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Value Assessment of Wetland Ecosystem Services in the Da Hinggan Mountains, China

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Abstract: This study examined regional differences in ecosystem services for the Da Hinggan Mountains (DHM), China. A correction index was constructed based on ten-year average net primary productivity (NPP) data. A new equivalent factor table that was suitable for the assessment of wetlands in the DHM was formed by using the expert weight determination method (EWDM). An evaluation model was established for evaluating the ecosystem service value (ESV) of wetlands in the DHM. The results show that in 2020, the total ESV of wetlands reached 93 361 $\times 10^6$ USD, with the forest swamp and marsh ecosystems contributing the most. From the perspective of value composition, regulating services and supporting services are the main service functions of wetlands in the DHM. From 2010 to 2020, ESV provided by wetlands increased by 4337 $\times$ 10^6 USD/yr in the DHM. The value of forest swamp and peatland ecosystems increased by 18.6% and 12.7%, respectively, whereas the value of swamp, shrub swamp, and marsh decreased. The research results are of significance for contributing to local government performance evaluation and determining financial compensation for the provision of wetland ecosystem services.

Keywords: wetlands; ecosystem services value; net primary productivity (NPP); Da Hinggan Mountains; expert weight determination

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1 Introduction

Wetlands are dynamic ecosystems lying between aquatic and terrestrial ecosystems (Zedler and Kercher, 2005; Salimi et al., 2021). Wetland ecosystems have high productivity and provide numerous ecological benefits, such as pollution control, water purification, and wildlife habitat (Weis and Weis, 2004; Mitsch, 2005; Erwin, 2009). The Da Hinggan Mountains (DHM) have important forest and wetland ecosystems, which are under great threat because of lumbering and other human activities (Li et al., 2020a; Wang et al., 2021). Over the past few decades, the DHM has lost approximately 50% of its wetlands (Dang et al., 2020). The degradation of the ecological services of the wetland ecosystems of the DHM has increased the frequency of natural disasters, such as flooding, droughts, and forest fires (Li et al., 2019; Jia et al., 2020; Xue et al., 2021).

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Various methods for evaluating the value of wetland ecosystem services have been used in previous studies (Brinson et al., 1995; Woodward and Wui, 2001; De Groot et al., 2002; Costanza et al., 2014). According to whether the data sources are obtained from the direct investigation of the research site, the evaluation methods can be divided into two types: original evaluation method and equivalent factor method (Zhao et al., 2021). The former method is based on the structure (composition) and function (process) of ecosystems and the supply-demand relationship of markets. The original evaluation method can accurately assess the value of some service functions in a small region. However, it usually requires ecological process models and additional input parameters, and the calculation process can be time-consuming and complicated (De Groot et al., 2006; Xie et al., 2015; Costanza et al., 2017). The equivalent factor method assumes that ecosystems with similar habitats can provide empirical values per unit area (Costanza et al., 1997). The equivalent factor method is more effective and widely used in large-scale studies (Li et al., 2020b; Zhou et al., 2020).

Although scholars have proposed several equivalent factor tables of wetland ecosystems, these equivalent factor tables may ignore the differences among categories of wetland (Costanza et al., 1997; Xie et al., 2015). To accurately evaluate the ecosystem services value (ESV) of wetlands, it is necessary to improve the equivalent factor tables for different categories of wetlands. Further, because of differences in inner structure, services offered by different wetland ecosystems have certain spatial heterogeneity that should not be neglected during evaluation (Zhang et al., 2017). Thus, when the equivalent factor method is used to evaluate the ecological value of wetlands, the corresponding spatial correction of the equivalent factor is essential (Zhao et al., 2021). Net primary productivity (NPP), which is closely related to ecosystem functions such as organic matter production, gas regulation, and nutrient cycling, is frequently used as a spatial correction coefficient (Wang et al., 2014; Huang et al., 2018; Ma et al., 2021).

The assessment of ecosystem services requires the initial identification and weight of the services that a particular wetland provides. In this study, by using the expert weight determination method (EWDM), the weight of each service provided by wetlands in the DHM was determined, and a new equivalent factor table that was suitable for the assessment of wetlands in the DHM was developed (Medland et al., 2020; Zhai et al., 2021). Then, we chose vegetation net primary productivity (NPP) as the correction index, which closely relates to material and energy conversion in terrestrial ecosystems, to measure wetlands' capability of providing ecosystem services (Nemani et al., 2003; Hu et al., 2018; Koju et al., 2020). The *Wetland_NPP_Index* was calculated based on a ten-year annual average NPP and used to correct the values of different services of each wetland category in the DHM (Zhu et al., 2017; Dubey et al., 2021). Finally, we constructed a regional value evaluation to assess the change in ESV of wetlands from 2010 to 2020. The valuation framework and result in this study can provide a scientific basis for local policymakers in wetland conservation and restoration.

