

# Evolution of Potential Spatial Distribution Patterns of *Carex* Tussock Wetlands Under Climate Change Scenarios, Northeast China

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**Abstract:** *Carex* tussock plays an important role in supporting biodiversity and carbon sequestration of wetland ecosystems, while it is highly threatened by climate change and anthropogenic activities. Therefore, identifying the potential distribution patterns of *Carex* tussocks wetland is vital for their targeted conservation and restoration. The current and future (2050s and 2070s) potential habitats distribution of *Carex* tussocks in Northeast China were predicted using a Maximum Entropy (Maxent) model based on 68 current data of *Carex* tussock distributions and three groups of environmental variables (bioclimate, topography, soil properties). Results show that isothermality, seasonal precipitation variability and altitude are important factors that determine the distribution of *Carex* tussock. The high suitable habitat of *Carex* tussock is about  $5.7 \times 10^4$  km<sup>2</sup> and mainly distributed in the Sanjiang Plain, Songnen Plain, Changbai Mountains and Da Hinggan Mountains. The area of stable habitats of *Carex* tussock is significantly higher than the lost and expanded habitats in the future climate scenarios, and the unsuitable habitats mainly occur in Da Hinggan Mountains, Xiao Hinggan Mountains and Changbai Mountains. Overall, *Carex* tussock wetlands at high altitude and high latitude are more sensitive to climate change, and more attention should be invested in high latitude and high altitude areas.

**Keywords:** *Carex* tussock wetland; spatial distribution; climate change; Maxent model; suitable habitat

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## 1 Introduction

The responses and feedbacks of vegetation to climate change have been brought to the fore of geography, ecology and botany (Shen et al., 2015; Piao et al., 2019). Climate change may substantially change the structure and function of the ecosystem (Thomas et al., 2004; Piao et al., 2019; Bastiaansen et al., 2020; Geng et al., 2020), and affect its stability and biodiversity. Plant spa-

tial distribution is largely determined by climate and environmental conditions (Rabasa et al., 2013; Du et al., 2018). The differences of water, heat and their combinations alter plant growth and distribution pattern by affecting plant physiological and ecological processes (Rabasa et al., 2013; Shen et al., 2015; Du et al., 2018). Many evidences have indicated that climate warming could cause vegetation migration (Root et al., 2003), and increase the risk of species extinction (Bertrand et

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al., 2011; Bellard et al., 2012; Urban, 2015). Therefore, identify the spatial distribution and evolution characteristics of plant suitable habitats under climate change is of great significance for understanding the response process of ecosystem to climate change, as well as species protection.

The species distribution models are contributed to ecological risk assessment of the species and habitats. Species distribution models, including Maximum Entropy model (Maxent), Classification and Regression Tree (CART) and Genetic Algorithm for Rule-set Prediction (GARP), etc., are mainly used to predict the potential geographical distribution (Wei et al., 2021). Maxent is statistical modeling based on maximum entropy theory and takes the environmental characteristics of presence species distribution as constraint, and then predicts the potential distribution of the target by finding the probability distribution of maximum entropy under the constraint (Phillips et al., 2006). Due to its accurate prediction, easy analyses and simple approaches, Maxent model is widely used to predict the reserve construction (Urbina-Cardona and Flores-Villela, 2010; Wang et al., 2019c), the restoration and protection of endangered species (Qin et al., 2017) and the diseases spatial distribution (Sun et al., 2021), as well as the impact of climate change on wetland species distribution (Cao et al., 2020; Hu et al., 2020).

*Carex* tussock wetlands are widely distributed in floodplain wetlands and mountain valley wetlands in Northeast China (Zhang, 2017). Protruding *Carex* tussocks increase the surface area, roughness and microgeomorphological heterogeneity (Lawrence and Zedler, 2011), which provides support for biodiversity (Crain and Bertness, 2005; Peach and Zedler, 2006; Johnston and Zedler, 2012). Besides, *Carex* tussocks have many ecological functions including pollutant adsorption, nutrient accumulation, and biological carbon sequestration (Lawrence and Zedler, 2013). Research showed that the aboveground carbon pools of *Carex* tussock wetland (16.5–27.5 Mg /ha, C) was significantly higher than that of other herbaceous systems (Lawrence and Zedler, 2013). In particular, the unique hummock structure formed by *Carex* root tillering makes a significant contribution to the formation of herbaceous peat (Bai et al., 1999).

