and Anhui). In addition, during 1999–2012, the overall ecological security condition of the forest subsystem in the eastern and central areas improved considerably, with internal gaps shrinking. Regional difference within the western area widened, a result which we attribute to an obvious polarization phenomenon. These results clearly demonstrate

Fig. 6. Examples of output interfaces: (A-D) Bar charts of ecological security comprehensive evaluation value in different ecosystems.

that the ecological security condition of forest ecosystems improved in most provinces; greater attention must be paid and measures taken in provinces like Shanghai, Beijing, Tianjin, Ningxia, Qinghai and Xinjiang in order to prevent the degeneration of the forest ecosystem in these areas.

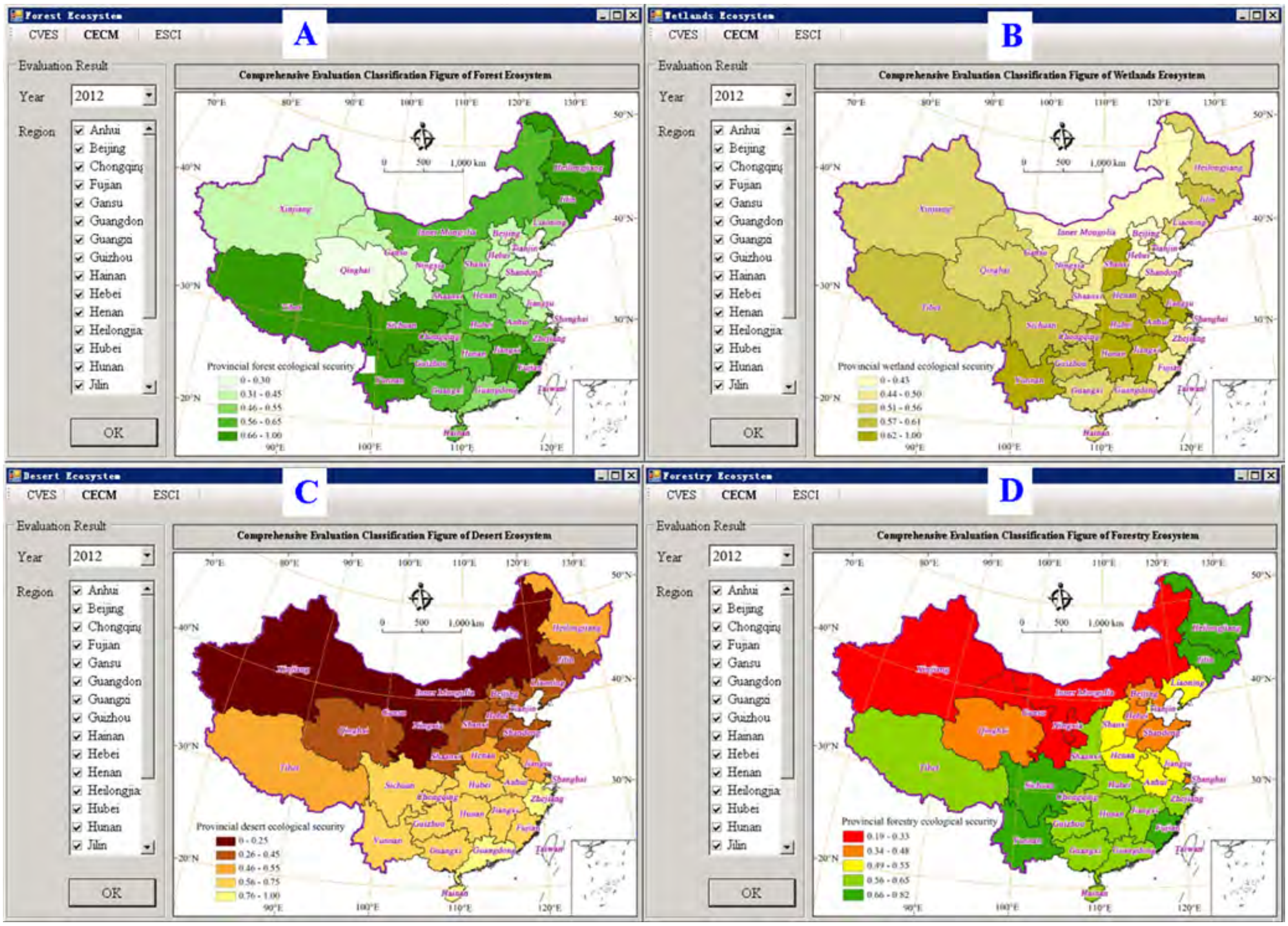
4.2. Results of the comprehensive evaluation of the ecological security of the wetlands subsystem

