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Prediction of wetland biodiversity pattern under the current land-use mode and wetland sustainable management in Sanjiang Plain, China

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ABSTRACT

Wetland destruction and degradation have been increasing gradually. The biodiversity of the remaining wetlands is under unprecedented threat. Identifying the future trend of wetland biodiversity is a critical step to provide early warnings for wetland biodiversity protection and management. However, studies have focused mainly on the current biodiversity assessment and protection, without emphasizing on the prediction of future changes. Combining the advantages of the key indicators of wetland biodiversity simulation (wetland pattern and hydrological connectivity; PHC) and CA_Markov of land use prediction, this study proposes a prediction framework for wetland biodiversity. Taking Sanjiang Plain as an example, this study predicted the changing trend of wetland biodiversity in the study area and evaluated the potential loss of wetland biodiversity in each reserve. The results revealed that the cultivated land occupation mainly caused the change in the spatial patterns of wetland biodiversity in the study area. According to the land use development trend from 2010 to 2015, the indexes of wetland PHC in the study area will decline significantly from 2020 to 2030, and the wetland biodiversity predicted by our framework will be transformed from the medium to the low level (the biodiversity conservation value will decrease 7.40% on average, with the wetland area reduced by 2.74%). Each reserve in the study area will experience various degrees of degradation in biodiversity due to the decrease in hydrological connectivity. The framework of wetland biodiversity prediction proposed in this study can provide technical support for predicting the changing trend in wetland biodiversity at the regional scale and a reference for long-term protection and monitoring strategies of wetland biodiversity at the reserve scale as an early warning.

1. Introduction

Wetlands are one of the most critical ecosystems for breeding biodiversity (Ayyam et al., 2019; Gibbs, 2000). However, since 1970, the global wetland has lost 35 % of its area (Coleman et al., 2008; Davidson, 2014), and the biodiversity of the remaining wetlands is under unprecedented threat (Clarkson et al., 2013; Zhang et al., 2020). From 1990 to 2015, the average annual loss rate of natural wetland was three times that of forests (−0.24 %) (Keenan et al., 2015). The disappearance of a large area of wetlands has threatened 25 % of the world's inland wetland-dependent species, 6 % of which are seriously endangered, resulting in a sharp decline in wetland biodiversity (Gardner and Finlayson, 2018). Wetland protection has gradually attracted great attention (Davis et al., 1997), and extensive studies have been conducted on this topic. So far, most studies have focused on optimizing the wetland conservation network by identifying biodiversity hotspots and setting conservation targets at different scales (Schleupner and Schneider, 2012; Cimon-Morin and Poulin, 2018), hoping to protect and restore the remaining wetland ecosystem and its biodiversity with the least cost and the highest efficiency (Hu et al., 2011; Guo, 2015; Ma, 2013; Qu et al., 2019). However, the above studies could only provide the current scheme for wetland protection and management, without considering the potential changing trend of wetland biodiversity in guiding wetland biodiversity conservation. Thus, a convenient and operable wetland diversity prediction framework should be constructed, which can help in evaluating the effectiveness of current land use and wetland conservation policies.

Hydrological processes are critical in maintaining biodiversity in wetland ecosystems (Melack and Coe, 2021; Zheng et al., 2022). Biodiversity is affected by some hydrological factors on most research

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scales (Konar et al., 2013). Studies have reported that hydrological disturbances, including droughts and floods, play an essential role in maintaining aquatic and floodplain biodiversity (Konar et al., 2010) and are important determinants of terrestrial vegetation diversity (Tilman and El Haddi, 1992). Wetland hydrological patterns and their connectivity are important indicators to characterize the functional stability of wetlands and are the functional basis for maintaining wetland biodiversity (Amoros and Bornette, 2002; Simioni et al., 2017). These indicators are of great significance to protecting and restoring wetland biodiversity. The decrease in connectivity usually signifies the degradation of wetland ecological function, especially the maintenance ability of biodiversity (Cohen et al., 2016; Xu et al., 2019; Zhang and Wu, 2018).

Recently, some researches have established the connection between hydrological connectivity and wetland biodiversity and for the future simulation and prediction of wetland biodiversity (Zhang and Wu, 2018; Qu et al., 2022). For example, a regional-scale study reported a significant correlation between biodiversity and hydrological pattern, and wetland connectivity (Qu et al., 2022). The analysis of the correlation between the conservation value of wetland biodiversity based on systematic conservation planning and the wetland hydrological pattern and connectivity (HPC) indexes in the corresponding period (Margules and Pressey, 2000; Pressey et al., 2007) helped identify the key HPC indexes affecting the biodiversity conservation value of wetland. The regional wetland biodiversity was simulated by constructing a regression equation. Another model called CA_ Markov can effectively predict long-term spatial changes in land use (Sang et al., 2011), coupling the advantages of the Cellular Automata (CA) model in simulating spatial changes of complex systems and that of the Markov model in long-term prediction. This model has the ability to predict the changes of wetland spatial patterns in the future under a specific period or land-use policy, which provides the connection mode of historical, current biodiversity simulation, and future biodiversity prediction for wetland biodiversity based on HPC. The combination of CA_Markov prediction and HPC simulation constitutes a complete framework for monitoring wetland biodiversity in different periods (past, current, and future).

Sanjiang Plain is a wetland biodiversity concentrated distribution area, a national ecological functional area, and an important food production base with global significance in China (Dong et al., 2017). The hydrological connectivity of wetland ecosystem in Sanjiang Plain is of great significance to the protection of wetland biodiversity (Zheng et al., 2022). However, in recent years, under the dual effects of high-intensity human activities and climate change, wetland in Sanjiang Plain has encountered a series of serious ecological problems, including the reduction of wetland area, the cutting off of hydraulic connections between wetlands, the fragmentation of wetland habitat patches, the obvious disturbance of physical, chemical, hydrological, and biological connectivity between wetland patches, and the decline of wetland habitat quality (Luan and Zhou, 2013; Liu et al., 2019; Qu et al., 2022). These events have led to the reduction of biodiversity and the degradation of wetland ecological function. Thus, it is necessary to establish the relationship between wetland hydrological connectivity and biodiversity in Sanjiang Plain and predict the future changing trend of wetland biodiversity to provide the information needed for wetland protection and management in the future.