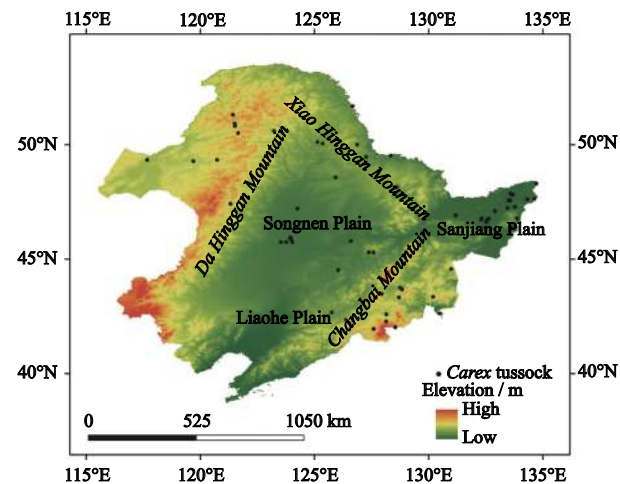
However, since 1961, an obviously rising trend of annual temperature and decreasing trend of precipitation

was found in Northeast China (He et al., 2013). According to the survey, nearly 72% of the existing wetlands in Northeast China are threatened by different factors, resulting in a decline in ecological function (Mao et al., 2018), and the variation of precipitation fluctuation is one of the important factors leading to the high risk of regional wetlands (Fu et al., 2020). Previous study shows that alpine swamp meadow would succession to typical meadow under climate drying and warming (Li et al., 2003). Coupled with the influence of human interference (grazing, mowing, reclamation and ditching, etc.), large area of *Carex* tussock wetland has been degraded or disappeared (Pan et al., 2006; Wang et al., 2019b) in Northeast China. Therefore, it is necessary to protect and restore *Carex* tussock wetland to exert its ecological functions. What are the spatial distribution characteristics of *Carex* tussock wetland in Northeast China? Where will the *Carex* tussock wetland be distributed in the future climate scenario? What is the stability of the potential suitable area of *Carex* tussock wetland? These questions need to be answered scientifically. Based on the above situation, in this study we used Maxent model to determine the evolution of potential distribution pattern of *Carex* tussock wetland under different climate scenarios. Our objectives are to: 1) identify the potential geographical distribution of *Carex* tussock wetlands under climate change, 2) explore the main environmental factors that affect the distribution of *Carex* tussocks, and 3) determine the patterns of habitat shifts and stability for the *Carex* tussock. This study provides theoretical support for the ecological conservation and targeted management of *Carex* tussock wetlands in Northeast China and has important reference value for the study of wetland stability.

## 2 Materials and Methods

### 2.1 Study area

This study focused on the Northeast China (38°43'N–53°33'N, 115°31'E–135°5'E), which includes Heilongjiang Province, Jilin Province, Liaoning Province and the eastern Inner Mongolia (Fig. 1). According to the topography and climatic conditions, the Northeast China include seven ecological functional regions: Eastern Inner Mongolia Plateau, Da Hinggan Mountains, Xiao Hinggan Mountains, Changbai Mountains, Sanjiang Plain, Songnen Plain and Liaohe Plain (Shen et al., 2019). And



**Fig. 1** Location of study area and *Carex* tussock wetland distribution

the Northeast China belongs to the temperate monsoon climate with an annual precipitation of 300–1000 mm (Li et al., 2019a). Due to the influence of complex topography, the climate in different ecological functional regions is significantly different. Wetlands in Northeast China are widely developed and of various types. The main plants include *Phragmites communis*, *Typha orientalis*, *Carex lasiocarpa*, etc. (Mao, 2014).