Fig. 6b illustrates a decrease in the ecological security comprehensive evaluation value for wetland ecosystems: from 0.5777 in 1999 to 0.5756 in 2012. Taking the initial year 1999 as the base year and the remaining years as the report years, the relative index for the ecological security of wetland ecosystems can be calculated (Table 3). Results reveal that with the exception of the four years of 2001, 2003, 2004 and 2007, a noticeable improvement can be witnessed in the relative index, which declined significantly over the remaining nine years. The peak value was found to be 100.03 in 2001 and 2004, and the valley value was 99.65 in 2012 (the base year = 100). In addition, when regarding last year as the base year, the maximum value was 100.08 in 2008, the minimum value was 99.86 in 2007, and the average value was 99.97 (the last year = 100). This suggests that the security condition underwent a slight deterioration.

The classification map for wetland ecological security comprehensive evaluation (Fig. 7b) shows that provinces with higher and high comprehensive evaluation value were mainly located in the middle and lower Yangtze River (including Jiangsu, Anhui, Hubei, Hunan and Jiangxi) as well as in the southwest regions (including Tibet, Sichuan, Yunnan, Guizhou and Chongqing). In contrast, provinces with lower and low comprehensive evaluation values were mainly located in northern China (including Beijing, Tianjin, Hebei and Shandong), the north-western regions (including Inner Mongolia, Ningxia and Shanxi) and some eastern coastal regions (including Shanghai, Zhejiang and Fujian). Comparison of the spatiotemporal pattern of wetland ecological security between 1999 and 2012 reveals that – with the exception of Shanghai, where values declined from the cluster zones of the high grade to the low grade, and Henan, where values dropped from the higher grade to the high grade – most of provinces maintained the same level.

4.3. Results of the comprehensive evaluation of the ecological security of the desert subsystem

From Fig. 6c, it is noted that desert ecological security comprehensive evaluation value fluctuated greatly during the research period, and in general witnessed a slight degradation. Taking the year 1999 as the base year (= 100) and the remaining years as the report years, the relative index for the ecological security of desert ecosystems can be calculated (Table 4). Desert ecological security was found to deteriorate: of all the years, only 2010 improved on the 1999 results (in all other years, results were lower). The maximum index (the best) was 101.82 in 2010, while the minimum index (the worst) was 89.78 in 2004. After reaching the best condition in 2010, 2011 suffered a considerable decline. Whilst the index value then improved in 2012, it remained less than the maximum. Taking the last year of the study period as the base year, the maximum value and the minimum values were found to be 110.49 in 2012, and 88.47 in 2011 (the last year = 100). These results indicate that the ecological security condition of desert ecosystems in China was not stable during the research period.



Year 2012

Region
☑ Anhui
☑ Beijing
☑ Chongqing
☑ Fujian
☑ Gansu
☑ Guangdong
☑ Guangxi
☑ Guizhou
☑ Hainan
☑ Hebei
☑ Henan
☑ Heilongjiang
☑ Hubei
☑ Hunan
☑ Jilin

Fig. 7. Examples of output interfaces: (A-D) Classification map of ecological security comprehensive evaluation value in different ecosystems.