In this study, taking Sanjiang Plain as a case, we focused on how to combine wetland biodiversity simulation based on HPC and CA_Markov models to predict the future biodiversity pattern at the regional scale. First, we determined the distribution of wetlands in future land use predicted by the CA_Markov model. Second, we calculated the wetland pattern and hydrological connectivity indexes, and simulated the wetland biodiversity according to the regression equation of the HPC model. Finally, by calculating the difference between the predicted results and the current biodiversity simulation, we predicted the changing trend of wetland biodiversity in the future. Our work aims to build a modeling framework to predict wetland biodiversity changes under a certain land-use strategy and to provide a technical support for predicting the changing trend in wetland biodiversity at both regional and reserve scales. The method has the ability to produce quantitative estimates of wetland biodiversity dynamics at a desired spatial and temporal resolution and also scenario modeling for projected land use changes.

2. Overview of the study area

Sanjiang Plain is located in the east of Heilongjiang Province (Fig. 1). It is the largest freshwater swamp distribution area in China (Luo et al., 2022). Its geographical coordinates are 43° 49′ 55″ to 48° 27′ 40″ N and 129° 11′ 20″ to 135° 05′ 26″ E. Sanjiang Plain wetland is rich in biodiversity resources. It is one of the biodiversity hotspots determined by the Ministry of Environmental Protection of China and is known as the “unique gene bank of wildlife” (CMEP, 2010). However, after more than half a century of social and economic development, Sanjiang Plain has become China’s largest commercial grain base. Excessive agricultural reclamation and destruction of the natural environment have led to many ecological and environmental problems, such as the fragmentation of wetland landscape, reduction of river runoff, decline of groundwater level, intensification of environmental pollution, and loss of biodiversity (Lv, 2009; Qu et al., 2022). Significant agricultural land occupation has sharply reduced the habitat area of wetland species, and the remnant habitat has been experiencing the loss of animal and plant species due to the degradation of vegetation, thereby seriously threatening the wetland biodiversity of Sanjiang Plain (Zhang et al, 2010).

3. Research methods

3.1. Prediction of land-use change based on the CA-Markov model

To predict land-use changes, we used CA_ Markov model, which combines the advantages of CA model and Markov model. CA model is a spatio-temporal dynamic simulation model based on discontinuity, and it considers time, space, and state as discrete entities, which is its main characteristic (Clarke et al., 1997). A CA system usually includes four elements: unit, state, proximity range, and transformation rules (Vellarayil and Jeganathan, 2018). Markov model refers to a system transferring from one state to another. Land-use/cover change has the characteristics of no aftereffect, which meets the conditions of the Markov model. Therefore, the dynamic process of changing land use/cover can be regarded as a Markov process. The land-use/cover type of the central cell can be predicted by considering the pixel as the cell in the CA model, the land-use/cover type of the pixel as the cell state, the adjacent pixel as the cell neighbor, pixel size as the scale size of the cell, and then applying Markov model to these pixels and their neighbors (Fu et al., 2018; Hishe et al., 2020; Jayanthi et al., 2021).

Taking Sanjiang Plain as the case study area, we collected the land-use data for three periods, namely 2010, 2015, and 2020. With the participation of experts and the field measured data, we interpreted the Landsat TM remote sensing images to obtain the 30 m × 30 m land-use data under a national secondary classification system. We used the random forest classifier in ENVI remote sensing processing software for classification and interpretation. Furthermore, we determined the characteristics of change in land use with the annual change rate and dynamic degree of spatial change to simulate the change in land use in Sanjiang Plain using the CA_Markov model. We considered 2010 as the base year to predict the land-use spatial pattern in Sanjiang Plain in 2020. Then we verified this predicted land-use with the actual interpretation of land-use data for 2020 and we test its accuracy with the kappa coefficient. Using the validated model, we predicted the land-use spatial pattern of Sanjiang Plain in 2030 to determine the dynamic changing trend of land use.

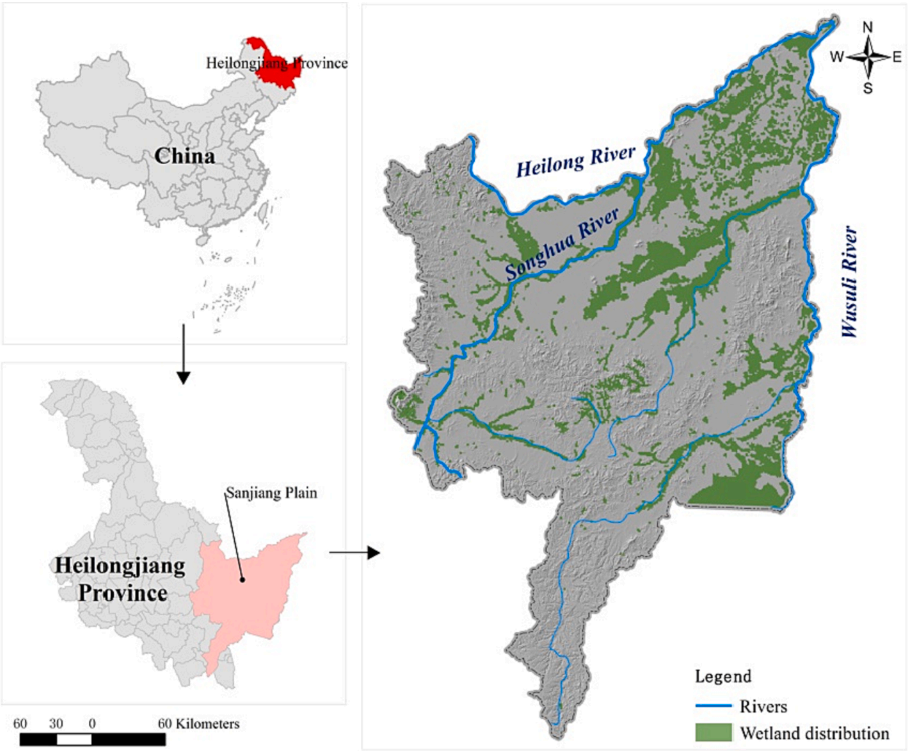


Fig. 1. The location of the study area.

