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Analysis of driving forces on wetland ecosystem services value change: A case in Northeast China

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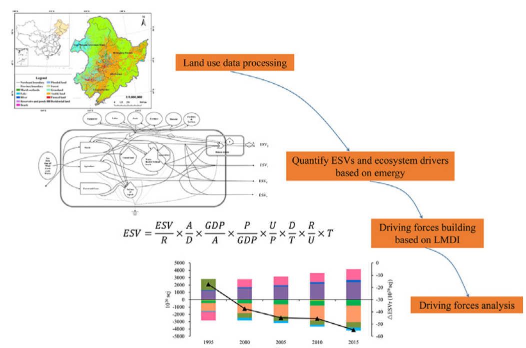
HIGHLIGHTS

- The area of natural wetlands (A) decreased, mainly converted to arable land.
- Emergy accounting was applied to calculate the ecosystem services value (ESV).
- LMDI was applied to identify the drivers of changes in ESV.
- △GA, △PG, and △T were the the main driving force factors.
- Social-economic development influence ESVs greatest, followed by human activity.

GRAPHICAL ABSTRACT



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ABSTRACT

Social development and changes in natural conditions have seriously affected the ecosystem services value (ESV) of wetlands. It is important for social sustainable development and human welfare to identify and evaluate the driving factors that lead to changes in ESVs. Based on the land use data of Northeast China (NEC) from 1980 to 2015, the Emergy method and Logarithmic Mean Divisia Index decomposition analysis (LMDI) was applied to calculate the main ESVs of wetlands and clarify the contributions of different driving factors to ESVs changes. The results showed that the value of provision services (ESV_p) and cultural services (ESV_c) increased significantly, while the value of regulation services (ESV_r) and supporting services (ESV_s) decreased. Overall, the ESV of wetlands increased by 7.31×10^{22} solar emjoules (sej), with a growth rate of 127.73%. The most obvious factors driving ESV changes were the wetland supporting factor (△GA), per capita GDP factor (△PG), and protection investment factor (△T). The combined average contribution weight of the three factors was above 50%. From the perspective of driving force category, social-economic development effect had the greatest impact on ESVs, with average contribution weights ranging from 45.18% to 54.59%, followed by human activity effect, average contribution weights ranging from 33.45% to 40.14%, and the influence of natural factor effect was relatively small. The research results would provide a reference for protecting and improving the ESV of the wetland ecosystem.

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1. Introduction

Wetland is one of the most important ecosystems on the earth. It not only provides a variety of ecosystem services (ES) for human survival

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and development (e.g. providing living and production materials and a good living environment), but also provides living space for animals (Zhang et al., 2017a; Yang et al., 2019). The value of these ecosystem services (ESV) makes wetlands the most valuable ecosystem per unit area (Costanza et al., 2014). Millennium Ecosystem Assessment (2005) divided these ESs into four categories: provision services, regulation services, cultural services, and supporting services. To obtain more production materials and development space following the social progress, the original ecosystem was constantly disrupted and destroyed which always increased the provision services value (ESV_p), while decreased the regulation services value (ESV_r) and supporting services value (ESV_s) (Ricaurte et al., 2017; Xu et al., 2019). Cultural services value (ESV_c) has uncertainties due to the regional cultural background and economic development (Queiroz et al., 2017; Pedersen et al., 2019).

The research on the ESV has gradually shifted from evaluating their values, in the early stage, to analyzing the distribution of ESVs at different types of ecosystems and its driving factors. Li et al. (2019) applied the InVEST model to analyze the trade-off relationship between agricultural production and key ES in Zhangye City and provided suggestions for the sustainable management of the city's ecosystem. Su et al. (2020) analyzed the relationship between land use changes and ESV in Fujian Province and provided basic support for regional ecological compensation. Song and Deng (2017) studied the relationship between land use and ESV in China and compared it with the global ESV changes during the same period. Besides human-dominated systems, research has also been conducted on natural-dominated ecosystems. For example, Yang et al. (2019) used the emergy method to calculate the distribution of aquatic ESV in several Chinese provinces. Zhang et al. (2017) developed a wetland ES assessment method to provide support for wetland conservation in Beijing. Zhang et al. (2019) identified driving factors for the development of ESV in Ebinur Lake Wetland National Nature Reserve and provided suggestions for balancing regional ESV differences. Besides, there are many studies about the impact of economic development (He et al., 2014), urbanization (Liu et al., 2019a; Liu et al., 2019b), and changes in natural conditions (Huq et al., 2020) on the ESV.

Although market methods (Pirard and Lapeyre, 2014), non-market methods (Oleson et al., 2018), preference methods (Börger et al., 2018) and InVEST model (Kusi et al., 2020) have been widely used to the evaluation of ESV, there are still difficulties in integrating the ESVs and different driving forces into the same dimension for evaluation and analysis. The emergy method can convert the value of ecosystem services and some driving factors that are difficult to quantify into the same dimension, such as investment in the development and protection of the ecosystem, and uniformly convert them into an emergy unit—solar equivalent joules (sej) for evaluation. In Yunnan, the emergy method was used to quantify the various input elements and ESVs in the process of wetland restoration, and assess the sustainability of the wetland (Sun et al., 2019). In Brazil, the emergy method was used to calculate various factors affecting the sustainable development of Brazilian pine and eucalyptus systems and provide solutions for sustainable land use. Wang et al. (2017) applied the emergy method to calculate input of the circular agricultural ecosystem and evaluate the sustainable development of the system. Dong et al. (2012) used the same method to calculate the ESV of Chinese grasslands, and suggested that small-scale intensive grazing should be used to promote the sustainable development of grasslands and enhance ESVs. In terms of driving force analysis, decomposition analysis is a common method that mainly includes logarithmic mean divisia index (LMDI), laspeyres index method (LAI) and arithmetic mean divisia index (AMDI). However LAI usually has the problem of a large residual, and AMDI fails to deal with the zero value (Ang, 2005). By comparison, LMDI can be used to overcome the two weaknesses shown above, so it is suitable for more situations (Ang et al., 2009). While many studies have used LMDI to analyze