Table 2
Relative index of national forest ecological security.

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
1999	0.54176													
2000	100.73	0.54569												
2001	101.34	100.61	0.54904											
2002	102.17	101.44	100.82	0.55354										
2003	102.91	102.17	101.55	100.72	0.55752									
2004	103.71	102.96	102.34	101.51	100.78	0.56187								
2005	104.47	103.72	103.08	102.25	101.52	100.73	0.56597							
2006	104.96	104.21	103.57	102.73	102.00	101.21	100.47	0.56865						
2007	105.53	104.77	104.13	103.28	102.55	101.75	101.02	100.54	0.57172					
2008	106.24	105.47	104.83	103.98	103.23	102.43	101.69	101.21	100.67	0.57554				
2009	107.16	106.39	105.74	104.88	104.13	103.33	102.58	102.09	101.55	100.87	0.58055			
2010	107.96	107.18	106.53	105.66	104.91	104.10	103.34	102.85	102.30	101.62	100.75	0.58488		
2011	108.72	107.93	107.28	106.40	105.64	104.83	104.07	103.57	103.02	102.34	101.45	100.70	0.58898	
2012	109.74	108.95	108.29	107.41	106.64	105.82	105.05	104.55	103.99	103.30	102.41	101.65	100.94	0.59454

From the classification map of comprehensive evaluation values for the desert subsystem (Fig. 7c), the spatiotemporal distribution pattern displays significant differentiation: desert ecological security in the south of China was much better than that in the north. The provinces belonging to the higher, high and medium cluster zones were mainly located south of the Qinling Mountain-Huaihe River Line, and were especially concentrated in the Yangtze River region and the Pearl River region. A comparison of the spatiotemporal pattern of desert ecological security between 1999 and 2012 suggests that most provinces in the north of China achieved considerable improvements in desert ecological security, while some provinces in the south exhibit degradation trends. For example, Heilongjiang and Henan rose from the cluster zone of the low grade to the medium grade, while Jiangxi, Fujian and Hunan dropped from the higher grade to the medium grade. Concerted efforts must be made in relation to provinces such as Inner Mongolia, Xinjiang and the Ningxia autonomous regions in order to prevent the further degeneration of the desert ecosystem in these areas.

4.4. *Results of the comprehensive evaluation of forestry ecological security*

From Table 5, forestry ecological security comprehensive evaluation values demonstrate an upward trend over the study period, with some

Table 3
Relative index of national wetland ecological security.

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
1999	0.57764													
2000	99.98	0.57750												
2001	100.03	100.05	0.57780											
2002	100.00	100.03	99.97	0.57765										
2003	100.02	100.05	99.99	100.02	0.57777									
2004	100.03	100.05	100.00	100.03	100.01	0.57780								
2005	100.00	100.03	99.97	100.00	99.98	99.97	0.57765							
2006	99.91	99.94	99.89	99.91	99.89	99.89	99.91	0.57714						
2007	99.78	99.80	99.75	99.78	99.76	99.75	99.78	99.86	0.57636					
2008	99.85	99.88	99.83	99.85	99.83	99.83	99.85	99.94	100.08	0.57679				
2009	99.76	99.78	99.73	99.76	99.74	99.73	99.76	99.84	99.98	99.90	0.57624			
2010	99.74	99.77	99.72	99.74	99.72	99.72	99.74	99.83	99.97	99.89	99.99	0.57616		
2011	99.66	99.68	99.63	99.65	99.63	99.63	99.65	99.74	99.88	99.80	99.90	99.91	0.57565	
2012	99.65	99.68	99.62	99.65	99.63	99.62	99.65	99.74	99.87	99.80	99.89	99.91	100.00	0.57563

fluctuations. Taking the year 1999 as the base year, the forestry ecological security relative index was calculated. The maximum index value was 104.43 in 2010 and 2012, and the minimum index value was 97.26 in 2004 (the base year = 100). Although the relative index for forestry ecological security was shown to fall in value in several years between 1999 and 2012, it still rose to new heights by a large margin in 2010 and 2012. When using the last year as the base year, the maximum value was found to be 104.31 in 2012, the minimum value was 95.87 in 2011, and the average value was 100.3638 (the last year = 100). Generally, Chinese forestry ecological security experienced substantial improvement during the period 1999–2012.