3.2. *Prediction of spatial pattern of wetland HPC indexes*

The HPC indexes include three indexes of area (Total landscape area [TA], Largest patch index [LPI], and Mean area of patches [AREA_MN]), two indexes of density (Number of patches and Patch density [PD]), five indexes of shape (Shape index [SHAPE_MN], Landscape shape index [LSI], Fractal dimension [FRAC_MN], Perimeter area ratio [PARA_MN], and Related circumscribing circle [CIRCLE_MN]), and five indexes of connectivity (Contagion index [CONTAG_MN], Proportion of like adjacency [PLADJ], Division index [DIVISION], Patch cohesion index [COHESION], and Aggregation index [AI]). See details of these indexes in user's manual or literature (McGarigal and Marks, 1995).

These HPC indexes are landscape pattern indexes used to reflect the characteristics of landscape spatial structure. These indexes are affected by various ecological processes, such as interference, on the landscape at different scales. In this study, we calculated HPC indexes for each 1 km × 1 km grid, taking the circular area with 5000 m radius of the grid as the calculation unit. We determined radius as 5000 m because of the strongest correlation between wetland HPC indexes and biodiversity conservation value (Qu et al., 2022). To generate their spatial gradient patterns in the region, we calculated these HPC indexes in each grid by using FRAGSTATS4.2 (McGarigal et al., 2012). Moreover, we predicted HPC indexes for 2030 based on the wetland distribution extracted from predicted land use in 2030 by using the CA_Markov model.

3.3. *Prediction of future biodiversity spatial pattern through the estimation of wetland biodiversity based on the HPC*

To simulate wetland biodiversity in 2030, we performed the estimation of wetland biodiversity based on the hydrological pattern and connectivity (EWBHPC). EWBHPC model simulates wetland biodiversity by constructing the regression equation between biodiversity conservation value (BCV) and HPC indexes of wetland. BCV is the wetland biodiversity conservation value calculated according to the available potential distribution of representative wetland biodiversity features. BCV is represented by the irreplaceability index, which indicates the importance of planning units (regular grids or irregular districts or catchments that need to be protected) in achieving the overall conservation goals and is defined as the possibility of a specific planning unit to achieve the conservation goals. BCV is a continuous value between 0 and 1. The higher the value, the higher the conservation value of the planning unit and fewer the requirements of other planning units to replace the unit to complete the conservation targets (Carwardine et al., 2007). Further, we constructed a regression equation to simulate wetland biodiversity (SBCV) by analyzing the correlation between wetland HPC indexes and BCV in the corresponding period. Finally, we determined the wetland biodiversity simulation equation based on wetland HPC indexes as follows (Qu et al., 2022):

$$\mathrm{SBCV} = 0.414 \times \mathrm{AREA\_MN} + 0.345 \times \mathrm{AI} + 0.056$$

SBCV is the simulated biodiversity conservation value of wetland, AREA_ MN is the average patch area of wetland within a radius of 5000 m, and AI is the aggregation degree of wetland patches within a radius of 5000 m. AREA_ MN describes the average patch area of landscape. For species habitats, the size of different regions reflects the differences in species, energy, nutrients, and other information flows. AI describes the degree of aggregation of different habitat patches in the landscape and reflects a certain number of habitat patches (McGarigal et al., 2012).

3.4. *Optimized management strategies based on the changing trend of BCV*

Changing trend of BCV (CTBCV) refer to the difference between the predicted BCV (PBCV) in 2030 and simulated BCV (SBCV) in 2020. Combining the actual meaning of CTBCV and its numerical similarity, we divided CTBCV into six grades: $\mathrm{CTBCV} < -3$, $-3 < \mathrm{CTBCV} \leq -1.5$, $-1.5 < \mathrm{CTBCV} < 0$, $0 \leq \mathrm{CTBCV} \leq 1$, $1 < \mathrm{CTBCV} \leq 2$, and $\mathrm{CTBCV} > 2$, representing greatly reduced, moderately reduced, slightly reduced, slightly increased, moderately increased, and greatly increased, respectively. We analyzed the CTBCV at the regional and reserve scales and evaluated the potential threat of wetland biodiversity loss. At the regional scale of Sanjiang Plain, we analyzed the areal proportion of CTBCV at various levels inside and outside the conservation network system and evaluated the overall conservation efficiency of the system. At the individual scale of the reserve, we calculated the areal proportion and numerical change of CTBCV within each reserve and analyzed the potential loss of wetland biodiversity in reserve for 2030 under the current land-use policy. Finally, we proposed the protection and early warning strategies for wetland biodiversity for the whole Sanjiang Plain Region and each reserve, as well as the priority ranks of management (PRM). PRM 1 to 5 represent the degrees of threat to wetland biodiversity in the future. PRM of 1 is the highest, in which the early warning level is high, warranting priority management. PRM of 5 is the lowest, in which the early warning level is low, implying that it can sustain the current wetland protection and land-use strategies.

4. Results

4.1. Future land-use pattern predicted using the CA-Markov model

Fig. 2 shows the land-use maps of Sanjiang Plain in 2010 and 2015 (the referenced periods), 2020 (the verification period), and 2030 (the predicted period). According to the land-use status in 2010 and 2015, the simulated land-use pattern in 2020 was verified by the actual land-use pattern in 2020, with the kappa coefficient being 0.9596. Cultivated land is the main land-use type of Sanjiang Plain, and the proportion of its area is increasing every year.

Table 1 shows the change in land-use area in Sanjiang Plain from 2010 to 2030. If the study area develops according to the current land-use policy, the cultivated land will increase by 4.95 % in 2030 compared with that in 2020. Forest is the second-largest land-use type in Sanjiang Plain, and its area is decreasing annually. By 2030, the area proportion is predicted to reduce by 2.2 %. Although the proportion of wetland in Sanjiang Plain is not high (only approximately 10 %), it is the land-use type with the largest reduction, and the wetland area is predicted to reduce by 2.74 % by 2030. In addition to forest and wetland, the area of grassland has decreased, and the area percentage is predicted to decrease by 0.58 % by 2030. Construction land area is predicted to increase slightly, and the unused land area will be stable.

4.2. Predicted spatial pattern of wetland HPC indexes

The results indicate only HPC indexes included in BCV simulation (AREA_MN and AI). Fig. 3A and B show the changes of AREA_MN and AI within the 5000-m radius of the center of the planning unit in 2010, 2015, and 2020 and the predicted results for 2030.