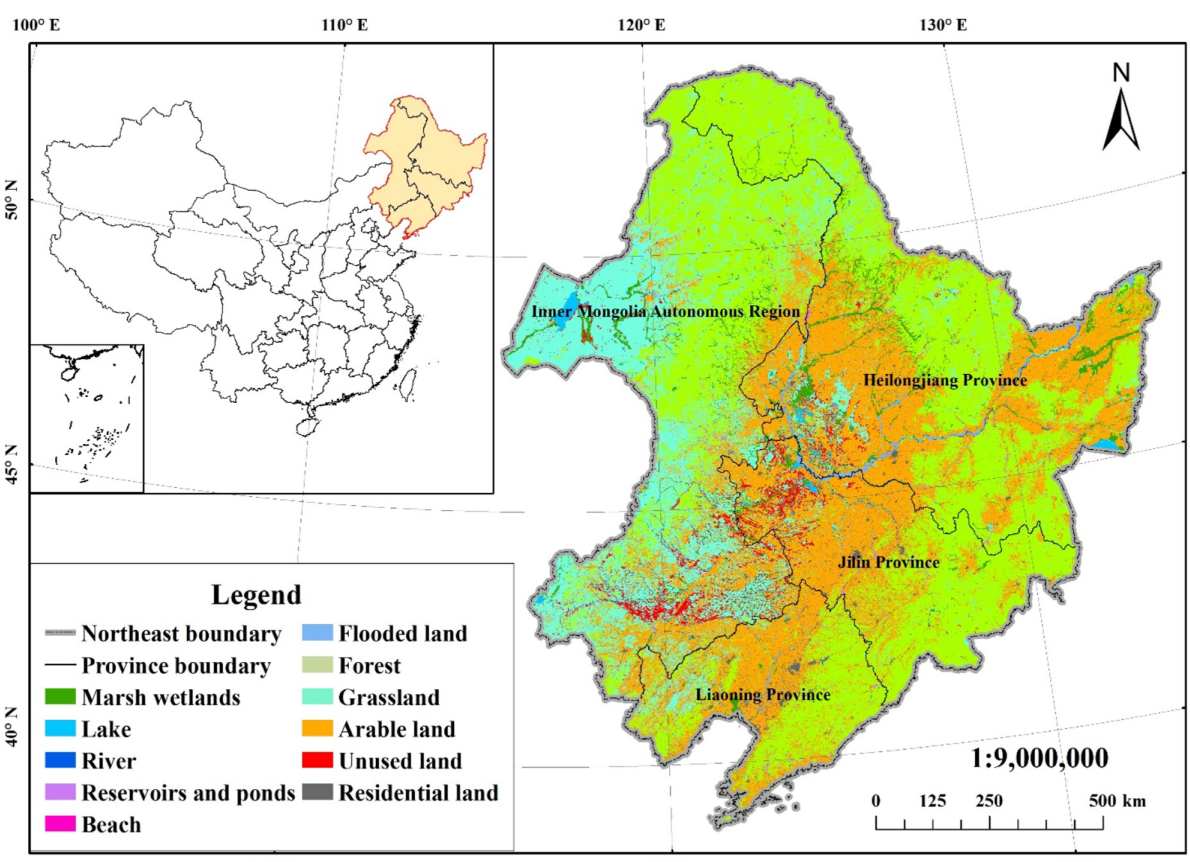

Fig. 1. Location and land use of NEC (2015).

pollution emission (Chang et al., 2018) and energy consumption (Wang et al., 2017), very few studies combined the emergy method and LMDI together in the field of ecosystem evaluation (Liu et al., 2019; Song et al., 2020).

Northeast China (NEC) is one of the most widely distributed areas of wetlands in China, and the area of marsh wetlands accounts for about 50% of that in the whole country (Liu, 2005; Niu et al., 2009). The large number of wetlands provide an important ecological barrier function for China (Zhou and Kou, 2009). In the past, due to government policies and neglect of the ESV of wetlands, many wetlands were converted to agricultural land, aquaculture land or industrial construction sites (Xing et al., 2011; Wang et al., 2012), resulting in water quality deterioration, non-point source pollution, habitat destruction and so on (Chu et al., 2015; Liu and Liu, 2006). The ESV of the wetland also changed with this process. To obtain the ESV in line with the needs of social development, it is necessary to explore the driving forces leading to its change.

This study applied the emergy method to quantitatively evaluate and analyze ESVs changes and their driving force factors, and then the LMDI method was used to identify the most important driving factors. The specific goals are: (1) calculating and analyzing the changes in the major ESVs of wetland in NEC; (2) identifying the driving forces and their impacts that led to changes in the ESVs. The results are helpful for future wetland planning and management in this area.

2. Materials and methods

2.1. Study area

NEC (115° 30′ ~ 135° 06′ E, 38° 43′ ~ 53° 34′ N) includes Liaoning Province, Jilin Province, Heilongjiang Province and four cities in Inner Mongolia Autonomous Region (i.e. Hulun Buir, Hinggan League, Tongliao City, Chifeng City). The region is characterized by a temperate continental climate, with an average annual precipitation of around 519 mm, an average annual temperature from −4 °C to 12 °C, and a total land area of around 1.24 million km^2. According to the 2015 land use data (Fig. 1), forest, arable land, and grassland are the most important land use types accounting for 41%, 31%, and 19% of the total land area, respectively. Natural wetlands, by comparison, only account for 5% of the total area which is higher than that of urban construction land and other types. NEC is an important grain-producing area in China, as well as an important distribution area of forests and wetlands. At present, 15 wetlands have been listed as internationally important wetlands, accounting for 26% of China. In order to protect and restore natural wetlands and obtain higher ESVs, the government implemented the "National Wetland Conservation Program (2002-2030)" (NWCP) and NEC was listed as one of eight important wetlands regions.

2.2. Methods

Influenced by continuous changes in land use, natural wetlands constitute an ecosystem that includes multiple land use types (Fig. 2). In this study, it was regarded as a broad wetland ecosystem. It can be seen that changes in natural conditions outside the system boundary and input from human society will affect the ESV of wetland ecosystems.

In general, this study can be divided into three steps (Fig. 3): The first step is to process the land use data of the wetland ecosystem in the study area, the second step is to clarify the main ES, calculate and analyze the changes of ESVs, and the third step is to construct the driving factors that lead to changes in ESV and perform quantitative analysis. The specific process is as follows:

2.2.1. Land use data processing

From a long-term perspective, in the process of the destruction and restoration of natural wetlands, the natural wetland and other land use types always existed mutual conversion. As a first step, natural wetland areas of NEC in 1980, 1995, 2000, 2005, 2010, and 2015 were extracted from the land use data provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC). Then the vector data of each period were merged through ArcGIS, and the scope of the study area was determined. Finally, by cutting the original land use vector data with this scope, the land use data of the study area in different periods were obtained (Fig. 4).

According to the Ramsar Convention (Ramsar Convention, 1971), the Wetland Classification (Li and Liu, 2014), and the Current Land Use Classification (China), natural wetlands in this study were classified into five types: marsh wetlands, river wetlands, flooded wetlands, beach wetlands, and lake wetlands. Other land use types were classified into six types: reservoir and ponds, arable land, forest, grassland, residential land, and unused land.

2.2.2. Ecosystem services frame

As shown in Table 1, some major and representative ESs were selected to analyze the impact of different driving factors on their value changes (Li et al., 2018; Gómez-Baggethun et al., 2019). Referring to

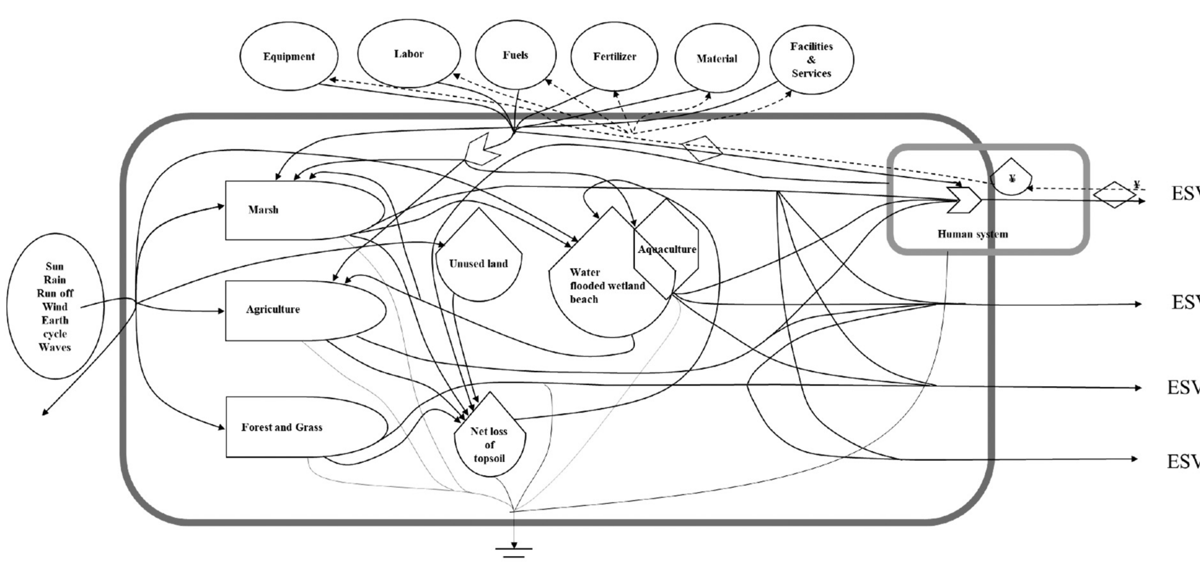

Fig. 2. Main emergy flows and ESVs in the study area.