**2.2 Species occurrence records**

*Carex* tussocks are developed in wet valley wetlands and flooded wetlands, which are the key symbols of *Carex* tussock wetlands. In this study, the distribution of *Carex* tussock was used to predict the potential spatial distribution pattern of *Carex* tussock wetland under future climate scenarios. The distribution information of *Carex* tussock was obtained according to the records of *Wild Vascular Plant in Wetlands of Northeast China* (Yi, 2008), the academic researches (Man and Cai, 2005; Wang et al., 2014; Wang et al., 2015; Zhang et al., 2016; Zhang, 2017; Han et al., 2018; Liu et al., 2018; Lou et al., 2018; Wang et al., 2019a; Wang et al., 2021) and the filed investigation (2016–2019). We deleted the duplicate records and ensured that there was only one distribution point in the 1 km × 1 km range, and finally screened out 68 valid samples for building the Maxent model (Fig. 1). Among them, 58 samples (85%) came from the related researches and filed investigation, and the other 10 samples (15%) were the distribution sites of tussock-forming species (*Carex appendiculata*, *Carex schmidtii*, *Carex meyeriana*) recorded in *Wild*

*Vascular Plant in Wetlands of Northeast China* and they were also verified by historical record such as news reports, meeting reports, memoirs, expert experience and wetland park website that there were *Carex* tussock developed here. The *Carex* tussock occurrence records are derived from 1958 to 2019, and about 18% samples were recorded before 2000.

**2.3 Environmental data acquisition and pretreatment**

28 environmental variables, including climate, topography and soil properties, which affect the distribution of *Carex* tussock were selected to simulate the potential spatial distribution of *Carex* tussock (Zong, 2014; Zhang, 2017; Wang et al., 2019b; Zhang et al., 2019b). Among them, the climate data including 19 bioclimatic factors (Bio1 to Bio19, Table 1) were downloaded from the WorldClim Database (<https://www.worldclim.org/>) under current (1950–2000) and future conditions (2050s and 2070s) of different climate scenarios (RCP 2.6, RCP 4.5 and RCP 8.5) with resolution of 30" (about

**Table 1** Bioclimatic variables and its connotation included in Maxent model

Bioclimatic variables		Connotation
Bio1	Annual mean temperature	
Bio2	Mean diurnal range (Mean of monthly (max temp-min temp))	
Bio3	Isothermality (Bio2/Bio7) × 100	
Bio4	Temperature seasonality (standard deviation × 100)	
Bio5	Max temperature of warmest month	
Bio6	Min temperature of coldest month	
Bio7	Temperature annual range (Bio5–Bio6)	
Bio8	Mean temperature of wettest quarter	
Bio9	Mean temperature of driest quarter	
Bio10	Mean temperature of warmest quarter	
Bio11	Mean temperature of coldest quarter	
Bio12	Annual precipitation	
Bio13	Precipitation of wettest month	
Bio14	Precipitation of driest month	
Bio15	Precipitation seasonality (Coefficient of variation)	
Bio16	Precipitation of wettest quarter	
Bio17	Precipitation of driest quarter	
Bio18	Precipitation of warmest quarter	
Bio19	Precipitation of coldest quarter	

1 km). RCP is the representative concentration pathway, and RCP 2.6, 4.5 and 8.5 refer to radiative forcing reaches 2.6 W/m<sup>2</sup>, 4.5 W/m<sup>2</sup> and 8.5 W/m<sup>2</sup> by 2100, respectively. The current bioclimatic data is only up to the year 2000, and the future distribution under climatic conditions in 2050s (2040–2060) and 2070s (2060–2080) were modeled using environmental factors generated by BCC\_CSM1–1 climate model (CMIP 5 data). The topography data were derived from Geospatial Data Cloud ASTERGDEM 30M digital elevation data (DEM) (<http://www.gscloud.cn>), and the slope and aspect were calculated by ArcGIS 10.2. (ESRI, USA) Soil variables (physical and chemical properties) were downloaded from the Soil Database of China for Land Surface Modeling (<http://globalchange.bnu.edu.cn/research/soil2>), including soil pH, bulk density (BD), soil porosity (Por), cation exchange capacity (CEC), total nitrogen (TN) and total phosphorus (TP). In order to maintain the comparability of the time series of the model and analyze the potential spatial distribution of *Carex* tussock wetlands under different climatic scenarios, soil properties and topography factors remain unchanged in the prediction in the future.