From 2010 to 2015, the proportion of no wetland patches within the 5000-m radius of the planning unit increased by 45.24 %. This proportion increased by 62.57 % from 2010 to 2020. If the land-use policy continues, this proportion is predicted to increase by 500.04 % by 2030. From 2010 to 2020, the average value of AREA_MN in different levels revealed that the low-level proportion decreased, and the medium- and the high-level proportion increased in 2015 and then decreased in 2020 (Table 2). By 2030, the average value of AREA_MN of wetland in the study area will greatly decrease to 893.83 hm^2, and the unit number with medium- and high-level AREA_MN will be greatly reduced.

Table 3 shows the spatial pattern change of the average value of AI from 2010 to 2020. The number of units with AI of 0 continued to increase, that with low- and medium-level was stable, and that with high levels increased in 2015 and then decreased in 2020. If the current land-use policy continues, the proportion of units with AI of 0 will have a 5-fold increase compared with that in 2010. If the cultivated land expansion continues to follow this trend, the units with high AI value will decrease significantly, and their average value will drop from 91.17 to 82.16 by 2030.

4.3. Predicted spatial pattern of wetland biodiversity by EWBHPC

Fig. 4 depicts the spatio-temporal changes of SBCV (2010, 2015, and 2020) and PBCV (2030) obtained using the EWBHPC model. SBCV and PBCV are divided into high (>0.6), medium (0.4–0.6), and low (<0.4) categories according to the original BCV division criteria by New South Wales National Parks and Wildlife Service (NSWNPWS, 2001). The change in wetland biodiversity in Sanjiang Plain mainly occurs in the northeast and central parts of the region, and there is also a certain degree of degradation in the east. In particular, the occupation of cultivated land has greatly reduced the biodiversity in the intersections of Songhua, Naoli, Heilong, and Wusuli Rivers.

Figs. 5 and 6 show the statistical changes in SBCV of different levels (high, medium, and low) in 2010, 2015, and 2020 and the predicted results for 2030. From 2010 to 2020, the proportion of high-level wetland biodiversity areas remained stable but will decline by approximately 3 % by 2030; its value exhibited an overall upward trend (from 0.75 to 0.80), whereas the proportion of medium-level wetland biodiversity areas exhibited a downward trend. By 2030, its proportion will be approximately 35 % lower than that in 2010 and 16 % lower than that in 2020; additionally, its value change exhibited a downward trend. The proportion of low-level wetland biodiversity areas exhibited an upward trend, which will increase by 38 % compared with that in 2010 and by 20 % compared with that in 2020. The value decreases significantly, mainly because of the reclamation of a large number of wetlands into

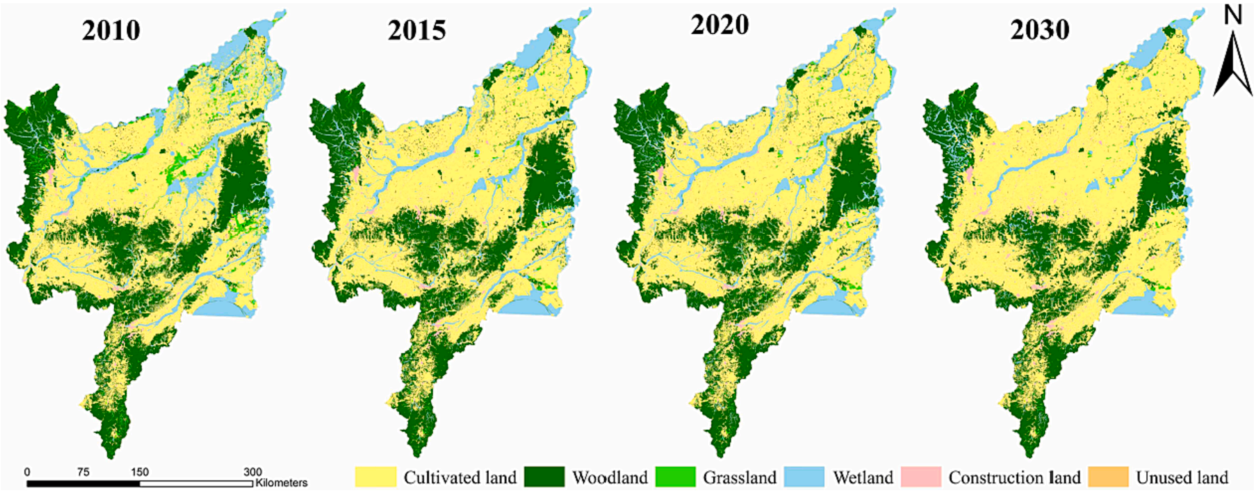


Fig. 2. Land use of Sanjiang Plain in 2010, 2015, and 2020 and land-use prediction in 2030.

Table 1
Characteristics of the change in land-use area in Sanjiang Plain from 2010 to 2030.

Land use	2010		2015		2020		2030		2010–2020	2010–2030	2020–2030
	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Area (km^2)	Area (km^2)
Farm land	5.39	49.57	5.87	54.04	5.98	55.08	6.52	60.03	0.60	1.14	0.54
Forest	3.31	30.51	3.26	29.96	3.25	29.96	3.02	27.76	−0.06	−0.30	−0.24
Grass land	0.43	3.92	0.21	1.91	0.21	1.91	0.14	1.33	−0.22	−0.28	−0.06
Wetland	1.50	13.82	1.28	11.80	1.17	10.73	0.87	7.99	−0.34	−0.63	−0.30
Built-up area	0.23	2.14	0.25	2.27	0.25	2.30	0.31	2.88	0.02	0.08	0.06
Unused land	0.00	0.03	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00