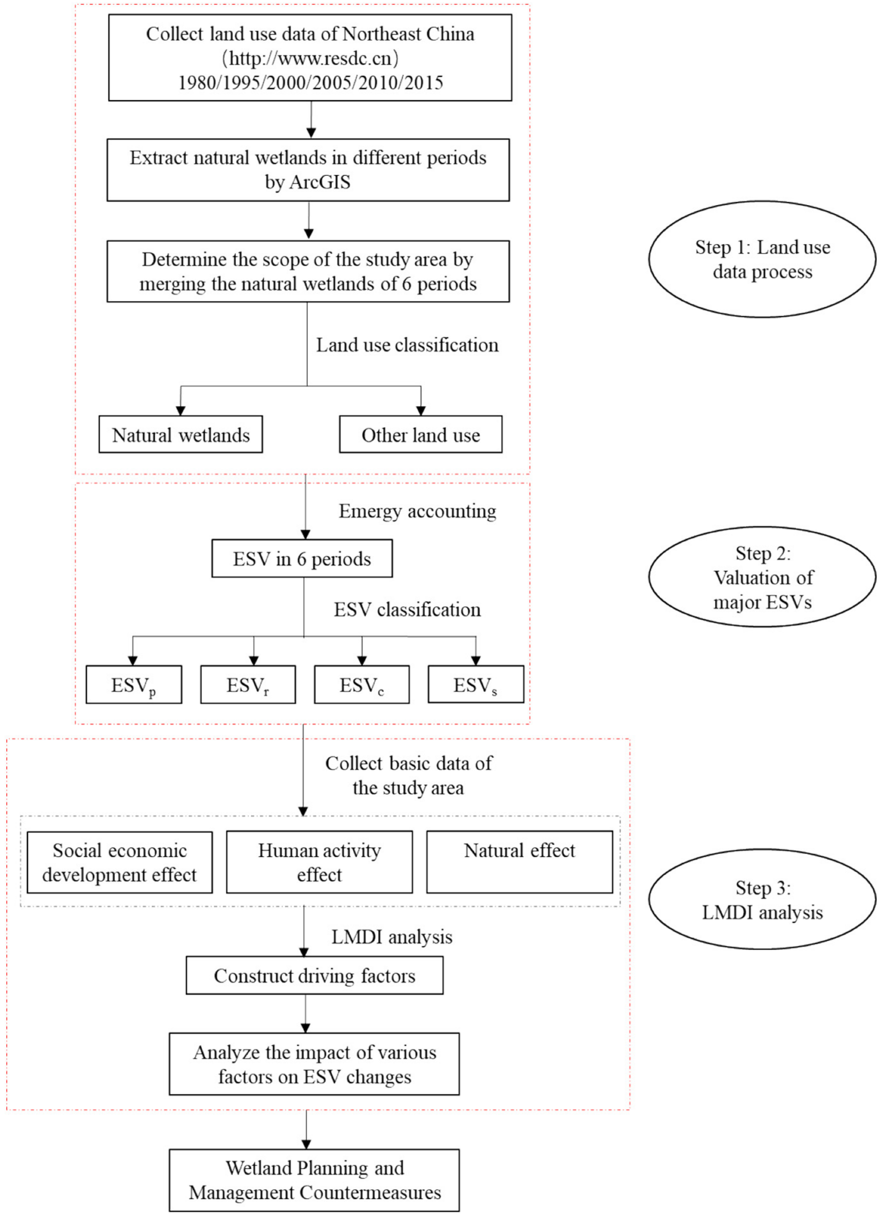

Fig. 3. Flowchart of the study.

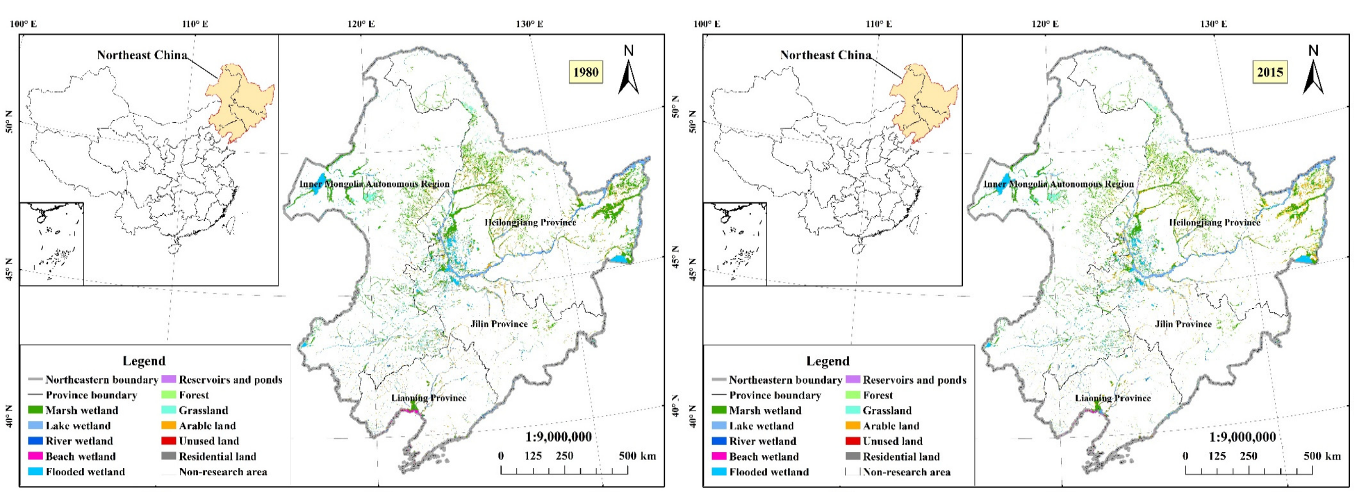

Fig. 4. The scope and land use of the study area (1980 and 2015).

Table 1
The framework of the study area ecosystem service evaluation.

Item	Services	Natural wetlands					Other land use types					
		Marsh	River	Lake	Beach	River beach	Reservoir and ponds	Arable land	Forest	Grassland	Residential land	Unused land
	Provisioning services											
1	Fish harvest		●	●			●					
2	Food							●				
3	Raw materials	●										
4	Water supply		●	●								
	Regulating services											
5	Disturbance regulation	●		●			●					
6	Gas regulation	●						●	●	●		
7	Waste treatment	●		●			●					
8	Supplementing groundwater	●										
	Cultural services											
9	Recreation	●	●	●	●	●	●		●	●		
	Supporting services											
10	Gross primary production (GPP)	●							●	●		

the ecosystem services classification system of the Millennium Ecosystem Assessment (2005), the ESs were divided into four categories: provision services, regulation services, cultural services, and supporting services. Also, the abbreviations used in this study are shown in Table 2.

2.2.3. Emergy accounting on ecosystem services

In the emergy method, all materials, energy, or information can be converted from conventional units (J, g, money) to emergy units (solar emjoules, sej) through their solar transformity (UEV) to calculate their emergy values. The ESV in this study can be calculated according to the following emergy method calculation formula (Odum, 1996):

$$\mathrm{E} = \sum f_i \times UEV_i \; i = 1, \ldots, \mathrm{n} \tag{1}$$

E represents emergy value; f_i represents the ith material flow, information flow, or energy flow; UEV_i represents the solar transformity of the ith material flow, information flow, or energy flow. The detailed emergy calculation of ESV is shown in the supplementary material.