2 Materials and Methods

2.1 Study area

The DHM (119°42′E–127°01′E, 48°29′N–53°33′N), with a total area of 17.7×10^4 km^2, is one of the most important wetlands regions in China (Fig. 1). The mountain range is dominated by low hilly terrain with an altitude range from 137 to 1511 m (Zhao et al., 2016; Fu et al., 2018). The perennial permafrost is concentrated in the northern part of the DHM (Li et al., 2008; Zhu et al., 2021), and the permafrost thickness ranges from 0.8 to 1.5 m (Jin et al., 2007). The highest temperatures in the region occur in July with an average temperature of 20 °C. The average annual precipitation of the area is 400–500 mm, and most of the precipitation is concentrated between May and September (Li et al., 2020c). The annual average wind speed in the region is 2–3 m/s, with a maximum wind force of 7–8 m/s. The total population of the DHM in 2020 was 33.13×10^4, according to the seventh national population census (http://www.dxal.gov.cn/).

2.2 Remote sensing data and processing

We used Landsat TM (Thematic Mapper) and Landsat 8 OLI (Operational Land Imager) cloudless images downloaded from the United States Geological Survey (https://earthexplorer.usgs.gov) to obtain spatial data of wetlands in the DHM in 2010 and 2020. In total, 18 Landsat TM images and 17 Landsat 8 OLI images acquired primarily in the growing season from June to

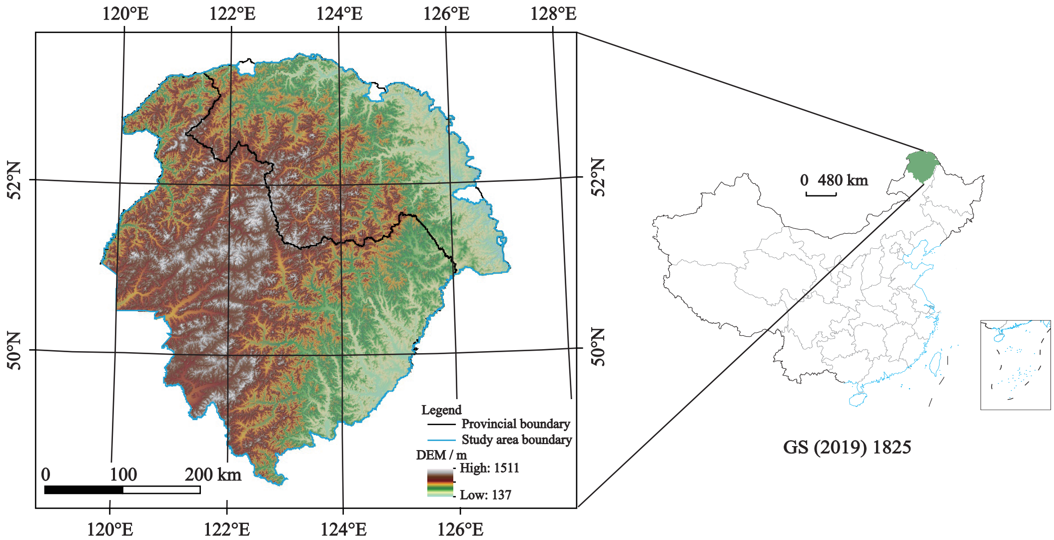

Fig. 1 Location of the Da Hinggan Mountains (DHM), China

September were selected in the DHM. After geometric correction, the visual interpretation method was employed to extract wetland information from Landsat images. The wetland classification system contains five types, including peatland, marsh, shrub swamp, forest swamp, and swamp. According to field survey data obtained in 2019, the accuracy of the remote sensing interpretation results of the DHM wetlands in all categories was greater than 85%.

We used the MOD17A3HGF Version 6 product from 2001–2020 provided by the U.S. National Aeronautics and Space Administration (NASA) as spatial correction coefficient. MOD17A3HGF Version 6 is a global dataset of interannual variation in terrestrial vegetation net primary productivity (NPP) calculated by the BIOME-BGC model at 500 m spatial resolution. The average annual NPP data of each wetland patch in the DHM was calculated with the raster calculator tool of ArcGIS 9.3. The ten-year average annual NPP from 2001 to 2010 and 2011 to 2020 was used to calculate the *Wetland_NPP_Index* of each wetland patch in the two periods. The *Wetland_NPP_Index* calculation is shown in Equ. (1):

$$Wetland\_NPP\_Index = 0.5 + \frac{NPP_i - NPP_{\min}}{NPP_{\max} - NPP_{\min}} \times \frac{NPP_i}{2NPP_{\max}} \quad (1)$$

where NPP_i is the ten-year average annual NPP value in the two periods of patch i; $NPP_{\min}$ is the minimum NPP value in the two periods; $NPP_{\max}$ is the maximum NPP value in the two periods. The *Wetland_NPP_Index* scores ranged from 0.5 to 1.0, 0.5 represents that wetland patch i is less productive and provides fewer ecosystem services, and 1.0 represents that wetland patch i is more productive and provides more ecosystem services. The results of the ten-year average annual NPP and *Wetland_NPP_Index* in the DHM in 2010 and 2020 are shown in Fig. 2.

2.3 Weight of each service provided by wetlands in the Da Hinggan Mountains (DHM)

We designed a survey questionnaire to determine the weight of 23 ecosystem services provided by the five wetland types in the DHM. In the questionnaire, each service had five response options (1 = high; 2 = medium; 3 = low; 4 = no providing; 5 = uncertain). We distributed 50 questionnaires to experts who have long been engaged in wetland-related studies. The questionnaire was fully completed by 43 experts. According to the opinions of experts, the weight of ecosystem services of the DHM wetland ecosystem was rated as High (1.0), Medium (0.75), and Low (0.5) (Table 1).