All environmental datasets were re-projected and unified into GCS\_WGS\_1984 coordinate system with a spatial resolution of 30" using ArcGIS 10.2. Moreover, in order to avoid the model over-fitting that caused by environmental variables multi-collinearity, person correlation analysis of the environmental variables was conducted by SPSS 23 (IL, USA). When the correlation coefficient is  $\geq 0.8$ , the environmental factors with small biological significance and low contribution will be excluded (Liu et al., 2018). Finally, 16 environmental variables including Bio1, Bio3, Bio11, Bio14, Bio15, Bio18, aspect, cation exchange capacity (CEC), elevation, pH, soil porosity (SP), slope, soil total nitrogen (TN), were selected for model building.

## 2.4 Spatial modeling and validation

The model of the potential spatial distribution of *Carex* tussock wetland was built in Maxent 3.4.1 ([https://biodiversityinformatics.amnh.org/open\\_source/maxent/](https://biodiversityinformatics.amnh.org/open_source/maxent/)), 75% of the occurrence data were randomly selected as the training set to build the model, and the remaining 25% points were used as the test set for model verification. The options of ‘Create response curve’ and ‘Do jackknife to measure variable importance’ were selected

to test the contribution rate of environmental variables to the distribution of *Carex* tussock. The accuracy of model prediction was evaluated by the area under the curve (AUC) value of the receiver operator characteristics (ROC) plot. The AUCs (0.5–1.0) with high values refers to accurate results: an AUC value in 0.9–1.0 represents excellent model performance, in 0.8–0.9 represents good performance, in 0.7–0.8 represents fair, in 0.6–0.7 represents poor and in 0.5–0.6 represents fail (Thuiller et al., 2006).

## 2.5 Suitable habitats classification

The occurrence probability grid map of *Carex* tussock was obtained by ArcGIS 10.2 software to visually analyze the simulation results. The occurrence probability ( $P$ ) value is in the range of 0–1.0, and the higher  $P$  value is the higher probability of the existence of *Carex* tussock. The habitat suitability of *Carex* tussock was classified into 4 classes: unsuitable ( $0 < P < 0.2$ ), low suitable ( $0.2 \leq P < 0.4$ ), moderate suitable ( $0.4 \leq P < 0.6$ ) and high suitable ( $0.6 \leq P < 1.0$ ). By comparing the ranges of suitable distribution regions under current and future scenarios, the shifts of distribution regions were obtained by mask extraction and then the *Carex* tussock habitats were divided into stable region, expanded region and lost region. Finally, we calculated the habitat areas ( $CTS_i$ ) by the following formula:

$$CTS_i = \frac{N_i}{N_{\text{total}}} \times S_{\text{total}} \quad (1)$$

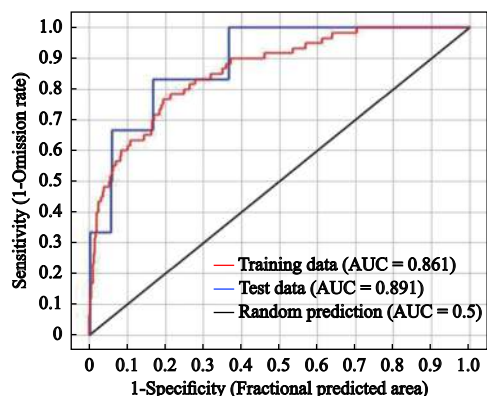
where  $CTS_i$  is the habitat area of *Carex* tussock,  $i$  is the habitat category,  $N_i$  and  $N_{\text{total}}$  denote the pixel number of habitat  $i$  and total study area, respectively, and  $S_{\text{total}}$  denotes the total area of our study.