From Table 6 and Fig. 7d, it is noted that the forestry ecological security comprehensive evaluation values varied from 0.19337 to 0.81577 between the country's provinces. Yunnan was found to have the highest forestry ecological security value with 0.80929, 0.80635 and 0.81577 in 1999, 2004 and 2012 respectively. In contrast, Xinjiang has the lowest value with 0.22643, 0.20226 and 0.19337 in 1999, 2004, and 2012 respectively. Furthermore, the spatiotemporal pattern of forestry ecological security shows high values in the south and low values in the north. Provinces belonging to the higher, high and medium cluster zones were mainly located in the south of the Yangtze River regions and in the northeast regions. Meanwhile, the northwest regions (including Xinjiang, Inner Mongolia, Gansu, Ningxia and Qinghai) were in the worst forestry ecological security condition. Forestry ecological security in the Bohai Bay area (including Beijing, Tianjin, Hebei and Shandong) has deteriorated to a remarkable extent and will be further threatened by rapid urbanization accompanying the integrated development of Beijing-Tianjin-Hebei. During 1999–2012, Hubei, Zhejiang and Shaanxi advanced to the rank of the high grade from the medium grade, and Henan, Shanxi and Tianjin also progressed to the medium grade from the low grade. Only Shanghai fell form the high grade to the low grade, results which demonstrate that most provinces achieved improvements in their forestry ecological security.

5. Discussion

5.1. Performance of the FESEDSS

The FESEDSS has three modules: man-machine interaction, data management and the model module. The system components are generally interdisciplinary, requiring the linkage of different components with complex interactions. For man-machine interaction, the FESEDSS packages all the operations, and users can simply click on the button on the interface to easily assess ecological security. In addition, the FESEDSS processes possible errors that may occur to ensure the stable operation of the system. For data management, users can customise the index system by adding or deleting indexes based on their needs. They can also import data relevant for the purposes of ecological security assessment. The system can also automatically save the evaluation result, which users can refer to again in future sessions. The system designs different components and complex interconnections to deal with the interdisciplinary nature of the model.

The test, trial operation, as well as actual use, of the FESEDSS show that the system is characterised by excellent stability and reliability, with no calculation errors or system crashes occurring. Since ecological security evaluation is often annual and phase-based, the system performs the unified calculation after the data acquisition is completed. In the follow-up application, the calculation results are stored and can be directly queried and used for statistics, which avoids the repeated calculation of each application and improves system performance. The test results have proved that it would take 2 min and 37 s to complete a calculation, consuming only milliseconds for the following application

Table 4
Relative index of national desert ecological security.

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
1999	0.56745													
2000	98.68	0.55995												
2001	96.31	97.6	0.54652											
2002	96.12	97.4	99.8	0.54542										
2003	96.84	98.13	100.54	100.75	0.54949									
2004	89.78	90.98	93.22	93.41	92.72	0.50947								
2005	97.9	99.21	101.65	101.65	101.1	109.04	0.55552							
2006	94.76	96.03	98.39	98.59	97.86	105.55	96.8	0.53774						
2007	93.91	95.16	97.5	97.7	96.97	104.59	95.92	99.09	0.53286					
2008	97.19	98.49	100.91	101.12	100.37	108.25	99.28	102.56	103.5	0.55151				
2009	92.96	94.21	96.52	96.72	96	103.54	94.96	98. 1	99	95.65	0.52752			
2010	101.82	103.19	105.72	105.94	105.15	113.41	104.01	107.45	108.43	104.77	109.53	0.57779		
2011	90.09	91.29	93.53	93.72	93.03	100.34	92.02	95.06	95.93	92.69	96.9	88.47	0.51119	
2012	99.54	100.87	103.35	103.56	102.79	110.87	101.68	105.04	106	102.42	107.07	97.76	110.49	0.56483

Table 5
Relative index of national forestry ecological security.