2.4 Value equivalent factor

Compared with other assessment methods, the equivalent factor method is more intuitive and suitable for ESV assessment at regional and global scales (Costanza et al., 1997; Yin et al., 2021). To enhance the comparability of the assessment results, we used the maximum monetary value equivalent of wetland ecosystem services provided by the *Ramsar Technical Report* (De Groot et al., 2006) to evaluate the value of wetland ecosystem services in the DHM (Table 2).

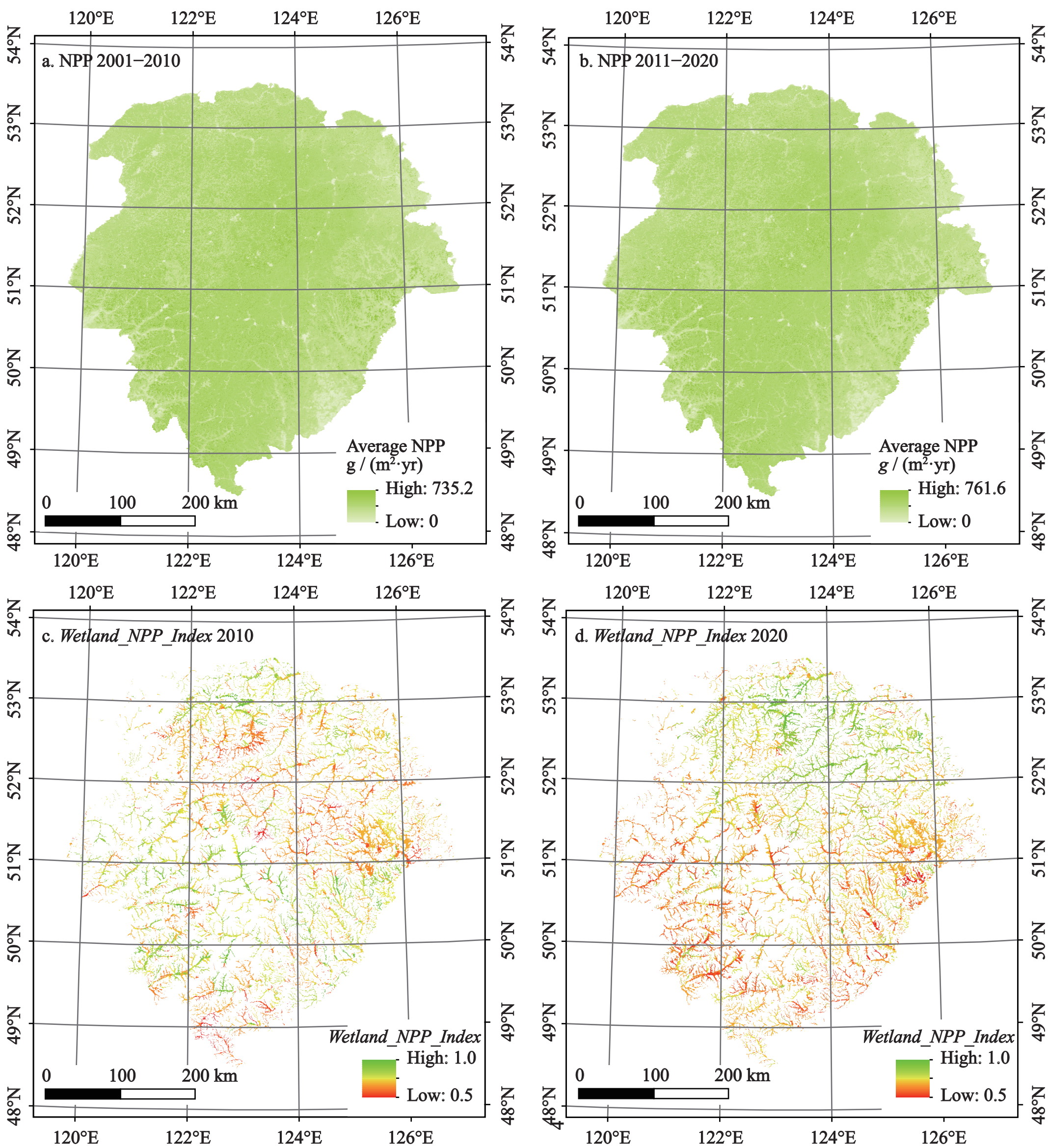

Fig. 2 Ten-year average annual net primary productivity (NPP) (a, b) and *Wetland_NPP_Index* (c, d) of the wetlands in the Da Hinggan Mountains (DHM), China in 2010 and 2020

2.5 Evaluating the ecosystem services value (ESV) of wetland

Based on the calculation of the ESV of each wetland patch, the total ESV of wetlands in the DHM was calculated using the following equation:

$$ESV = \sum_{i=1}^{N} A_i \times VC_i \times W \times Wetland\_NPP\_Index_i \qquad (2)$$

where *ESV* is the total value of wetland ecosystem in the DHM (USD), A_i is the area of the wetland ecosystem patch *i* (ha), VC_i is the value equivalent factor (USD/ ha), $Wetland\_NPP\_Index_i$ is the spatial correction coefficient of the wetland ecosystem patch *i*, *W* is the weight of the services provided by the five wetland types, and *N* is the total number of wetland patches in the DHM.