## 3 Results

### 3.1 Performance of Maxent model and potential distribution characteristics

Maxent model performed well at predicting the potential spatial distribution of *Carex* tussock wetland with AUC values of 0.861 (training data) and 0.891 (test data) respectively (Fig. 2), which indicate ‘good’ (AUC = 0.8–0.9) model performance. The current potential spatial distribution pattern (Fig. 3) indicates that the potential suitable habitats of *Carex* tussock are mainly distributed in the Sanjiang Plain, Songnen Plain, Changbai Mountains and Hinggan Mountains, with a total area of





**Fig. 2** The receiver operator characteristics (ROC) curve in the Maxent model predictions for *Carex* tussock wetland in Northeast China. AUC is the area under the curve

$49.4 \times 10^4 \text{ km}^2$ . The high suitable region is about  $5.7 \times 10^4 \text{ km}^2$ , accounting for 4.6% of the total area of Northeast China, which concentrated in Sanjiang Plain, Changbai Mountains and along the rivers in the Songnen Plain, and sporadically distributed in Da Hinggan Mountains.

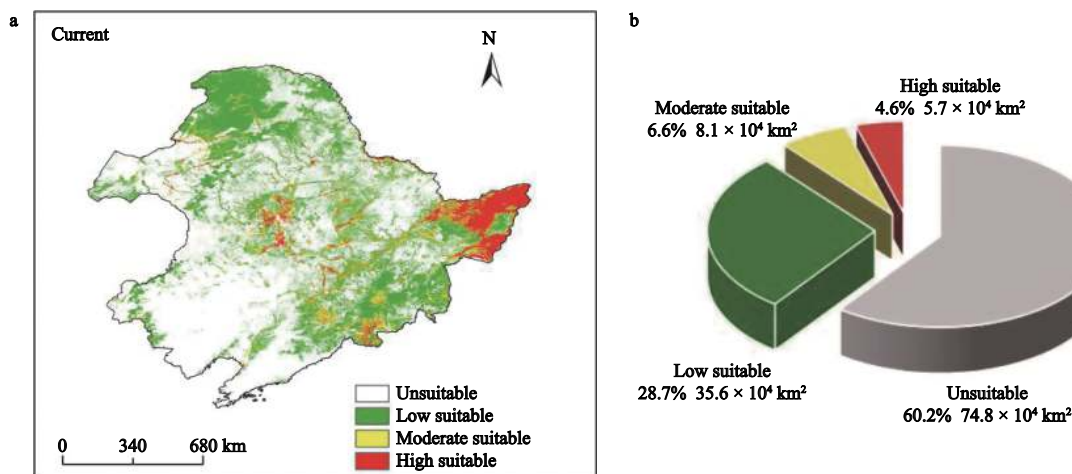
### 3.2 Effect of the environmental factors

Based on the Jackknife module of Maxent model, the contribution rate of environmental variables was tested, and results showed that isothermality (Bio3), precipitation seasonality (coefficient of variation) (Bio15) and elevation had greater gains on the prediction results (Fig. 4), indicating that the distribution probability of *Carex* tussock was sensitive to these factors. Furthermore, the response curve of *Carex* tussock to main environmental factors exhibited that with the increase of Bio3 and Bio15, the presence probability of *Carex* tus-

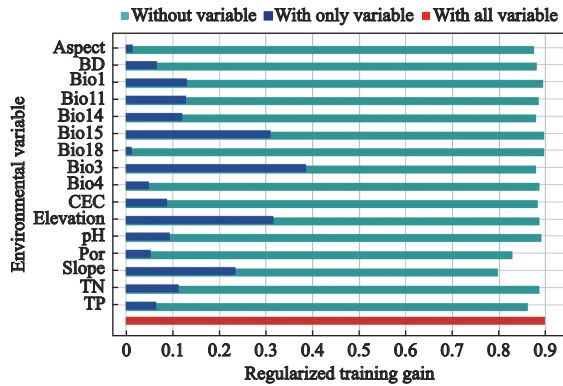
sock decreased step by step. Additionally, the influence of elevation is shown in Fig. 5, which indicates that *Carex* tussock would prefer lower elevation and maintain at low presence probability when the altitude was higher than 180 m. As the presence probability of *Carex* tussock  $\geq 0.6$  represents the high suitable habitat, the Bio3 ranges from 18.4 to 21.5, the Bio15 ranges from 65.7 to 93.9, and the elevation is 23.5–107.1 m.