2.2.4. Logarithmic Mean Divisia Index decomposition analysis (LMDI)

LMDI decomposes the target value into several factors based on mathematical calculations and gives the contribution of each factor to identify the factor that has the greatest impact on the target value.

The ESV is decomposed into eight driving factors from the three perspectives of social and economic development effect, human activity effect, and natural factor effect (see formula (2)). The calculation formula and the driving factors are as follows (Ang, 2005):

$$ESV = \frac{ESV}{R} \times \frac{A}{D} \times \frac{GDP}{A} \times \frac{P}{GDP} \times \frac{U}{P} \times \frac{D}{T} \times \frac{R}{U} \times T \tag{2}$$

$$= ER \times AD \times GA \times PG \times UP \times DT \times RU \times T$$

Where, ESV is the ecosystem services value; R stands for rainfall; A stands for natural wetland area; D stands for developmental inputs in wetland ecosystems, including fertilizer, machinery and other inputs for agriculture, fishery, and wetland industries; GDP stands for the GDP of NEC; P is the population of NEC; U represents the non-agricultural population of NEC; T represents protective inputs for natural wetlands, including inputs of ecological restoration and restoration of wetlands.

ER represents the ESV produced by the unit rainfall, the larger the value, the greater the ESV of the ecosystem; AD represents the pressure factor caused by the developmental investment in the study area to the natural wetland. The larger the value, the larger the area of the natural wetland carrying the unit developmental investment, that is, the smaller the interference pressure of the natural wetland per unit area; GA stands for the support factor of natural wetlands to regional economic development, the greater the value, the greater the support capacity of natural wetlands for economic development. PG is the reciprocal of GDP per capita and represents the degree of social and economic development. The smaller the value, the higher the degree of

Table 2
Abbreviation.

NEC	Northeast of China	ESV_c	Cultural services value of the study area
UEV	Unit emergy value, sej/unit	ESV_s	Supporting services value of the study area
A	Natural wetland area	ESV_t	Total services value of the study area
GDP	Gross National Product	ESV_{nap}	Provision services value of the natural wetland in the study area
U	Urbanization Rate	ESV_{nar}	Regulation services value of the natural wetland in the study area
P	The population of Northeast China	ESV_{nac}	Cultural services value of the natural wetland in the study area
R	Average rainfall in the study area	ESV_{nas}	Supporting services value of the natural wetland in the study area
D	Development investment	ESV_{nat}	Total services value of the natural wetland in the study area
T	Protection investment	ESV_{otp}	Provision services value of the other land use types in the study area
ES	Ecosystem services	ESV_{otr}	Regulation services value of the other land use types in the study area
ESV	Ecosystem services value	ESV_{otc}	Cultural services value of the other land use types in the study area
ESV_p	Provision services value of the study area	ESV_{ots}	Supporting services value of the other land use types in the study area
ESV_r	Regulation services value of the study area	ESV_{ott}	Total services value of the other land use types in the study area

social and economic development; UP stands for urbanization rate, the larger the value, the higher the regional urbanization level; DT is the ratio of developmental and protective inputs in the ecosystem. The larger the value, the better the anti-interference ability of the ecosystem, and the lower the demand for protective inputs; RU is the ratio of rainfall to the urban population. The larger the value, the greater the amount of precipitation per capita in urban areas. T represents the protective input of the wetland ecosystem. The larger the value, the greater the protection intensity of the system.

According to the LMDI method, ESV is decomposed by the following formulas (Ang, 2005):

$$\Delta\alpha = \alpha^t - \alpha^0 = \Delta\alpha_a + \Delta\alpha_b + \Delta\alpha_c + \Delta\alpha_d + \Delta\alpha_e + \Delta\alpha_f + \Delta\alpha_g + \Delta\alpha_h \tag{4}$$

$$\Delta\alpha_a = \varepsilon \times \ln\left(\frac{a^t}{a^0}\right) \tag{5}$$

$$\Delta\alpha_b = \varepsilon \times \ln\left(\frac{b^t}{b^0}\right) \tag{6}$$

$$\Delta\alpha_c = \varepsilon \times \ln\left(\frac{c^t}{c^0}\right) \tag{7}$$

$$\Delta\alpha_d = \varepsilon \times \ln\left(\frac{d^t}{d^0}\right) \tag{8}$$

$$\Delta\alpha_e = u \times \ln\left(\frac{e^t}{e^0}\right) \tag{9}$$

$$\Delta\alpha_f = u \times \ln\left(\frac{f^t}{f^0}\right) \tag{10}$$

$$\Delta\alpha_g = u \times \ln\left(\frac{g^t}{g^0}\right) \tag{11}$$

$$\Delta\alpha_h = u \times \ln\left(\frac{h^t}{h^0}\right) \tag{12}$$

$$\varepsilon = \frac{\alpha^t - \alpha^0}{\ln\alpha^t - \ln\alpha^0} \tag{13}$$

α_t represents the value of ESV in the t year; α_0 represents the value of ESV in the base year; a, b, c, d, e, f, g, and h represent the eight driving force factors of ESV.

2.3. Data sources

All data sources for this study can be found in Table 3 below. Among them, the tourism income data and water resources data were incomplete before 2000, so statistics and estimates were made based on the statistical yearbooks of different administrative districts in NEC.

2.3.1. Provision services value

Aquatic products. Freshwater natural fishing and artificial farming.

Food production. Food production in the area from natural wetlands to arable land.

Raw materials. Reeds are the main raw materials produced by the wetlands in NEC and have formed a large-scale industry. Other raw materials are used less and did not form a scale. Therefore, in this study, reeds were used as the raw materials for the wetland ecosystem output.

Water supply. The chemical emergy value of water resources provided by the wetland ecosystem for social production and living (Campbell and Brown, 2012).

Table 3
Data sources.

Data category	Descriptions	Sources
Socioeconomic data [a] (GDP, Population, Urbanization rate)	GDP refers to the gross domestic product of the NEC, including the primary, secondary and tertiary industries. Population refers to the total population of the NEC in the year. Urbanization rate equals non-agricultural population divided by total population.	Hei Longjiang statistical yearbook 1996/2001/2006/2011/2016 Jilin statistical yearbook 1996/2001/2006/2011/2016 Liaoning statistical yearbook 1996/2001/2006/2011/2016 Inner Mongolia statistical yearbook 1996/2001/2006/2011/2016 50 years'brilliance (1947–1997)[b] China tourism statistical yearbook [c]
Water supply	Water supply includes production water, domestic water, and ecological water supply.	Water Resources Bulletin of Songliao River Basin (http://www.slwr.gov.cn/szy2011/) Statistical yearbook mentioned above [d]
Rain data	Average rainfall in NEC.	National Meteorological Information Center
Land use data	The study area was determined by the consolidation of wetlands of six periods (1980, 1995, 2000, 2005, 2010 and 2015) extracted from the land use data set. Including natural wetlands and non-natural wetlands converted from natural wetlands.	Data Center for Resources and Environmental Sciences, Chinese Academic of Sciences (RESDC) (http://www.resdc.cn). 1 km × 1 km resolution
Investment	Including developmental investment and protective investment in the study area. Development investment includ fertilizer, machinery and other inputs for agriculture, fishery, and wetland industries. Protective investment include the inputs for ecological restoration and restoration of wetlands in the study area.	National Wetland Conservation Program (20022030) National Wetland Protection Project Implementation Plan (2005-2010) National Wetland Protection Project Implementation Plan (2011–2015) National 13th Five-Year Plan for Wetland Protection
UEV data	Transformity of materials, energy, or information	https://nead.um01.cn/home [e] Research by other scholars

[a] The 1980 data is included in the later yearbook.
[b] This is the statistical yearbook of Inner Mongolia.
[c] The source of tourism income data for 2000–2005 is the statistical yearbooks of the provinces; the source of tourism income data for 1980 and 1995 is an estimate based on the average national tourism income.
[d] Due to the progress of data update, the monetary emergy conversion rate in 2015 is based on 2014 data.
[e] Since there is no data on water resources bulletins before 2000, statistics and estimates are based on statistical yearbook data.