3 Results

3.1 Change of wetlands area in the Da Hinggan Mountains

The overall changes of wetlands in the DHM from 2010 to 2020 are shown in Table 3. Forest swamp and swamp are the largest wetland types in the DHM, followed by shrub marsh, marsh, and peatland. Forest swamp and swamp account for over 80% of the total wetland area in the DHM. Both swamp and peatland account for a small

Table 1 Weight of each service provided by wetland types in the Da Hinggan Mountains, China

Ecosystem service	Service type	Peatland	Marsh	Shrub swamp	Forest swamp	Swamp
Provisioning services	Food	0.75	1.00	0.75	1.00	0.75
	Materials	0.75	1.00	0.75	1.00	0.75
	Genetic resources	0.50	0.50	0.75	1.00	0.75
	Medicinal resources	0.50	0.50	0.50	0.50	0.50
	Ornamental plant resources	0.50	0.50	0.75	1.00	0.75
Regulating services	Gas regulation	0.50	0.50	0.75	0.75	0.50
	Climate regulation	1.00	0.75	0.75	0.75	0.75
	Interference regulation	0.50	0.75	0.75	1.00	0.5
	Hydrological regulation	0.75	1.00	1.00	1.00	0.75
	Water supply	1.00	1.00	0.75	1.00	0.75
	Soil conservation	0.75	0.75	0.75	1.00	0.75
	Pollution control	0.75	1.00	1.00	1.00	0.75
	Pollination	0.50	0.50	0.50	0.50	0.50
	Biological control	0.75	0.75	0.75	0.75	0.75
Supporting services	Shelter	0.50	0.75	0.75	1.00	0.75
	Cultivation	0.50	0.75	0.50	0.50	0.75
	Soil formation	0.75	0.50	0.50	0.75	0.50
	Nutrient cycling	0.75	0.50	0.50	0.50	0.50
Cultural services	Aesthetic value	0.75	0.75	0.75	0.75	0.75
	Leisure and travel	0.50	0.75	0.75	0.75	0.50
	Culture and arts	0.50	0.75	0.75	0.75	0.50
	Spiritual historical value	0.75	0.75	0.75	0.75	0.50
	Educational value	1.00	1.00	1.00	1.00	0.50

Table 2 The maximum monetary value of wetland ecosystem services USD/(ha·yr)

Ecosystem service	Service type	Maximum currency value
Provisioning services	Food	2761
	Materials	1014
	Genetic resources	112
	Medicinal resources	112
	Ornamental plant resources	145
Regulating services	Gas regulation	265
	Climate regulation	223
	Interference regulation	7240
	Hydrological regulation	5445
	Water supply	7600
	Soil conservation	245
	Pollution control	6696
	Pollination	25
	Biological control	78
Supporting services	Shelter	1523
	Cultivation	195
	Soil formation	10
	Nutrient cycling	21 100
Cultural services	Aesthetic value	1760
	Leisure and travel	6000
	Culture and arts	25
	Spiritual historical value	25
	Educational value	25

Note: Based on data from De Groot et al. (2006), http://www.ramsar.org/pdf/lib/lib_rtr03.pdf

Table 3 Wetland annual net primary productivity (NPP) and area in the Da Hinggan Mountains (DHM), China

Year	Wetland type	Average NPP/ (g/(m^2·yr))	Average *Wetland_NPP_Index*	Area / ha
2010	Peatland	465.0	0.633	1310
	Marsh	447.6	0.701	1 077 993
	Shrub swamp	451.2	0.707	388 719
	Forest swamp	462.9	0.705	1 127 640
	Swamp	451.9	0.709	66 848
2020	Peatland	481.9	0.731	1321
	Marsh	459.0	0.718	1 034 075
	Shrub swamp	465.8	0.753	304 828
	Forest swamp	484.8	0.753	1 222 272
	Swamp	462.7	0.715	52 928

proportion. Forest swamp is located mainly in the northern and eastern parts of the DHM, and marsh is located mainly in the southern and western parts (Fig. 3). In terms of wetland ecosystem changes, the area of forest swamps continues to increase, while the area of other wetland types has slightly decreased. The area of forest swamps in the DHM increased by 9.5×10^4 ha, but that of all the wetland ecosystems together still decreased by 4.7×10^4 ha.

3.2 Change of NPP in the Da Hinggan Mountains

In 2020, the NPP of forest swamp was the highest with an average of 484.87 g/(m^2·yr)(C) (Table 3), and the NPP of the marsh was the lowest with an average of 459.0 g/(m^2·yr). Over the past 20 yr, the ten-year average annual NPP of wetlands in the DHM has shown an increasing trend (Table 3). The NPP increased significantly in forest swamp and peatland, which were 21.9 g/(m^2·yr) and 16.9 g/(m^2·yr), respectively. The average *Wetland_NPP_Index* in the DHM shows an increasing trend, with an overall average *Wetland_NPP_Index* of 0.691 in 2010 and 0.734 in 2020 (Table 3).