### 3.3 Spatial distribution pattern of *Carex* tussock wetland under climate change

Under different climatic scenarios, the high suitable and moderate suitable habitats of *Carex* tussock are generally consistent with the current distribution pattern (Fig. 6), which are also concentrated in the Sanjiang Plain, and relatively scattered in the Songnen Plain, Changbai Mountains and Da Hinggan Mountains, while the spatial distribution pattern of low suitable habitats exhibit greatly changes. Besides, it is found that the area changes of low suitable habitat are higher than that of the moderate and high suitable habitat (Fig. 7). Under RCP 2.6, the total suitable habitat of *Carex* tussock decreased by 18.2% and 25.6% in 2050s and 2070s, respectively. Under RCP 4.5, the total suitable habitat had a slightly increase in 2050s, while it was significantly decreased in 2070s, especially the low suitable habitat decreased by 42.7%. As for RCP 8.5 scenario, the reduction of moderate and high suitable habitats in 2050s resulted in a decrease of 2.1% of the total suitable habitat. Although the moderate and high suitable habitats decreased in 2070s, the total suitable habitat still increased due to the larger area and increase of the low



**Fig. 3** Potential spatial distribution (a) and areas (b) of *Carex* tussock wetland in Northeast China



**Fig. 4** Jackknife result of *Carex* tussock wetland distribution prediction in Northeast China. The Jackknife result represents the contribution of each environmental variable on the habitat spatial distribution. ‘BD’ is ‘bulk density’; ‘Bio1’ is ‘annual mean temperature’; ‘Bio11’ is ‘mean temperature of coldest quarter’; ‘Bio14’ is ‘precipitation of driest month’; ‘Bio15’ is ‘precipitation seasonality (coefficient of variation)’; ‘Bio18’ is ‘precipitation of warmest quarter’; ‘Bio3’ is ‘isothermality’; ‘Bio4’ is ‘temperature seasonality’; ‘CEC’ is ‘cation exchange capacity’; ‘Por’ represents ‘soil porosity’; ‘TN’ refers to ‘soil total nitrogen’; ‘TP’ refers to ‘soil total phosphorus’.

suitable habitat (Fig. 7).

### 3.4 Habitat stability analysis

The stable suitable habitats of *Carex* tussock are mainly distributed in the Sanjiang Plain, Songnen Plain and Changbai Mountains in the future climate scenarios (except for RCP 2.6 in 2070s) (Fig. 8), which is generally consistent with current spatial distribution pattern. In addition, the area of stable habitat ( $29.98 \times 10^4$ – $41.75 \times 10^4$  km<sup>2</sup>) is significantly higher than that of expanded region and lost region (Table 2,  $P < 0.01$ ), indicating that the potential suitable habitat of *Carex* tussock is relatively stable.