2.3.2. Regulation services value

Disturbance regulation. Floodwater trapped by lakes, reservoirs, and marsh.

Gas regulation. Wetland plants absorb CO_2, release O_2, and regulate atmospheric components during photosynthesis.

Thus, 1.63 g carbon dioxide is needed and 1.19 g oxygen is released for every 1 g of dry matter.

Waste treatment. ESV of N and P pollutants for wetland purification.

Supplementing groundwater. Groundwater recharge from different land use types in the study area. The formula is as follows (Yang et al., 2019):

$$W = \sum R \times S_i \times \rho \times k_i \tag{14}$$

Where, W is the total amount of groundwater recharge; R is the average annual rainfall (m/yr); S_i is the area of different land use types

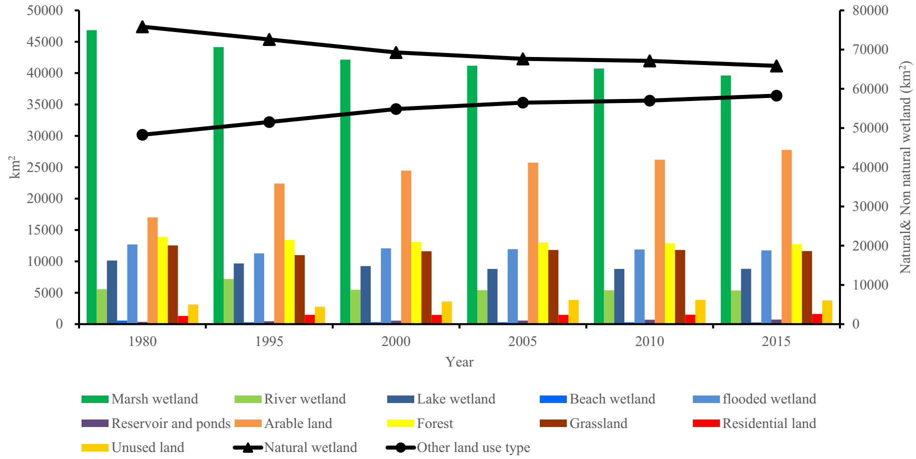

Fig. 5. Land use change in the study area.

(km^2); ρ is the density of water (kg/m^3); k_i is the penetration of different land use (%).

2.3.3. Cultural services value

Wetland ecosystems have rich landscapes and provide places for recreation. It is one of the important ecosystem services of wetlands (Sinclair et al., 2019). According to the results of the "Comprehensive Analysis Report of the 2000 Sampling Survey of Inbound Tourists", 52.5% of the tourists take landscapes and scenery as tourism purposes. Therefore, the income of tourism in the study area can be estimated by the proportion of wetland, forest, and grassland in the total area of NEC and the total tourism income of NEC. The formula is as follows (This study):

$$M = M_a \times r \times \frac{\sum S_i}{S_a} \quad (15)$$

Where, M is the tourism income of the study area (¥); M_a is the total tourism income of NEC (¥); r is the proportion of wetland, forest, and grassland in total tourism income, $r = 52.5\%$; S_i is the area of different land use (km^2); S_a is the total area of wetlands, forests and grasslands in NEC (km^2).

2.3.4. Supporting services value

Supporting services are the basis for the existence of other services, so in this research, ESV_s mainly calculated the support effect of vegetation on the ecosystem, expressed as the gross net production of the vegetation (Campbell and Brown, 2012).

3. Results

3.1. Land use

As shown in Fig. 5, from 1980 to 2015, the proportion of natural wetland areas in the study area decreased from 61.10% to 53.05%, and an area of 9982.12 km^2 converted into the other land use types, which accounted for 13.16% of the area of natural wetland. Among them, the largest reduction occurred for the marsh, accounting for 72.41% of the total reduction area, followed by lakes, accounting for 13.26% of the total reduction area, and river, river beach, and beach reduction areas accounting for 14.33% of the total reduction area.

Among the other land use types, arable land was the most important type of land use. The proportion in non-natural wetlands increased from 35.25% to 47.67%, and the area increased by 10,742.19km^2. Among them, 82.95% of the area was converted from natural wetlands, 16.90% of the area was converted from forests and grasslands, and the remaining 0.15% was converted from other land-use types. It can be seen that

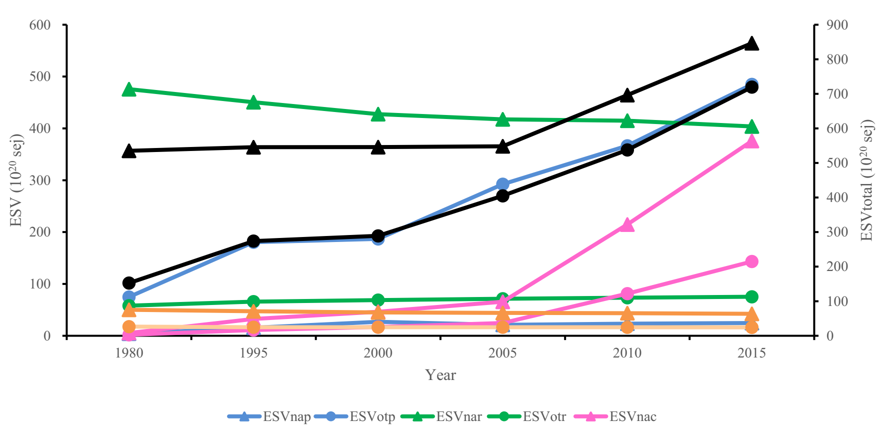

Fig. 6. Changes in ESVs of the natural wetland and the non-natural wetland.

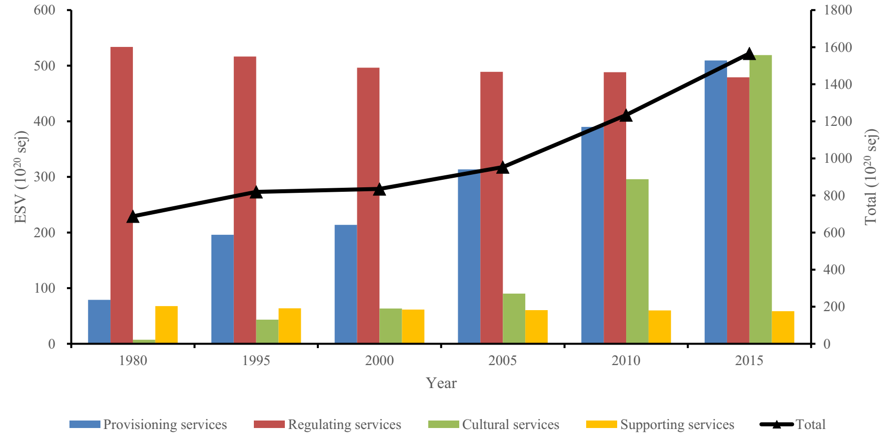

Fig. 7. Changes in ESVs of the wetland.

agricultural farming was the main cause of land use change in the wetland ecosystem in NEC.