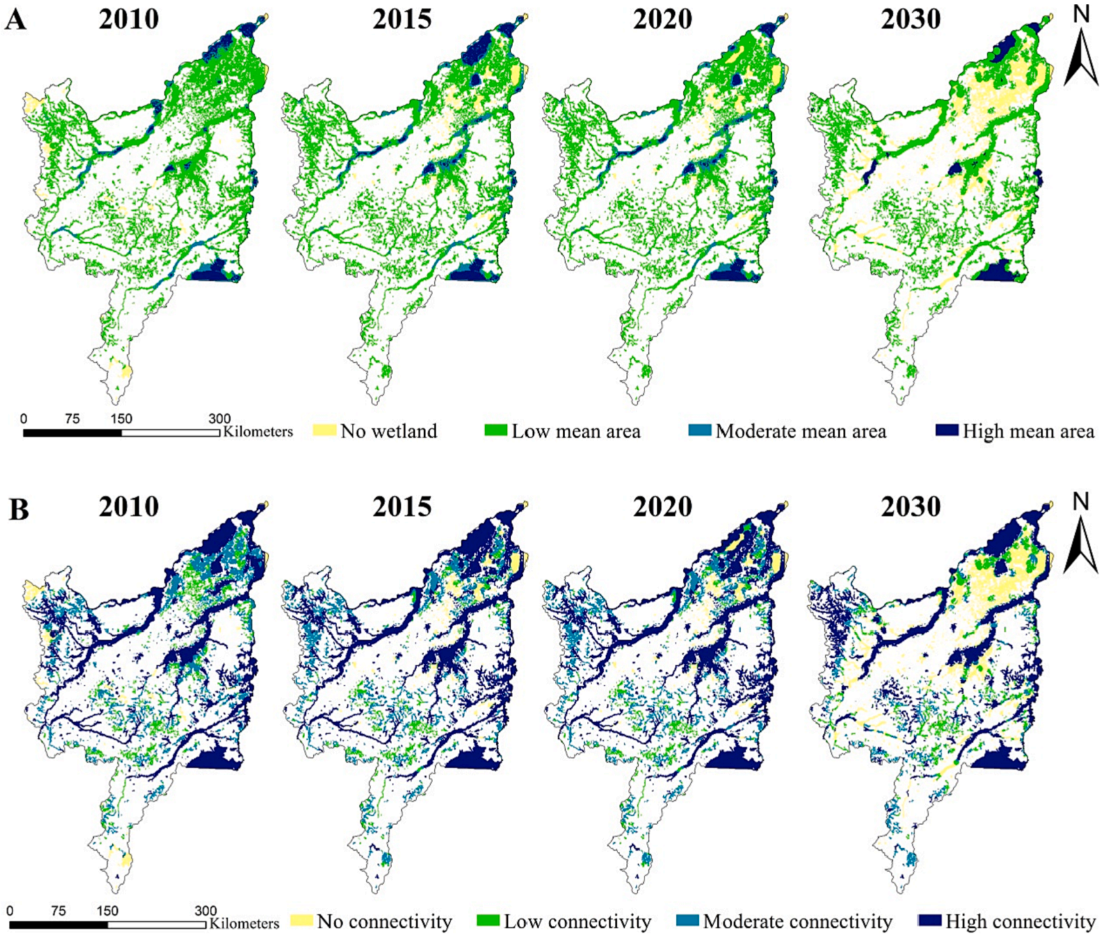


Fig. 3. Spatial changes of AREA_MN and AI in 2010, 2015, and 2020 and the predicted results for 2030.

Table 2
Changes of the planning unit number in different levels of AREA_MN in 2010, 2015, and 2020 and predictions for 2030.

AREA_MN	Planning unit number in 2010	Planning unit number in 2015	Planning unit number in 2020	Planning unit number in 2030
0	1472	2138	2393	8897
<2000 hm^2	34,056	31,271	32,337	29,293
2000–5000 hm^2	3368	4704	4369	1312
>5000 hm^2	2442	3225	2239	1836

Table 3
Changes in the planning unit number in different levels of AI (a value from 0 to 100 without unit) in 2010, 2015, and 2020 and predictions for 2030.

AI	Planning unit number in 2010	Planning unit number in 2015	Planning unit number in 2020	Planning unit number in 2030
0	1479	2152	2409	8931
0–90	5606	3937	4042	6269
90–95	12,265	10,778	10,955	6394
>95	21,988	24,471	23,932	19,744

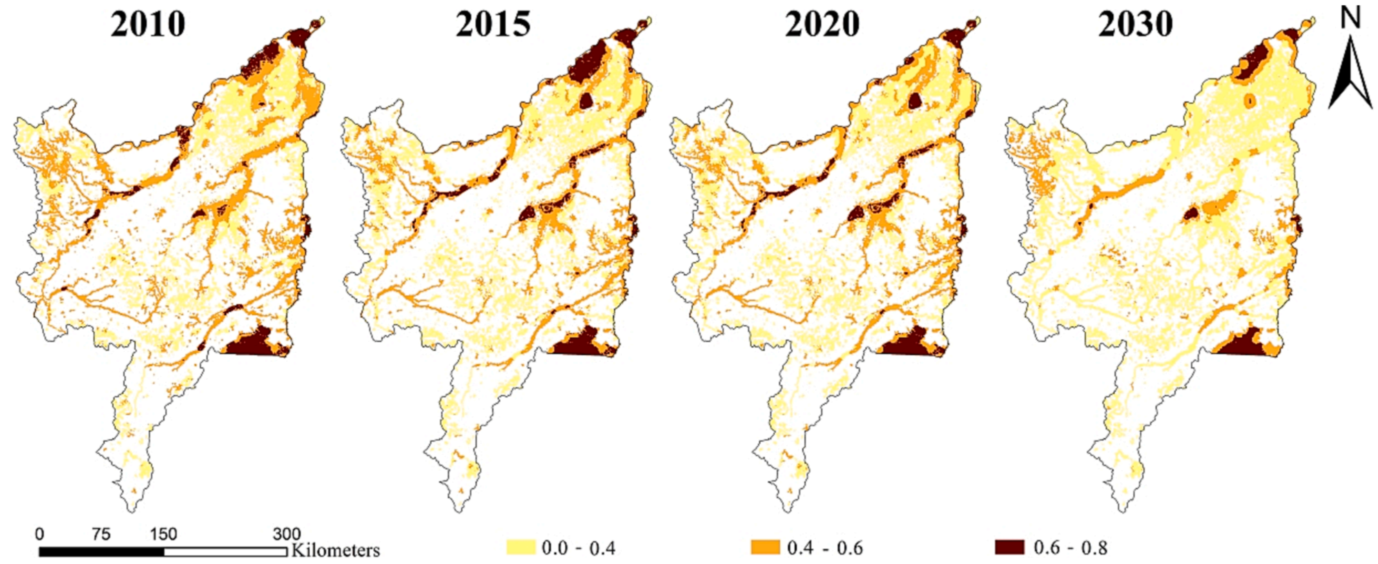
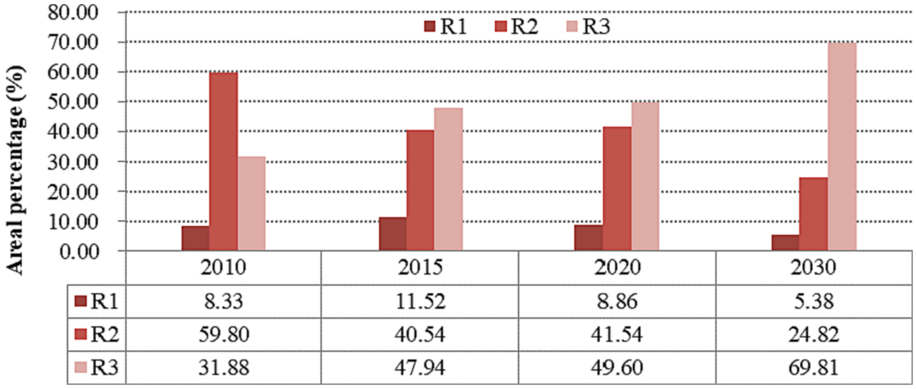