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
1999	0.55668													
2000	99.70	0.55503												
2001	98.93	99.22	0.55070											
2002	99.22	99.52	100.30	0.55234										
2003	99.88	100.18	100.97	100.67	0.55602									
2004	97.26	97.55	98.32	98.03	97.38	0.54146								
2005	101.09	101.39	102.18	101.88	101.21	103.93	0.56273							
2006	100.03	100.32	101.11	100.81	100.15	102.84	98.95	0.55683						
2007	99.96	100.26	101.05	100.75	100.08	102.77	98.89	99.93	0.55647					
2008	101.68	101.98	102.79	102.48	101.80	104.54	100.59	101.65	101.72	0.56604				
2009	100.43	100.73	101.52	101.22	100.55	103.26	99.35	100.41	100.47	98.77	0.55910			
2010	104.43	104.74	105.56	105.25	104.55	107.36	103.30	104.40	104.47	102.70	103.98	0.58132		
2011	100.12	100.42	101.21	100.91	100.24	102.93	99.04	100.09	100.16	98.46	99.69	95.87	0.55734	
2012	104.43	104.74	105.56	105.25	104.56	107.37	103.31	104.40	104.47	102.70	103.98	100.00	104.31	0.58134

query and statistics, thereby satisfying users requirements.

5.2. Uncertainty of the data for the FESEDSS

To ensure scientific quality and rigor, the study did not select data before 1999. This was for three reasons: 1) The earlier statistical data sources were scattered, with low integrity. 2) The statistical calibre was inconsistent. 3) The statistical technology was not good enough. However, with improvements in national statistical data, the quality of the data improved continuously from 1999 onwards, increasingly being able to better meet the need of researches. In addition, national statistics data are conducted on a nationwide scale, cover a wide range of fields, and are open to the public; as such, we consider the reliability and authority of national statistical data from 1999 to 2012 to be high.

In view of the evaluation method proposed in this paper, we have also undertaken relevant experiments to determine the final retained decimal places. We found that when we gradually increase the number of decimal places to five decimal places, not only the comprehensive evaluation value of each system is highly distinguishable, but also the system has the least computational complexity (Tables 2–6). As the relative index was calculated as the ratio of the comprehensive evaluation value of the report period to the base period, two decimal places were considered adequate.

5.3. Verification of the research results based on the FESEDSS

At present, a number of scholars are focusing on ecological security evaluation in their research. In terms of the forest subsystem and its ecological security, we can take Beijing as an example, and note that the overall improvement of the ecological security situation was generally due to the substantial growth in forestry investment during 2000–2012 (Li et al., 2015). Spatially, the health value of the forest ecosystem was higher in Fangshan in Beijing than in Fengtai; this is attributed to the influence of human activity, the lack of forest resources and the poor ability to recover (Liu et al., 2008). These existing studies have concluded that the more resource-abundant and structurally complex the forest ecosystem is, the higher performance it achieves in terms of stability, anti-interference ability and security.

In terms of the ecological security of wetland ecosystems, during 2005–2013 the ecological security of Chinese inland lakes has been observed to be in overall terms in good condition. It was found that the stress on the wetland ecosystem mainly came from the high pollution load resulting from human social and economic activities. Taking the wetlands of the South Bay Lake Basin and the Laizhou Bay's Coastal Plain as examples, the major influencing factors included floods, droughts, fertilisers and pesticide pollution, sewage and water shortages (Mei, 2010; Zhang and Gao, 2016). The results of these studies show an improved security condition in recent years, since the government began to pay increasing attention to the management and protection of wetland ecological ecosystems.