3.2. Changes in ecosystem services value

3.2.1. Changes in ESVs of natural wetland and the other land use

Major ESVs of different land use types were calculated in this study (Fig. 6). The results showed that change in the ecosystem services value of natural wetland (ESV_{na}) mainly gone through two stages. In the first stage (1980–2005), the ESV_{na} basically remained unchanged, and in the second stage (2005–2015), the was on the obviously rising trend. During the entire study period, the ESV_{na} increased from 5.35×10^{22} sej to 8.47×10^{22} sej, an increase of 58.16%. However, due to the increase in the ESV of the other land use types (ESV_{ot}), its proportion in the total ESV (ESV_t) of the study area decreased from 77.83% to 54.05%. The ESV_{ot} increased from 1.53×10^{22} sej to 7.20×10^{22} sej, an increase of 371.89%.

3.2.2. Changes in different ESVs

From the perspective of the entire study area, the change in the ESV_t was mainly divided into two stages (Fig. 7). In the first stage (1980–2000), the change in the ESV_t was small, showing a slight growth trend, from 6.88×10^{22} sej to 8.35×10^{22} sej, with a growth rate of 21.44%. In the second stage (2000–2015), the ESV_t showed a clear upward trend, from 8.35×10^{22} sej to 1.57×10^{23} sej, with a growth rate of 87.52%. During the whole research period, the ESV_t increased by 7.31×10^{22} sej, with a growth rate of 127.73%.

Among the four types of ESVs, the ESV_p continued to increase from 7.89×10^{21} sej to 5.09×10^{22} sej, an increase of 545.60%, and its proportion in the ESV_t also increased from 11.47% to 32.53%. The ESV_r was the most important ecosystem services in the study area. However, it continued to decrease during the study period, from 5.34×10^{22} sej to 4.79×10^{22} sej, a decrease of 10.25%. Its share in the ESV_t dropped from 77.62% to 30.59%, which was mainly due to the increase in the ESV_p and ESV_c. The ESV_c increased most significantly among the four ESVs, from 7.24×10^{20} sej to 5.19×10^{22} sej, an increase of 7066.54%, and the proportion in the ESV_t increased from 1.05% to 33.14%. The ESV_s continued to decrease, from 6.78×10^{22} sej to 5.86×10^{22} sej, a decrease of 13.50%.

3.3. Drivers of ecosystem services value

3.3.1. Drivers of the ESV_p

As shown in Fig. 8, △GA was the largest positive driving factor for the ESV_p, and the weight was 20.60%–27.60%. △PG was the largest negative driving force, with a weight of 18.90%–25.55%, second only to △GA. △T generally presented a positive contribution, with a weight of 15.55% ~ 19.50%. In addition to 1995, △DT had a negative contribution, with a weight of 7.62% to 10.35%. The positive contribution of △ER was 6.92% ~ 10.33%, and the negative contribution of △AD was slightly less than △ER, and its weighting was 5.81% ~ 8.64%. The weight of the

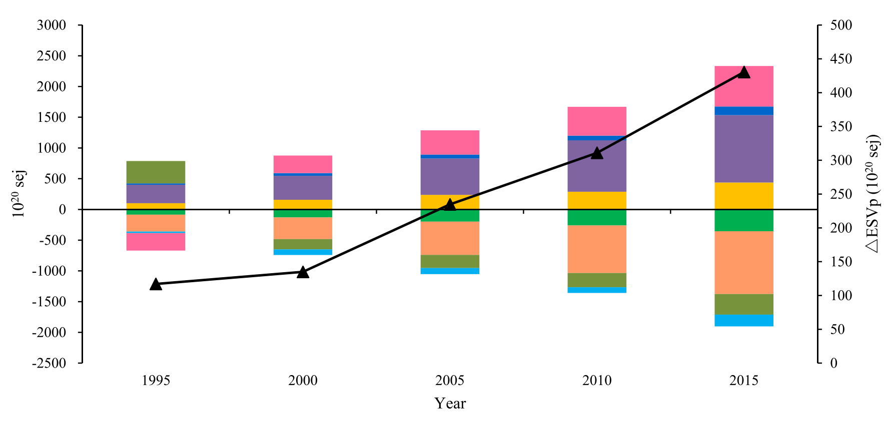

Fig. 8. ESV_p LMDI decompositions and ESV_p changes (ER stands for the ratio of ESV_p to rainfall; AD stands for the ratio of natural wetland area and development investment; GA stands for the ratio of GDP to natural wetland area in Northeast China; PG stands for the reciprocal of GDP per capita; DT stands for the ratio of development investment and protective investment; RU stands for the ratio of rainfall to non-agricultural population; T stands for protective input; ESV_p stands for the value of provision services.)

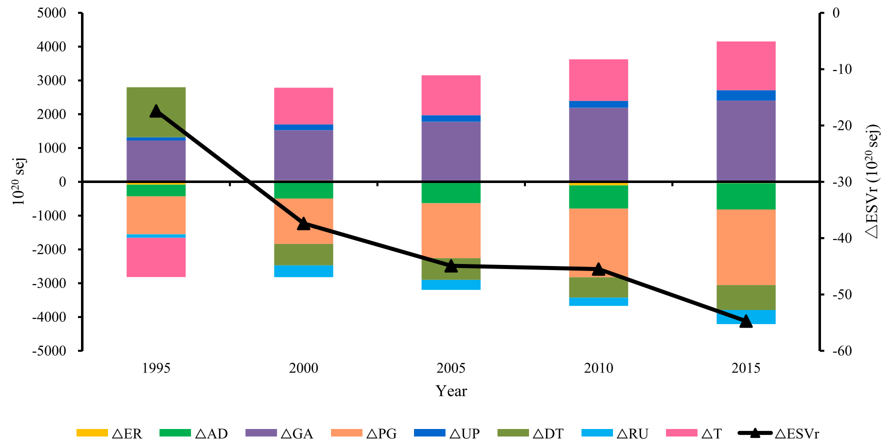

Fig. 9. ESV_r LMDI decompositions and ESV_r changes (ER stands for the ratio of ESV_r to rainfall; AD stands for the ratio of natural wetland area and development investment; GA stands for the ratio of GDP to natural wetland area in Northeast China; PG stands for the reciprocal of GDP per capita; DT stands for the ratio of development investment and protective investment; RU stands for the ratio of rainfall to non-agricultural population; T stands for protective input; ESV_p stands for the value of regulation services.)

positive contribution of △UP and the negative contribution of △RU were both small, below 6%. In general, the biggest driving forces for the change of ESV_p were △GA, △PG, and △T.

3.3.2. Drivers of the ESV_r

As could be seen in Fig. 9, △GA was the positive factor that drove the ESV_r to change the most, with a weight of 21.80%–30.06%. △PG was the largest negative driving force, with a weight of 20.00%–27.83%, second only to △GA. △T generally presented a positive driving force contribution, with a weight of 16.85%–20.64%. △AD and △DT (except 1995) had a negative driving force contribution to the changes of ESV_r, and their weights were 6.15%–9.41% and 8.30%–11.36% respectively. The weight of the positive contribution of △UP and the negative contribution of △RU were both small, and they were both about between 2% and 6%. △ ER generally showed a negative contribution, with a weight of less than 1.5%, which had little effect on the changes of ESV_r. According to the decomposition results, it could be seen that △GA, △PG, and △T were the most important driving forces for the changes of ESV_r.

3.3.3. Drivers of the ESV_c

According to the decomposition result (Fig. 10), △GA was the largest positive driving force for the change of ESV_c, with a weight of 19.11%–24.30%, followed by △ER, whose positive contribution was 13.65%–20.73%. △PG provided the largest negative contribution to the change of ESV_c, and the weight was 17.53%–22.50%. △T showed a positive contribution to driving force overall, with a weight of 13.62%–16.02%. △AD and △DT (except 1995) had a negative contribution to the change of ESV_c, and their weights were 5.39%–7.85% and 6.71%–8.44% respectively. The positive contribution of △UP accounted for less than 3%, and the negative contribution of △RU accounted for less than 5%, both of which had little effect on the ESV_c. Therefore, the main driving forces for changes in ESV_c were △ GA, △ER, △PG, and △T.