3.3 Overall value assessment of wetland ecosystem services in the Da Hinggan Mountains

In terms of wetland type, forest swamp and marsh provide the highest ESV, accounting for over 84% of the total, while peatland provides the lowest ESV (Table 4). In terms of service type, regulating services and supporting services provided the most value, accounting for over 79.8% of the total. In general, over the past 10 yr, the total value of wetland ecosystem services in the DHM increased from $89\ 023.55 \times 10^6$ USD in 2010 to $93\ 361 \times 10^6$ USD in 2020. The ESV of forest swamp and peatland increased by 18.6% and 12.7%, respectively. The ESV of the swamp, shrub swamp, and marsh decreased by 19.3%, 16.0%, and 1.7%, respectively.

4 Discussion

The results reveal that the value of wetland ecosystem services increased by 4.8% during the past 10 yr (Table 4), although the area of wetlands decreased slightly by 1.8% over the same period. The climate shifts and wetland protection were the main underlying reasons for the increase of NPP of wetlands, which increased production capacity to provide more ecosystem services. However, the wetlands outside nature reserves in the DHM are still vulnerable to human activities, such as land reclamation and deforestation (Zhao et al., 2018; He et al., 2021). Fortunately, in recent years, within the Ecological Functional Conservation Areas (EFCA) in China, the local government has placed increasing emphasis on local ESV as an important evaluation criterion, like local GDP (Ouyang et al., 2020; Liang et al., 2021). Our results can provide a basis for local government performance evaluation and determining financial compensation for the provision of wetland ecosystem services.

The results of our approach not only provided total ESVs reflecting the differences between the types of wetland ecosystems in the DHM but also provided comprehensive information on the spatial scale of important wetlands to local decision-makers. Our results can reveal the location and intensity of ESV providing by wet-

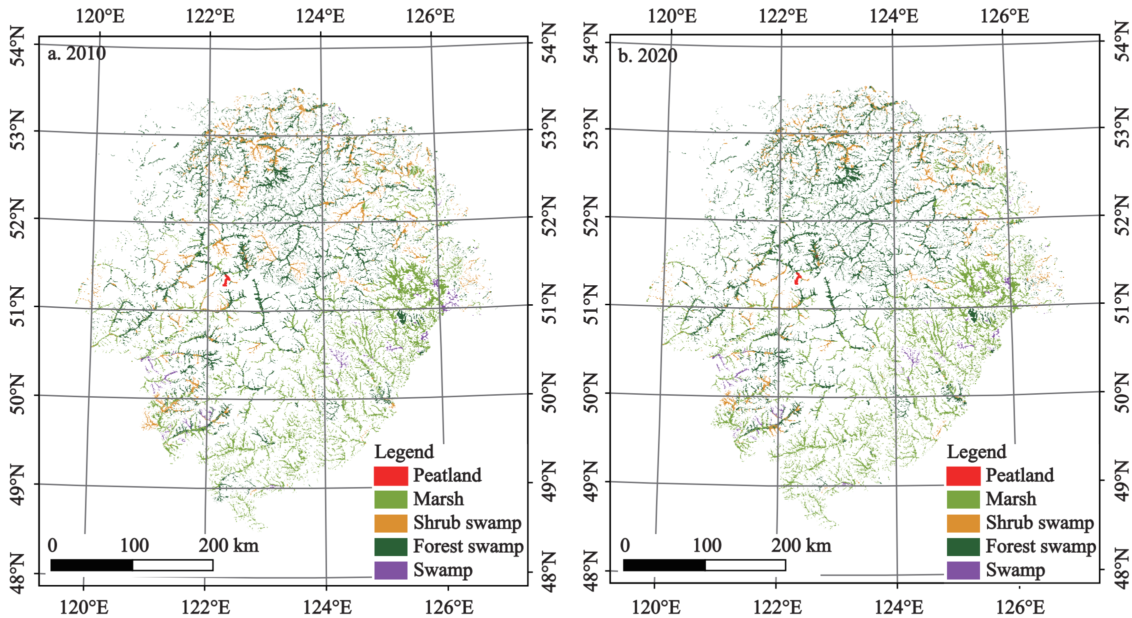

Fig. 3 Distribution of wetlands types in 2010 (a) and 2020 (b) in the Da Hinggan Mountains (DHM), China

lands in the DHM (Fig. 4). From 2000 to 2020, the GDP of the DHM grew by 15.0 × 10^8 USD, with an annual growth rate of 6.3%. In the same period, the population of the DHM significantly declined by 40.1%, from 50.58 × 10^4 in 2010 to 33.13 × 10^4 in 2020. The total value of wetland ecosystem services in the DHM was over 50 times that of local GDP in 2020. For inland wetland ecosystems, especially those located in less-developed regions, the harmful impacts are mainly from socio-economic development and human intervention (Ayeni et al., 2019; Song et al., 2021). It is critical for the DHM and other similar EFCAs, featured by low GDP, low population density, and high ESV, to develop a method that converts ecosystem services into a common monetary metric.