In the future climate condition, the expanded/lost

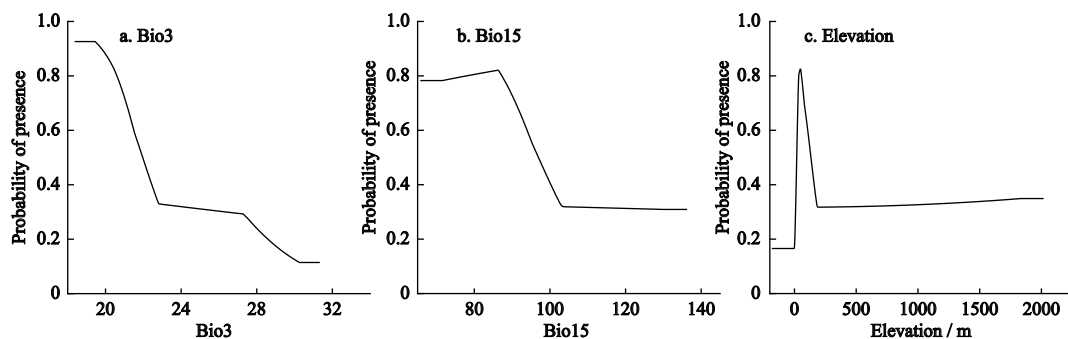
habitats (i.e. unstable habitats) of *Carex* tussock mainly distributed in Da Hinggan Mountains and Xiao Hinggan Mountains. Changbai Mountains also exhibits an obvious shrinking trend under RCP 2.6 in 2070s. Moreover, the largest habitat loss occurred in RCP 4.5 in 2070s, with an area loss of  $19.53 \times 10^4$  km<sup>2</sup> and wildly distributed in Northeast China. And the suitable habitat of *Carex* tussock in RCP 4.5 (2050s) and RCP 8.5 exhibit more obvious expansion than that in RCP 2.6, and the expanded area can reach up to 9.5% of the total area of Northeast China (Fig. 8, Table 2), which is mainly distributed in Da Hinggan Mountains and Xiao Hinggan Mountains.

## 4 Discussion

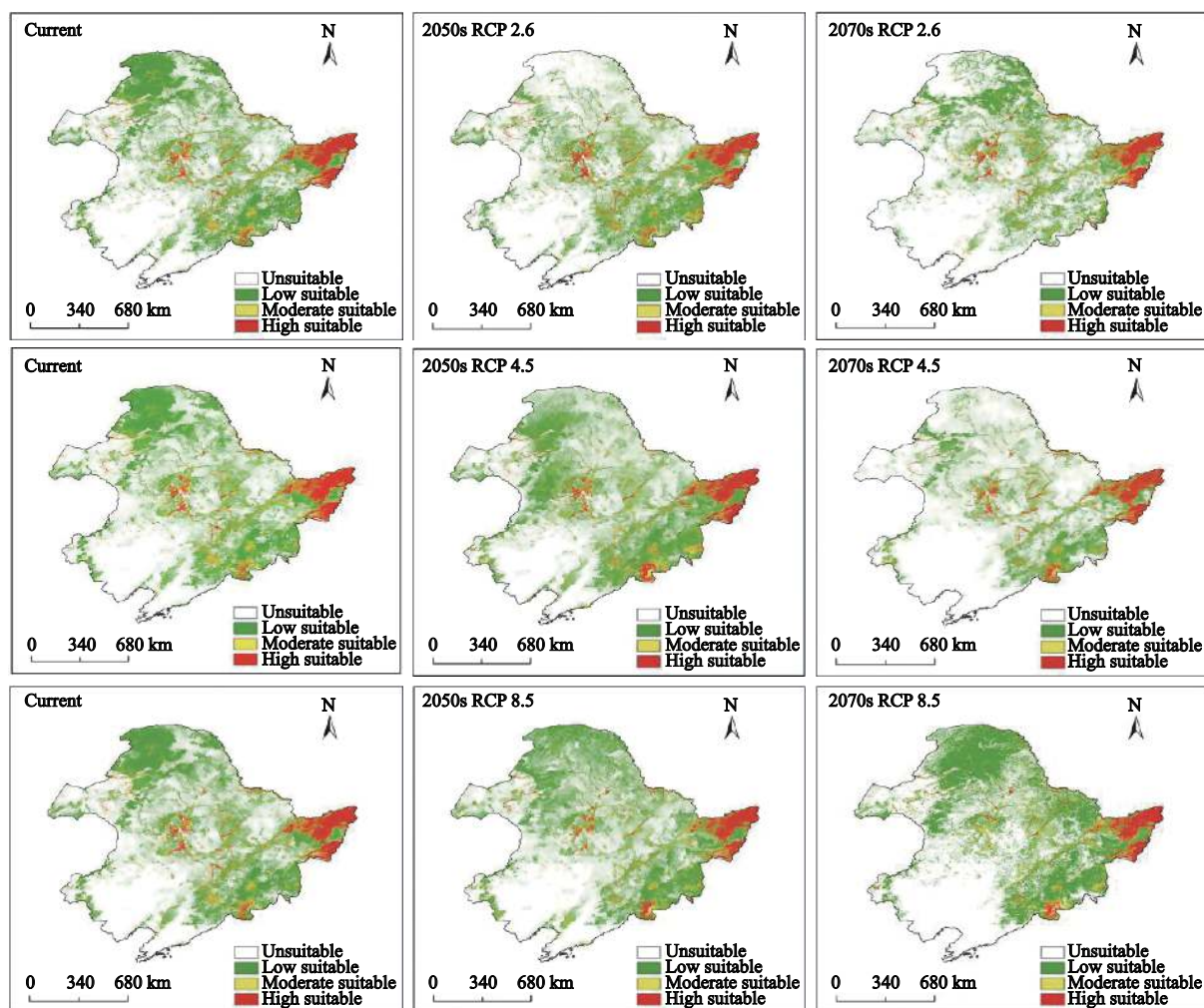
Maxent model has great applicability in prediction of wetland species distribution (Li et al., 2019b; Hu et al., 2020; Liu 2020) and the natural reserve construction (Hunter et al., 2012; Wang et al., 2019c) with the AUC value is 0.870–0.998. In this study, the model is used to predict the potential spatial distribution of *Carex* tussock wetland, the AUC value is 0.8–0.9 and the prediction results are consistent with the field observation, indicating that the Maxent model provide a good performance.