3.3.4. Drivers of the ESV_s

As shown in Fig. 11, the development trend of the driver of ESV_s was similar to ESV_r. The weight of △GA's positive contribution was 21.74%–30.00%. △PG was the largest negative driving force, with a weight of 19.95%–27.77%, second only to △GA. △T generally presented a positive contribution, with a weight of 16.81%–20.58%. △AD and △DT (except 1995) had a negative contribution to the change of ESV_s, and the weights were 6.13%–9.39% and 8.28%–11.39% respectively. The weight of the positive contribution of △UP and the negative contribution of △RU were both small, between 2% and 6%. △ER generally presented a negative contribution, with a weight of less than 2%, which had little effect on the change of ESV_s. The decomposition result above showed that △GA, △PG, and △T were the main driving forces to the change of ESV_s.

3.3.5. Drivers of the ESV_t

According to the decomposition result of ESV_t (Fig. 12), △GA was the largest driving force contributing positively to ESV_t, with a weight of 22.02% ~ 29.52%. △PG was the largest negative driving force, with a weight of 20.21% ~ 27.33%, second only to △GA. △T generally presented

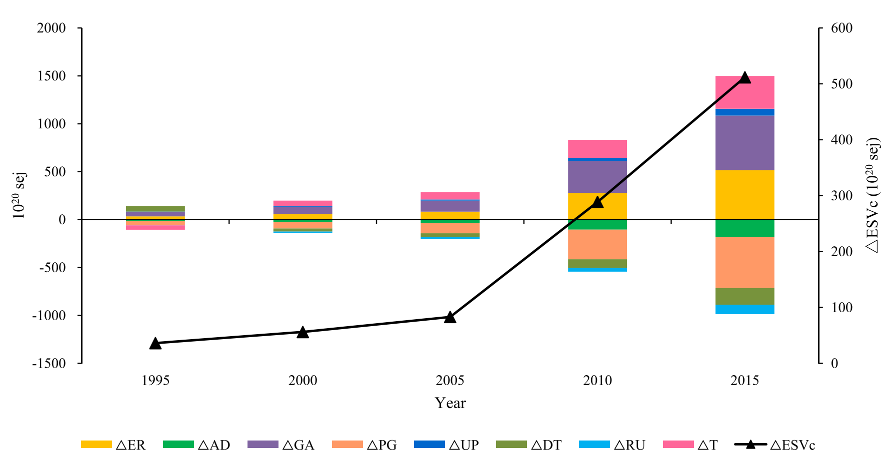

Fig. 10. ESV_c LMDI decompositions and ESV_c changes (ER stands for the ratio of ESV_c to rainfall; AD stands for the ratio of natural wetland area and development investment; GA stands for the ratio of GDP to natural wetland area in Northeast China; PG stands for the reciprocal of GDP per capita; DT stands for the ratio of development investment and protective investment; RU stands for the ratio of rainfall to non-agricultural population; T stands for protective input; ESV_c stands for the value of cultural services.)

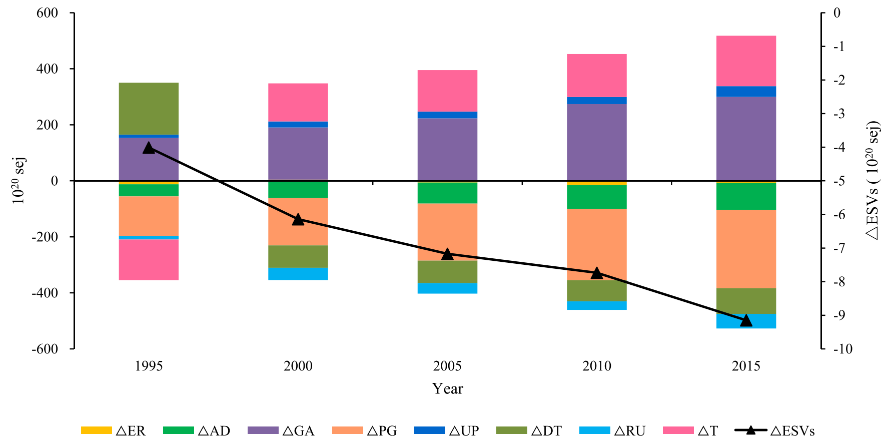

Fig. 11. ESV_s LMDI decompositions and ESV_s changes (ER stands for the ratio of ESV_s to rainfall; AD stands for the ratio of natural wetland area and development investment; GA stands for the ratio of GDP to natural wetland area in Northeast China; PG stands for the reciprocal of GDP per capita; DT stands for the ratio of development investment and protective investment; RU stands for the ratio of rainfall to non-agricultural population; T stands for protective input; ESV_s stands for the value of supporting services.)

a positive contribution, with a weight of 16.49%–18.68%. △AD and △DT (except 1995) had a negative contribution to the change of ESV_t, and their weights were 6.21%–9.24% and 8.15%–11.09% respectively. The positive contribution of △UP and △ER and the negative contribution of △RU both accounted for less than 6%. Therefore, the biggest driving forces for the change in ESV_t were △GA, △PG, and △T.

4. Discussion

4.1. Factors affecting the ESVs of the wetland

According to the classification of each driving factor, the social-economic development effect (△GA, △PG, and △UP) had the greatest impact on ESV changes, followed by human activity effect (△DT, △T, and △AD), and natural factor effect (△ER and △RU) had the least influence.

For the same region, the improvement of the socio-economic development level had changed the regional industrial structure, consumption patterns and dietary structure (Alexander et al., 2015), and then affected the use of natural wetlands. For example, cash crops could bring higher economic benefits, resulting in a large number of natural wetlands being reclaimed as cultivated land. People's dietary preferences tended to be diversified foods such as fish and meat, rather than simple food crops such as rice or corn (Worku et al., 2017), which had led to the transformation of wetlands to farming ponds and animal husbandry. Such a change had led to a huge increase in ESV_p (David et al., 2016). In terms of cultural services, the improvement of economic development level made people had a higher pursuit of quality of life, which was reflected in more expenditure on tourism consumption and stronger inclination to protect the scientific research value and religious value of natural wetlands (Roebeling et al., 2016; Pedersen et al., 2019). ESV_r and ESV_s were protected with increased awareness of wetlands, such as the Ramsar Convention, the wetland bank program in the United States, and the NWCP in China.

The impact of urbanization on the ESV varied at different scales and in different regions. Generally, in large-scale terrestrial ecosystems above the provincial level, urbanization positively drove the ESV (Lyu et al., 2018; Qi et al., 2020), which was consistent with the results of this study. However, the ESV in the vicinity of cities was negatively affected (Eigenbrod et al., 2011; Cheng et al., 2020). In small-scale ecosystems, due to a large amount of land occupied by cities, a large amount of natural vegetation had been destroyed, leading to a reduction in the ESV (Li et al., 2016a). Besides, such as coastal wetlands or river beach, urban construction infringed the space of the original ecosystem (Cui et al., 2016), which also led to the loss of the ESV.