Fig. 4. Changes in the spatial pattern of wetland biodiversity in Sanjiang Plain from 2010 to 2030.



	2010	2015	2020	2030
R1	8.33	11.52	8.86	5.38
R2	59.80	40.54	41.54	24.82
R3	31.88	47.94	49.60	69.81

Fig. 5. Changes in the areal proportion of different wetland biodiversity ranks in Sanjiang Plain from 2010 to 2030 (R1, R2, and *R*3 are high-, medium- and low-level SBCV/PBCV, respectively).

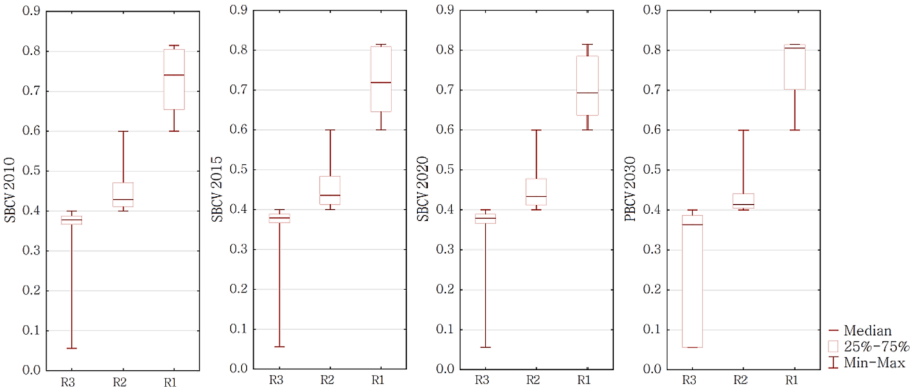


Fig. 6. Statistical changes of different BCV ranks in Sanjiang Plain from 2010 to 2030 (SBCV is the simulation value of BCV; PBCV is the prediction value of BCV).

farmlands.

4.4. Optimal management of wetland biodiversity in Sanjiang Plain

From 2010 to 2015, >20 protected areas existed in Sanjiang Plain, accounting for>40 % of the study area. However, our results revealed that the wetland biodiversity in the reserves is still facing a huge threat. If the land-use development strategy from 2010 to 2015 is continued, the overall CTBCV of the Sanjiang Plain wetland will decrease by 7.40 %, and the biodiversity level of wetland in the reserves will decrease by 7.90 % from 2020 to 2030. The wetlands in the north-central, northeast, and southeast regions of Sanjiang Plain will lose an average of 20 % of wetland biodiversity because of cultivated land occupation, and the wetland biodiversity in the northwest and south-central regions will

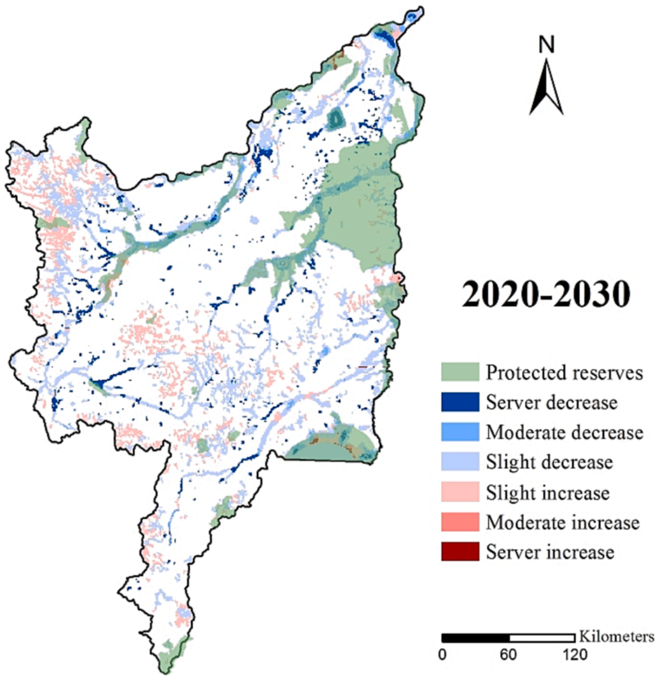


Fig. 7. CTBCV pattern in Sanjiang Plain in 2030.