Compared with original evaluation methods, remote sensing data enable a more reliable and rapid evaluation method of large areas, especially for wetlands in areas lacking experimental data on large scales. The application of remote sensing data based on local field surveys can reduce the evaluation uncertainty and exhibit the spatial distribution of the wetland ecosystem services. Our results not only provided the total value of wetland ecosystem services in the DHM but also highlighted

Table 4 The value of wetland ecosystem services in the Da Hinggan Mountains (DHM), China / (10^6 USD/yr)

Year	Wetland type	Provisioningservices	Regulating services	Supporting services	Cultural services	Total
2010	Peatland	2.49	17.26	13.76	3.58	37.09
	Marsh	2995.47	19 462.05	8959.93	4417.17	35 834.62
	Shrub swamp	847.46	6573.82	3258.74	1606.53	12 286.55
	Forest swamp	3207.66	21 705.83	9593.74	4581.39	39 088.62
	Swamp	143.30	883.05	548.75	201.57	1776.67
	Total	7196.38	48 642.01	22 374.92	10 810.24	89 023.55
2020	Peatland	2.78	19.27	15.36	4.40	41.81
	Marsh	2943.31	19 123.17	8803.92	4340.26	35 210.66
	Shrub swamp	711.64	5520.25	2736.47	1349.06	10 317.42
	Forest swamp	3804.18	25 742.42	11 377.87	5433.38	46 357.85
	Swamp	115.61	712.41	442.71	162.62	1433.35
	Total	7577.52	51 117.52	23 376.33	11 289.72	93 361.09

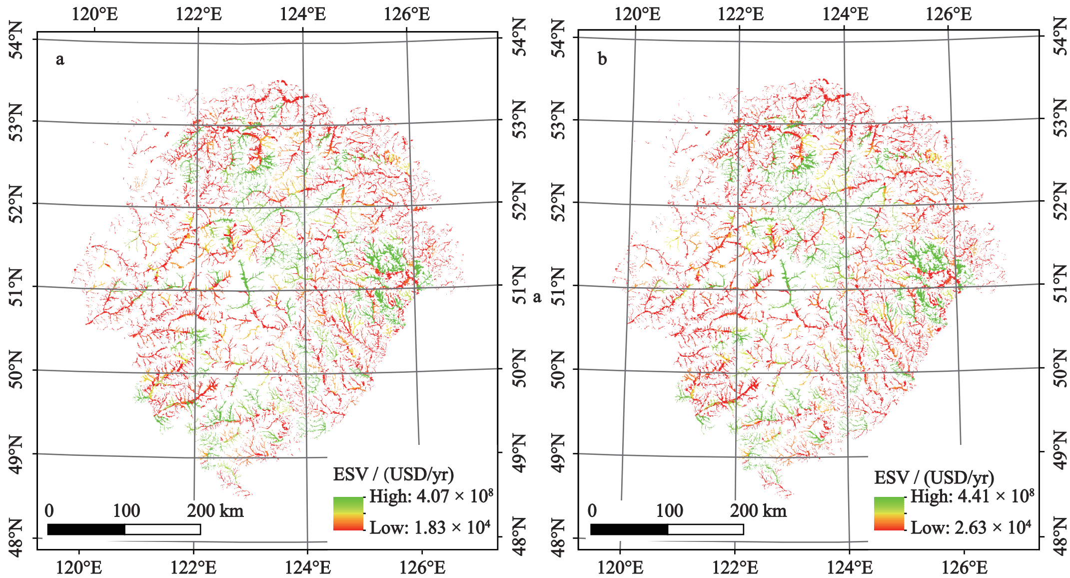

Fig. 4 Ecosystem Service Value (ESV) of the Da Hinggan Mountains (DHM), China in 2010 (a) and 2020 (b)

those wetlands with higher ESV, which have meaningful implications for the conservation and management of local wetlands. However, the results presented here are still preliminary due to the lack of NPP data at fine spatial resolution. The NPP equivalent method used in this study also has limited applicability in those wetlands that consisted largely of open water, such as rivers and lakes. Therefore, more high-resolution remote sensing data, socio-economic data, and field measurements should be involved in improving the ESV evaluation of wetlands in future studies.

5 Conclusions

According to the current wetlands situation in the DHM, we revised the equivalent factors of the Ramsar Technical Report by using the expert weight determination method (EWDM) and developed a correction index based on ten-year averaged NPP data in this study. A valuation framework for 23 ecosystem services provided by five wetland types in the DHM was developed and a regional value evaluation was used to evaluate the changes in ESV from 2010 to 2020. The results showed that the wetland ecosystem services in the DHM have a total value of 93 361 × 10^6 USD in 2020, of which the forest swamp and marsh ecosystems contributed the most with an increase of 4.8% over the past 10 yr. From 2010 to 2020, ESV provided by wetlands increased by 4337.54 × 10^6 USD while the area of wetlands in the DHM decreased by 1.8%, as a result of climate change and implementation of wetland protection policies. The application of questionnaire results based on the EWDM can improve evaluation accuracy for regional evaluation. Our results can serve as a source of information for evaluating local government performance and determining financial compensation for the provision of wetland ecosystem services.

References

Ayeni A O, Ogunsesan A A, Adekola O A, 2019. Provisioning ecosystem services provided by the Hadejia Nguru Wetlands, Nigeria–Current status and future priorities. *Scientific African*, 5: e00124. doi: 10.1016/j.sciaf.2019.e00124

Brinson M M, Hauer F R, Lee L C et al., 1995. *A Guidebook for Application of Hydrogeomorphic Assessments to Riverine Wetlands*. Vicksburg: U. S. Army Engineer Waterways Experiment Station.