The impact of human activities on the changes in the ESV of wetland had two aspects. One was the protection of natural wetland resources, which mainly included the protection of natural wetlands from the loss and restoration of natural wetland areas. Through the implementation of NWCP, the ESV per unit area of the wetland protection area in the

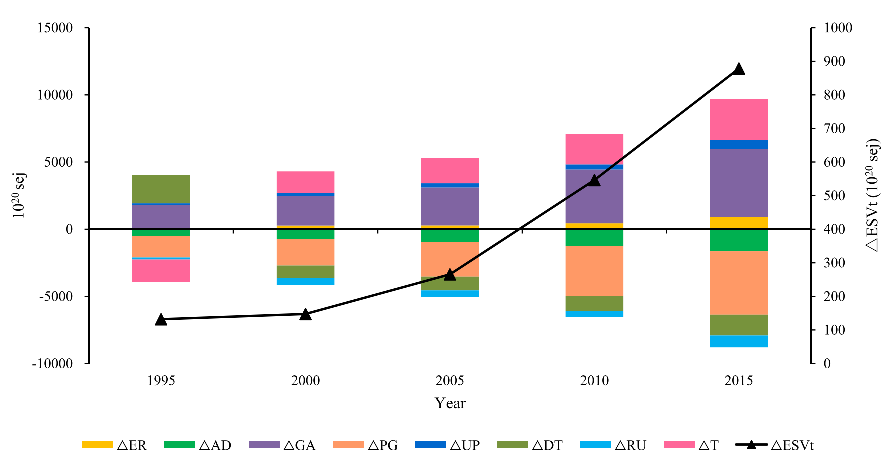

Fig. 12. ESV_t LMDI decompositions and ESV_t changes (ER stands for the ratio of ESV_t to rainfall; AD stands for the ratio of natural wetland area and development investment; GA stands for the ratio of GDP to natural wetland area in Northeast China; PG stands for the reciprocal of GDP per capita; DT stands for the ratio of development investment and protective investment; RU stands for the ratio of rainfall to non-agricultural population; T stands for protective input; ESV_t stands for the value of total services.)

Sanjiang Plain was significantly higher than the average level of wetlands in the Sanjiang Plain (Xiang et al., 2020). For example, the grain production capacity can reach more than 9 times. There were similar conclusions in other protected wetlands (Zhang et al., 2013; Li et al., 2016b). With the increase of protection investment, the ESV of wetlands can be substantively improved. In this study, the contribution of protective inputs (T) to total ESV in 2015 was 2.60E + 23sej (452.79 billion yuan), with a contribution rate of 360.99%. On the other hand was the negative impact of human activities on ESV. The development investment (D) had converted natural wetlands into other land use forms such as cultivated land, fish ponds, and construction land, which was a universal situation in the world (Davidson, 2014). As the ecosystem with the highest ESV per unit area (Costanza et al., 1997), the loss of natural wetland area caused the direct loss of wetland ESV (Song and Deng, 2017). The development investment also brought heavy environmental pressure, resulting in the decline of natural wetland quality and ESV (Mendoza-González et al., 2012).

The ESVs of wetland in areas with strong changes in climatic conditions were strongly affected by natural factors, such as tropical coastal areas (Langan et al., 2018; Mehvar et al., 2019). For inland wetland ecosystems, the impact of socio-economic development and human intervention on ESVs changes were usually greater than the impact of changes in natural factors(Zhang et al., 2017b; Ricaurte et al., 2017; Ayeni et al., 2019). In this study, in addition to the greater influence of cultural service value by △ER, the other three types of ESVs and ESV_t were less affected by it.

4.2. Countermeasures for improving the ESVs of the wetland

Wetlands were an important ecological foundation for sustainable social and economic development (Li et al., 2014; Song et al., 2020). For human society, especially in underdeveloped areas, wetlands were generally more inclined to change wetland into a more economical use type (Davidson, 2014; Guerry et al., 2015). This had led to an increase in the ESV_p for wetlands, while the ESV_r and ESV_s inevitably suffered losses. Therefore, it becomes very important to include the factors of ESVs in the consideration of social development decisions (Bateman et al., 2013).

According to the results, improving the level of social and economic development and urbanization rate had a positive effect on the growth of ESV. In addition, the more important is how to use wetland resources scientifically to achieve the goals of social development and the coordinated development of wetland ESV. In this study, the reed industry provided economic benefits as a way of using land types that did not change the natural wetland to other land use types. However, due to its low economic benefits (in 2015, for example, the value of grain is 1.49×10^{18} sej/km^2 and the value of reed is 8.60×10^{16} sej/km^2) and the current society 's demand for such resources is not high. The reed industry had not been able to expand on a larger scale. However, with the progress of science and technology and social development, there will inevitably be more demands for wetland resources. For example, lotus-root production systems (Lu et al., 2017). Wetland tourism is also an important method for the rational use of wetlands, which has been practiced in many regions(Lin et al., 2019; Aazami and Shanazi, 2020). Therefore, this study suggested that decision makers need to pay more attention to the development of natural wetland products or the development of wetland industry when formulating strategies for wetland management, so as to coordinate the conflicts between economic development and wetland protection.

4.3. Limitations and uncertainty

In the land use data, the marsh wetland included different types of vegetation, and its ecosystem services value was different. For example, *Phragmites communis*, *Scirpus triqueter*, and *Scirpus validus* and other wetland vegetation have different purification capabilities for pollutants (Jiang et al., 2005; Xu et al., 2010). Also, some wetland vegetation is an important place to live for waterfowls. For example, the *Suaeda salsa* wetland is the breeding place of black-billed gulls (*Larus saundersi*) (Liu et al., 2009), and the *Scirpus planiculmis* wetland is the habitat of white crane (*Grus leucogeranus*) (Jiang, 2016). In the emergy method, the calculation of biological habitats services value of wetland was mainly based on the number or species of waterfowl in the wetlands. However, because early data was difficult to obtain, it was not calculated. The above problems may have some impact on the size of ESV, especially underestimated the ESV_s (because the value of biological habitats was not calculated, a rough estimate of the loss of this value was about 7.15E + 24 sej), However, the purpose of this study was to clarify the impact of different factors on the main ESV changes, so the impact on the final result was not too great.

The emergy method is dependent on UEV and basic data. As research continues to evolve, UEV is constantly updated to become more accurate (Brown and Ulgiati, 2016). Besides, UEV, tourism income data, and water resources data came from different journals or databases, which may cause the calculation results to be inaccurate, but this study is a long-term and large-scale macro trend analysis, the uncertainty brought by these were limited, so it did not substantially affect the results (Zhong et al., 2018; Song et al., 2020).

5. Conclusion

This study estimated the main ESVs of the wetland ecosystem in NEC from 1980 to 2015 based on the emergy method, and the LMDI method was applied to decompose 8 driving factors from the three aspects of socio-economic development, human activity interference, and natural factor changes to analyze the impact of changes in ESVs. The study comes to the following conclusion:

(1) The ESV_t of the wetland increased by 7.31×10^{22} sej, of which the ESV_p and ESV_c increased by 4.31×10^{22} sej and 5.12×10^{22} sej, respectively. The ESV_r and ESV_s reduced by 5.47×10^{22} sej and 9.15×10^{22} sej, respectively.

(2) Overall, △GA, △PG, and △T were the most significant factors driving the change of ESV, and the average weight of the contribution value to the driving force of different types of ESVs was 22.33%–7.03%, 20.51%–24.83% and 15.40%–18.53%, respectively. From the perspective of the classification of driving factors, the social-economic development effect had the greatest impact on ESV, and the average contribution value accounted for 45.18%–54.69%, followed by the human activity effect, and the average contribution weighted 33.45%–40.14%, and the impact of natural factors was relatively small.

(3) Further improve the regional economic development level and urbanization rate, and rationally use wetland resources to develop wetland-related industries have a positive effect on improving the ESVs of wetlands.

Declaration of competing interest

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

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CRediT author statement

Fei Song and Fangli Su conceived the idea of this study and wrote the manuscript. Chenxi Mi and Di Sun collated the data and participated in the writing of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141778.

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