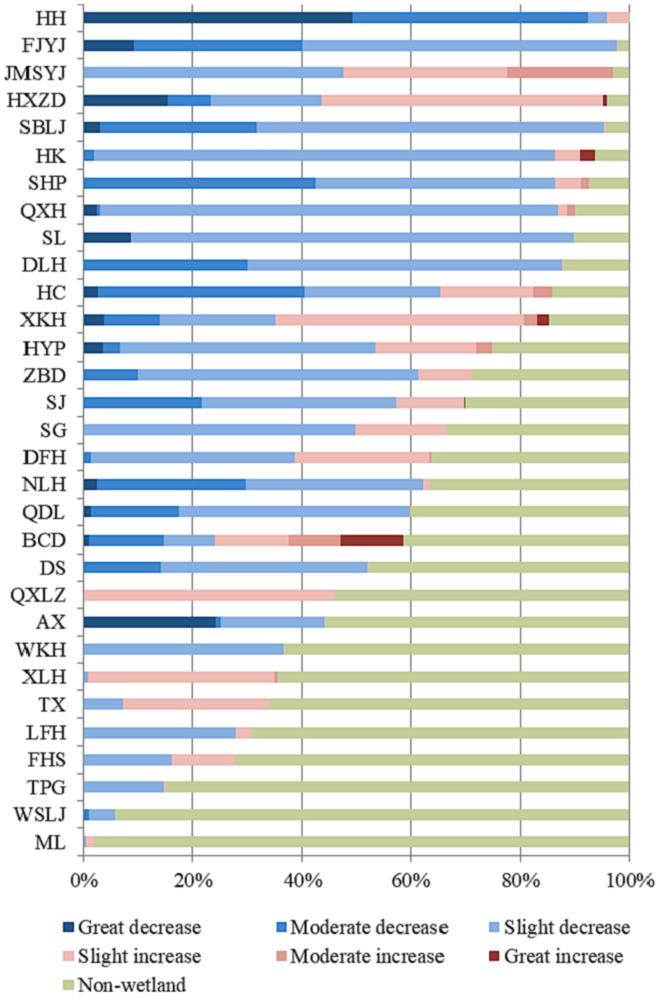


Fig. 8. Proportion of different CTBCV ranks in each reserve in 2030.

increase by approximately 7 % due to the increase in the area of forest wetlands (Fig. 7).

By 2030, the wetland biodiversity in 23 of the 31 reserves is predicted to undergo different degrees of loss, of which 14, 7, and 2 will lose<10 %, 10 %–20 %, and 20 %–30 %, respectively. Fig. 8 shows that almost all these established reserves in Sanjiang Plain have wetland distribution. More than half of the reserves have a biodiversity degradation area of>50 % of the corresponding reserve, and three reserves will even experience severe degradation with 10 % of the reserve area. Table 4 presents the predicted statistical data of CTBCV of wetland biodiversity in each reserve for 2030. Among the 31 protected areas, 11 are high-level warnings for biodiversity protection and management (3 PRM1 and 8 PRM2). Hence, the wetland protection and land-use management strategy must be adjusted and the occupation of cultivated land on wetland resources must be strictly controlled.

5. Discussion

Combining the CA_Markov model and biodiversity simulation method based on the wetland HPC, this study proposed the prediction framework of plain wetland biodiversity, with the goal of predicting the changing trend of wetland biodiversity under the current land-use strategy. The present study may provide scientific management and control strategies for wetland biodiversity protection and sustainable management. First, based on the land-use data in 2010 and 2015, we used the CA-Markov model to predict the land use in the study area in 2030. Second, using the wetland distribution extracted from the predicted land use, we calculated the key indicators of wetland HPC to simulate wetland biodiversity and predicted the spatial pattern of wetland biodiversity for 2030. Finally, by comparing the current and predicted wetland biodiversity, we propose the wetland protection and sustainable management strategies.

5.1. Trend of land use and HPC pattern

Our study revealed that under the land-use policy and wetland protection strategy from 2010 to 2015, the wetland area in the study area will be greatly reduced by 2030. At the same time, due to the change in wetland hydrological patterns, the indexes (Area_MN, AI) related to wetland biodiversity will be reduced, leading to a significant reduction in the proportion of medium and high biodiversity areas; in addition, the BCV will decrease. This result is consistent with the changing trend of macrobenthos and aquatic biodiversity affected by hydrological spatial connectivity (Davidson et al., 2012; Dou et al., 2016). It shows that the degree of hydrological connectivity will affect wetland biodiversity at both regional and local scales. Wetland biodiversity is closely related to climate variables (Karim et al., 2016; Rolls et al., 2018). Therefore, the difference in precipitation will affect the accuracy of mapping wetland distribution to a certain extent, affecting the calculation of hydrological-pattern-related indexes and prediction of wetland biodiversity. The average precipitation in the study area in 2015 increased by approximately 15 % compared with that in 2010. The wetlands in some areas expanded, and the hydrological connectivity increased. However, even in this case, cultivated land occupied a large area of wetlands, resulting in the increase in small wetland patches and the reduction in wetland biodiversity in other areas. This also explains that the predicted average value of high-level increases and that of low-level decreases.

5.2. Trend of wetland biodiversity pattern

The results of BCV prediction revealed that under the current land-use strategy, the wetland biodiversity of Sanjiang Plain will be greatly reduced by 2030. In particular, the BCV of medium level will be substantially reduced, indicating that the decline of wetland biodiversity caused by HPC mainly affects the wetland patches with medium BCV,

Table 4
Statistics of CTBCV in each reserve for 2030. CTBCV_min, CTBCV_max and CTBCV_mean are the maximum, minimum, and average values of CTBCV, respectively. PRM represents the priority ranks of management.

Reserve names	Name abbreviation	CTBCV_min	CTBCV_max	CTBCV_mean	PRM
Honghe	HH	−0.41	0	−0.29	1
Anxing	AX	−0.43	−0.01	−0.24	1
Fujinyanjiang	FJYJ	−0.34	0.01	−0.15	1
Naolihe	NLH	−0.42	0.15	−0.14	2
Duluhe	DLH	−0.3	−0.02	−0.13	2
Suibinliangjiang	SBLJ	−0.33	0.01	−0.12	2
Dongsheng	DS	−0.22	0	−0.12	2
Huachuan	HC	−0.33	0.14	−0.11	2
Qindeli	QDL	−0.34	0	−0.11	2
Sanjiang	SJ	−0.29	0.4	−0.1	2
Sanhuanpao	SHP	−0.26	0.16	−0.1	2
Shuilian	SL	−0.36	−0.02	−0.09	3
Heixiazidao	HXZD	−0.4	0.28	−0.09	3
Wusulijiang	WSLJ	−0.18	−0.03	−0.07	3
Qixinghe	QXH	−0.36	0.16	−0.06	3
Zhenbaodao	ZBD	−0.26	0.06	−0.06	3
Heiyupao	HYP	−0.43	0.12	−0.05	3
Xingkaihu	XKH	−0.38	0.36	−0.04	4
Wokenhe	WKH	−0.05	−0.01	−0.04	4
Dongfanghong	DFH	−0.17	0.1	−0.03	4
Hukou	HK	−0.19	0.36	−0.03	4
Liufenghu	LFH	−0.07	0	−0.03	4
Shuguang	SG	−0.07	0.01	−0.01	4
Fenghuangshan	FHS	−0.05	0.02	0	5
Muling	ML	−0.02	0.01	0	5
Taipinggou	TPG	−0.01	0.02	0	5
Jiamusiyanjiang	JMSYJ	−0.13	0.16	0	5
Bachadao	BCD	−0.31	0.35	0.01	5
Tiexi	TX	−0.01	0.01	0.01	5
Qixinglazi	QXLZ	0.02	0.05	0.03	5
Xilinhe	XLH	−0.01	0.15	0.04	5