In terms of the ecological security of desert ecosystems, we note that since the 2000 implementation of ecological restoration measures, the area of cultivated land and the number of livestock have declined steadily and the desertification area has gradually been reduced in the Tibet autonomous region and in the southern region of the Tengger Desert (Li et al., 2016; Guan et al., 2017). However, in some of western regions such as Inner Mongolia, Xinjiang and Ningxia Autonomous regions, due to the long-term overexploitation of land reclamation,

Table 6
Forestry ecological security comprehensive evaluation value in different provinces.

Provinces	1999	2004	2012	Provinces	1999	2004	2012
Anhui	0.48677	0.51734	0.54578	Jiangxi	0.63436	0.6602	0.66828
Beijing	0.39121	0.41601	0.42578	Liaoning	0.49594	0.52095	0.53035
Chongqing	0.58148	0.56246	0.57409	Inner Mongolia	0.31154	0.31744	0.32094
Fujian	0.71656	0.72338	0.73349	Ningxia	0.2269	0.2205	0.21636
Gansu	0.31065	0.29821	0.31271	Qinghai	0.3548	0.3468	0.37031
Guangdong	0.56073	0.55237	0.55241	Shandong	0.369	0.39529	0.39982
Guangxi	0.57786	0.60355	0.61398	Shanxi	0.43643	0.46019	0.47053
Guizhou	0.51985	0.5585	0.59331	Shaanxi	0.54825	0.57924	0.60529
Hainan	0.62515	0.61049	0.61946	Shanghai	0.56454	0.47677	0.43875
Hebei	0.34558	0.37712	0.39338	Sichuan	0.72243	0.72856	0.73443
Henan	0.43549	0.47036	0.48729	Tianjin	0.45188	0.47358	0.47218
Heilongjiang	0.68206	0.71519	0.74323	Tibet	0.60491	0.59439	0.57442
Hubei	0.5244	0.58072	0.59057	Xinjiang	0.22643	0.20226	0.19337
Hunan	0.55937	0.60003	0.58715	Yunnan	0.80929	0.80635	0.81577
Jilin	0.73979	0.75829	0.77322	Zhejiang	0.52587	0.56712	0.58567
Jiangsu	0.52988	0.49694	0.50534				

overgrazing and degradation of water resources, serious land degradation and soil erosion has been caused and finally leading to a soaring rate of desertification. Much attention still needed to be paid and measures needed to be taken to prevent the degeneration of desert ecosystem in these areas.

The research findings of this study appear consistent with those of the existing literature touched upon above. These studies have, however, tended focus more on the temporal or spatial scale of a certain region rather than considering the dynamic characteristics of the system in time and space. They also lack a comprehensive evaluation of larger scale units – i.e., the provincial or national level. Our study, in contrast, combines both time and space, evaluating ecological security from a multi-scalar perspective for Chinese forestry construction.

5.4. Extension of the FESEDSS

The FESEDSS, which is described in detail in this paper, is able to gauge the forestry ecological security index and to reflect changes in national and provincial forestry ecological security. Further quantitative research into thresholds remains a pressing task for scholars, and a forestry ecological security pre-warning system needs to be developed. Forestry ecological security warning systems predict reverse evolution, degradation and the deterioration of environmental quality and ecosystems – such systems carry out ecological security warnings and are able to issue ecological security crisis alerts in advance of a crisis. The establishment of warning models require the construction of evaluation index systems like the one described here. Based on the existing FESEDSS, the results of ecological security evaluation would need to be classified for the purposes of pre-warning. The basis and criteria of classification are key to the reliability of evaluation results and are also very important to research into forestry ecological security pre-warning. The following three grading principles should be followed in the extending the model set out here in order to accommodate this expanded program. Firstly, the determination of the index criteria should be as quantified to the greatest degree possible. Secondly, international, national, industrial standard values as well as programmed values listed in the regional planning files should be adopted if the indexes have specific standards. Thirdly, the values of ecologically well-developed regions around the world, based on the research results and indicated values presented by other scholars, could be utilised for indexes that do not contain specific standards. In this way, an extended FESEDSS would not only be able to reflect trends in forestry ecological security, but also to estimate the grade of ecological security. Eventually, the FESEDSS could thus form a comprehensive system that implements three functions—monitoring, evaluation and early warning.