Costanza R, d'Arge R, De Groot R et al., 1997. The value of the world 's ecosystem services and natural capital. *Nature*, 387(6630): 253–260. doi: 10.1038/387253a0

Costanza R, de Groot R, Sutton P et al., 2014. Changes in the global value of ecosystem services. *Global Environmental Change*, 26: 152–158. doi: 10.1016/j.gloenvcha.2014.04.002

Costanza R, De Groot R, Braat L et al., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go. *Ecosystem Services*, 28: 1–16. doi: 10.1016/j.ecoser.2017.09.008

Dang Y C, He H S, Zhao D D et al., 2020. Quantifying the relative importance of climate change and human activities on selected wetland ecosystems in China. *Sustainability*, 12(3): 912. doi: 10.3390/su12030912

De Groot R S, Wilson M A, Boumans R M J, 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics*, 41(3): 393–408. doi: 10.1016/s0921-8009(02)00089-7

De Groot R, Stuip M, Finlayson M et al., 2006. *Valuing Wetlands*: *Guidance for Valuing the Benefits Derived from Wetland Ecosystem Services*. Gland, Switzerland: International Water Management Institute.

Dubey S, Sharma A, Panchariya V K et al., 2021. Regional sustainable development of renewable natural resources using net primary productivity on a global scale. *Ecological Indicators*, 127: 107768. doi: 10.1016/j.ecolind.2021.107768

Erwin K L, 2009. Wetlands and global climate change: the role of wetland restoration in a changing world. *Wetlands Ecology and Management*, 17(1): 71–84. doi: 10.1007/s11273-008-9119-1

Fu Y Y, He H S, Zhao J J et al., 2018. Climate and spring phenology effects on autumn phenology in the Greater Khingan Mountains, Northeastern China. *Remote Sensing*, 10(3): 449. doi: 10.3390/rs10030449

He R X, Jin H J, Luo D L et al., 2021. Permafrost changes in the Nanwenghe Wetlands Reserve on the southern slope of the Da Xing'anling–Yile'huli mountains, Northeast China. *Advances in Climate Change Research*, 12(5): 696–709. doi: 10.1016/j.accre.2021.06.007

Hu L, Fan W J, Ren H Z et al., 2018. Spatiotemporal dynamics in vegetation GPP over the great khingan mountains using GLASS products from 1982 to 2015. *Remote Sensing*, 10(3): 488. doi: 10.3390/rs10030488

Huang L, Cao W, Xu X L et al., 2018. Linking the benefits of ecosystem services to sustainable spatial planning of ecological conservation strategies. *Journal of Environmental Management*, 222: 385–395. doi: 10.1016/j.jenvman.2018.05.066

Jia M M, Mao D H, Wang Z M et al., 2020. Tracking long-term floodplain wetland changes: a case study in the China side of the Amur River Basin. *International Journal of Applied Earth Observation and Geoinformation*, 92: 102185. doi: 10.1016/j.jag.2020.102185

Jin H J, Yu Q H, Lü L Z et al., 2007. Degradation of permafrost in the Xing'anling Mountains, northeastern China. *Permafrost and Periglacial Processes*, 18(3): 245–258. doi: 10.1002/ppp.589

Koju U A, Zhang J H, Maharjan S et al., 2020. Analysis of spatiotemporal dynamics of forest Net Primary Productivity of Nepal during 2000–2015. *International Journal of Remote Sensing*, 41(11): 4336–4364. doi: 10.1080/01431161.2020.1717667

Li F P, Zhang G X, Li H Y et al., 2019. Land use change impacts on hydrology in the Nenjiang River Basin. *Northeast China. Forests*, 10(6): 476. doi: 10.3390/f10060476

Li K W, Tong Z J, Liu X P et al. , 2020a. Quantitative assessment and driving force analysis of vegetation drought risk to climate change: methodology and application in Northeast China. *Agricultural and Forest Meteorology*, 282–283: 107865. doi: 10.1016/j.agrformet.2019.107865

Li X, Cheng G D, Jin H J et al., 2008. Cryospheric change in China. *Global and Planetary Change*, 62(3-4): 210–218. doi: 10.1016/j.gloplacha.2008.02.001

Li X W, Yu X B, Hou X Y et al., 2020b. Valuation of wetland ecosystem services in national Nature Reserves in China's coastal zones. *Sustainability*, 12(8): 3131. doi: 10.3390/su12083131

Li X Y, Jin H J, Wang H W et al., 2020c. Distributive features of soil carbon and nutrients in permafrost regions affected by forest fires in northern Da Xing'anling (Hinggan) Mountains, NE China. *CATENA*, 185: 104304. doi: 10.1016/j.catena.2019.104304

Liang L N, Siu W S, Wang M X et al., 2021. Measuring gross ecosystem product of nine cities within the Pearl River Delta of China. *Environmental Challenges*, 4: 100105. doi: 10.1016/j.envc.2021.100105

Ma S H, Wang L, Ji S W et al., 2021. Assessing the dynamic variations of ecosystem service value in response to land use change and socio-economic development. *Journal of Environmental Planning and Management*. doi: 10.1080/09640568.2021.1973973