rather than the wetland patches with high BCV. Therefore, more attention should be paid to the protection and management of wetlands with medium BCV. According to the relationship between HPC indexes and BCV, BCV is the linear expression of AREA_MN and AI. The larger the average area of wetland patches and the higher the AI, the higher the BCV (Qu et al., 2022). This provides a reference of rule restriction for the future planning and utilization of wetland resources in the Sanjiang Plain. For example, when we utilize wetland for farmland, the number of remnant wetland patches within a certain radius should be small and the patch area should be large enough to satisfy the species' minimum area requirement (Robbins et al. 1989; Lehmkuhl and Raphael 1993). In addition, the aggregation degree of wetland patches should be considered (Jaeger, 2000; He et al., 2000). An optimum degree of aggregation of wetland patches can enhance the ability to resist interference due to the landscape diversity and prevent the formation of fragmented habitats that cause species isolation. Reasonable degree of aggregation can be determined according to the relationship between AI and BCV.

5.3. *Protection and management strategies*

Various levels of wetland biodiversity conservation targets account for optimizing the wetland biodiversity protection and management strategies in the study area to achieve effective biodiversity conservation and sustainable development. At the regional or even the higher level, our study provides a reference for assessing changes in a wetland ecosystem and biodiversity and monitoring indicators within the framework of the sustainable development agenda and the water and sanitation development goals for 2030 (SDG 6.6 and SDG 15.5) (Dickens et al., 2017; Water, 2018). Moreover, the current study will help quantify the threat to wetland biodiversity, providing references for updating each country's National Biodiversity Strategy and Action Plan. At the reserve level, it provides information for identifying the areas of potential biodiversity loss in each reserve and has a practical guiding role. Different scales of wetlands have different biodiversity conservation objectives and different needs (Soutullo et al., 2008). Earlier, wetland biodiversity conservation was mainly considered at the national and regional scales. However, more specific biodiversity information at the reserve scale is necessary, as the degree of threat to wetland biodiversity varies across different reserves. If planning is limited to the scale above the region, implementing the protection or restoration objectives will be difficult. In this study, we highlighted and ranked the differences in the early warning for wetland biodiversity threats or biodiversity loss in each reserve. Furthermore, we visualized the change in the potential loss of wetland biodiversity so that local wetland biodiversity protection managers and decision-makers can balance the protection and use of resources in a better manner according to the actual situation of each reserve.

5.4. *Research deficiencies and future directions*

The present study may have inevitable uncertainties, even if the best available data were used—for example, the uncertainty related to data quality. First, the quality of remote sensing images and the standards and methods used in the interpretation process probably affected the quality of wetland distribution data and further the accuracy of the predicted wetland hydrological pattern indexes. Second, models of biodiversity simulation and land-use prediction may be the source of uncertainties (Palmate et al., 2022; Qu et al., 2022). Furthermore, climate change might have affected the research results. The spatial distribution of wetlands and simulation results of wetland biodiversity will vary under different climate conditions.

The prediction process of the CA_Markov model uses the land-use data of a benchmark year as the initial state and redistributes the land types according to the land-use transfer area and suitability map. Even if the climate factor is considered to some extent, it is only for the base period (historical). However, great uncertainty exists regarding future climate change. Because of these comprehensive uncertainties, our predicted potential change of wetland biodiversity in the study area may be over or underestimated. Although the predicted result is acceptable from the perspective of the relative potential threat between different regions in the study area, the results still need to be verified and optimized within the scope of the reserve.

Of note, this study predicted the changing trend of wetland biodiversity at the regional and reserve scales. However, improving the accuracy and practicability of the predicted results remains challenging. Our work is based on current knowledge. With the development of data availability and technology in the future, it may need to be refined. In future research, climate factors should be considered to optimize the CA_Markov prediction results, improve the accuracy of wetland spatial distribution data, and further improve the accuracy of wetland biodiversity prediction. Larger-scale research (such as national or global scale) should be considered to verify or explore scale differences. Past, current, and future simulation and prediction results at different scales should be integrated, which can provide a complete and comprehensive technical and strategic reference for protecting wetland biodiversity at different scales.

6. Conclusions

The wetland biodiversity is reliant partly on wetland HPC. Thus, changes in wetland HPC will affect the future wetland biodiversity pattern. To accurately predict the biodiversity changes, the relationship between HPC and biodiversity of wetland must be established. Combining the advantage of EWBHPC model to simulate wetland biodiversity through HPC and the advantage of CA-Markov model to predict land-use pattern, this study proposes a wetland biodiversity prediction framework based on HPC. The proposed framework can be used to predict the spatial pattern of wetland biodiversity at the regional scale and identify biodiversity changes at reserve scale. The results have the potential to supply the hydro-predicting indicator and help managers of wetland resources to pre-evaluate the changes of wetland biodiversity under certain land-use policies.

CRediT authorship contribution statement

Yi Qu: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **Xingyu Zeng:** Software, Formal analysis, Data curation. **Chunyu Luo:** Validation, Investigation. **Hongqiang Zhang:** Methodology, Resources, Writing – original draft. **Hongwei Ni:** Conceptualization, Writing – review & editing, Supervision.

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.

Data availability

No data was used for the research described in the article.

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