To obtain as well as uniformly manage data in a timely and effective manner represents a challenge to system promotion. Using a DSS with no data in forestry ecological security is like serving an empty bowl for breakfast (Dai et al., 2006). However, it is difficult for us to source all the comprehensive forestry data that the FESEDSS needs. On the one hand, this is because there a serious problem exists with respect to poor communication and low-level and repetitious construction activities between the forestry and other departments or among the different sectors of other departments, because they work independently. The same problem also exists between government and academics. An “information island” has formed, whereby a great amount of information cannot be shared, and the use of information resources has become inefficient and wasteful (Liu et al., 2014). Current data is at times inconsistent and incomplete, and it is difficult to obtain effective data. Under such circumstances, the state should offer strong support through policy formulation, resource investment and other measures. All government departments should work together, under the guidance of national policy, to eliminate barriers and establish professional organisations in order to produce a benign information release platform, ensuring the continuous supply of data information and conveying data and information to the people who need it through the internet. With the help of the new forestry inventory system, the accuracy, authority and continuity of data required for the FESEDSS can be assured.

In the future, the FESEDSS might include evaluations at the county level. Since the county is a basic unit of administrative management in China, changes in forestry ecological security in counties exert great influence on national forestry ecological security. It is difficult at present to ensure that the evaluation result of forestry ecological security at national and provincial levels play a role in the evaluation of smaller scale areas. Hence, in the future, we need to develop an evaluation monitoring system which covers the nation’s, the province’s and the county’s needs. We should adjust the existing index system, through availability analysis and expert demonstration, in order to remove and replace parts in a pragmatic manner and scientifically verify them at a theoretical level. In terms of research content, the system’s authority management should be improved and stepwise authority achieved. Further, the data delivery function needs to be expanded, allowing county data to be delivered in steps to the higher authorities in a manner that privileges authenticity, integrity and timeliness. By refining and optimising the evaluation index system and the monitored objects so as to render them specific to a given county, an extended FESEDSS would not only help local forest managers and decision makers to develop a deeper understanding of the evolution rules and spatiotemporal patterns of forestry ecological security in the forestry system and its subsystems, but also help them to scientifically formulate relevant policy.

6. Conclusions

A forestry ecological security evaluation and decision support system (FESEDSS) was developed to calculate comprehensive evaluation values for ecological security and a relative index of the forestry ecosystem (a system which includes forest, wetland and desert ecosystems) at both the national and provincial level. The FESEDSS uses a forestry ecological security evaluation index system in order to consider multiple factors within a general decision-support framework. In addition, the system integrates econometric models, mathematical methods, GIS and dynamic databases. The FESEDSS framework facilitates convenient access to the evolution rules and spatiotemporal patterns of national forestry ecological security, and provides a basis for making decisions that advance the improvement of national forestry ecological security. In this manner, it accesses the full potential of the ecosystem to protect the environment.

As the world’s largest developing country, China cannot sacrifice its environment to the goal of economic development. Instead, the country needs to stick to a path of sustainable development, in order to simultaneously achieve economic efficiency, environmental protection and social benefits. In this way, China ought to strengthen the management of the forestry ecosystem during the current phase of economic development and ensure the security of the forestry ecosystem and the retention of a high-quality ecological environment for economic development and human welfare. In the future, the functions of the FESEDSS can be expanded: its evaluation index system can be perfected, its databases can be enlarged and it can be used to put forestry ecological security evaluation into practice in ways that accord with the local condition of investigation areas. With ongoing database updates and program adjustments, the FESEDSS can promote the development and improvement of research into forestry ecosystem security.

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