Medland S J, Shaker R R, Forsythe K W et al., 2020. A multi-criteria wetland suitability index for restoration across Ontario's mixedwood plains. *Sustainability*, 12(23): 9953. doi: 10.3390/su12239953

Mitsch W J, 2005. Wetland creation, restoration, and conservation: a wetland invitational at the Olentangy River Wetland Research Park. *Ecological Engineering*, 24(4): 243–251. doi: 10.1016/j.ecoleng.2005.02.006

Nemani R R, Keeling C D, Hashimoto H et al., 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, 300(5625): 1560–1563. doi: 10.1126/science.1082750

Ouyang Z Y, Song C S, Zheng H et al., 2020. Using gross ecosystem product (GEP) to value nature in decision making. *Proceedings of the National Academy of Sciences of the United States of America*, 117(25): 14593–14601. doi: 10.1073/pnas.1911439117

Salimi S, Almuktar S A A A N, Scholz M, 2021. Impact of climate change on wetland ecosystems: a critical review of experimental wetlands. *Journal of Environmental Management*, 286: 112160. doi: 10.1016/j.jenvman.2021.112160

Song F, Su F L, Mi C X et al., 2021. Analysis of driving forces on wetland ecosystem services value change: a case in Northeast China. *Science of the Total Environment*, 751: 141778. doi: 10.1016/j.scitotenv.2020.141778

Wang S Q, Zhong R, Liu L et al., 2021. Ecological effect of ecological engineering projects on low-temperature forest cover in Great Khingan Mountain, China. *International Journal of Environmental Research and Public Health*, 18(20): 10625. doi: 10.3390/ijerph182010625

Wang Y, Gao J X, Wang J S et al., 2014. Value assessment of ecosystem services in nature reserves in Ningxia, China: a response to ecological restoration. *PLoS One*, 9(2): e89174. doi: 10.1371/journal.pone.0089174

Weis J S, Weis P, 2004. Metal uptake, transport and release by wetland plants: implications for phytoremediation and restoration. *Environment International*, 30(5): 685–700. doi: 10.1016/j.envint.2003.11.002

Woodward R T, Wui Y S, 2001. The economic value of wetland services: a meta-analysis. *Ecological Economics*, 37(2): 257–270. doi: 10.1016/S0921-8009(00)00276-7

Xie Gaodi, Zhang C X, Zhang L M et al., 2015. Improvement of the evaluation method for ecosystem service value based on per unit area. *Journal of Natural Resources*, 30(8): 1243–1254. (in Chinese)

Xue Z S, Jiang M, Zhang Z S et al., 2021. Simulating potential impacts of climate changes on distribution pattern and carbon storage function of high - latitude wetland plant communities in the Xing'anling Mountains, China. *Land Degradation & Development*, 32(9): 2704–2714. doi: 10.1002/ldr.3945

Yin Nan, Wang Shuai, Liu Y X, 2021. Ecosystem service value assessment: research progress and prospects. *Chinese Journal of Ecology*, 40(1): 233–244. (in Chinese)

Zedler J B, Kercher S, 2005. Wetland resources: status, trends, ecosystem services, and restorability. *Annual Review of Environment and Resources*, 30: 39–74. doi: 10.1146/annurev.energy.30.050504.144248

Zhai Y J, Hao L B, Zhang Y H et al., 2021. Wetland biodiversity disturbance evaluation induced by a water conservancy project in the flooded plain of the Huolin River lower reaches. *Sustainability*, 13(8): 4476. doi: 10.3390/su13084476

Zhang L L, Yu X F, Jiang M et al., 2017. A consistent ecosystem services valuation method based on total economic value and equivalent value factors: a case study in the Sanjiang Plain, Northeast China. *Ecological Complexity*, 29: 40–48. doi: 10.1016/j.ecocom.2016.12.008

Zhao D D, He H S, Wang W J et al., 2018. Distribution and driving factors of forest swamp conversions in a cold temperate region. *International Journal of Environmental Research and Public Health*, 15(10): 2103. doi: 10.3390/ijerph15102103

Zhao H Y, Gong L J, Qu H H et al., 2016. The climate change variations in the northern Greater Khingan Mountains during the past centuries. *Journal of Geographical Sciences*, 26(5): 585–602. doi: 10.1007/s11442-016-1287-y

Zhao X J, Wang J, Su J D et al., 2021. Ecosystem service value evaluation method in a complex ecological environment: a case study of Gansu Province, China. *PLoS One*, 16(2): e0240272. doi: 10.1371/journal.pone.0240272

Zhou J B, Wu J, Gong Y Z, 2020. Valuing wetland ecosystem services based on benefit transfer: a meta-analysis of China wetland studies. *Journal of Cleaner Production*, 276: 122988. doi: 10.1016/j.jclepro.2020.122988

Zhu C Y, Wang H Y, Li S A et al., 2021. Mineral magnetism variables as potential indicators of permafrost aggradation and degradation at the southern edge of the permafrost zone, Northeast China. *Boreas*, 50(2): 497–518. doi: 10.1111/bor.12496

Zhu Q, Zhao J J, Zhu Z H et al., 2017. Remotely sensed estimation of net primary productivity (NPP) and its spatial and temporal variations in the Greater Khingan Mountain Region, China. *Sustainability*, 9(7): 1213. doi: 10.3390/su9071213