### 4.1 Effects of environmental variables on *Carex* tussock wetland distribution

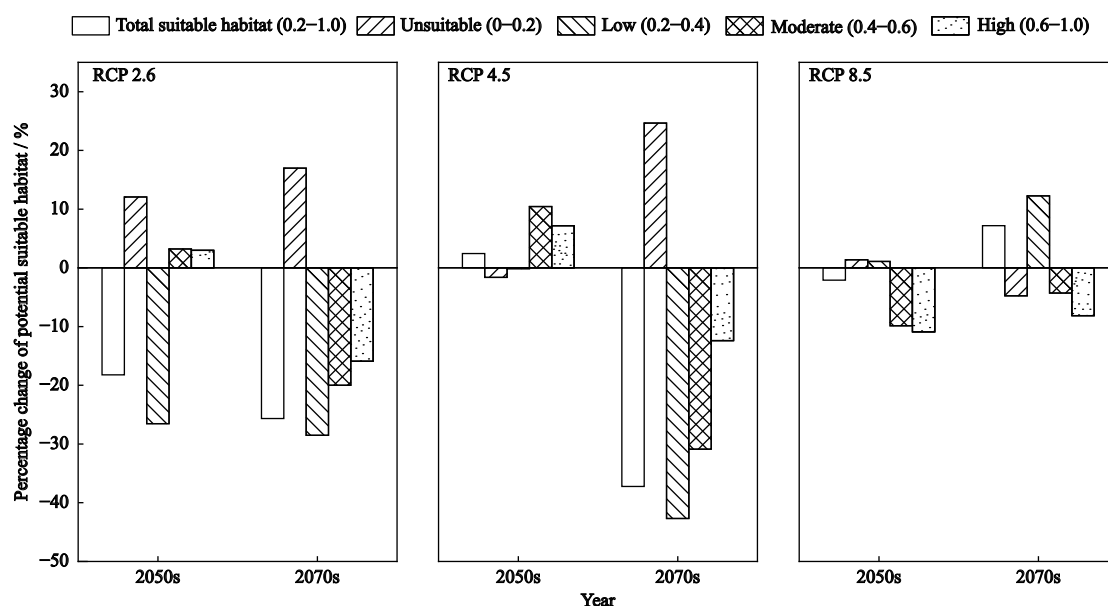
The presence of plant composition and distribution are the results of complex interaction of physiological and ecology tolerances in response to bioclimate, soil, topography, biology, etc. (Bonin and Zedler, 2008; Van der Putten et al., 2010; Osland et al., 2011; Saintilan et al., 2014; Zhang et al., 2020). In our study, the Maxent



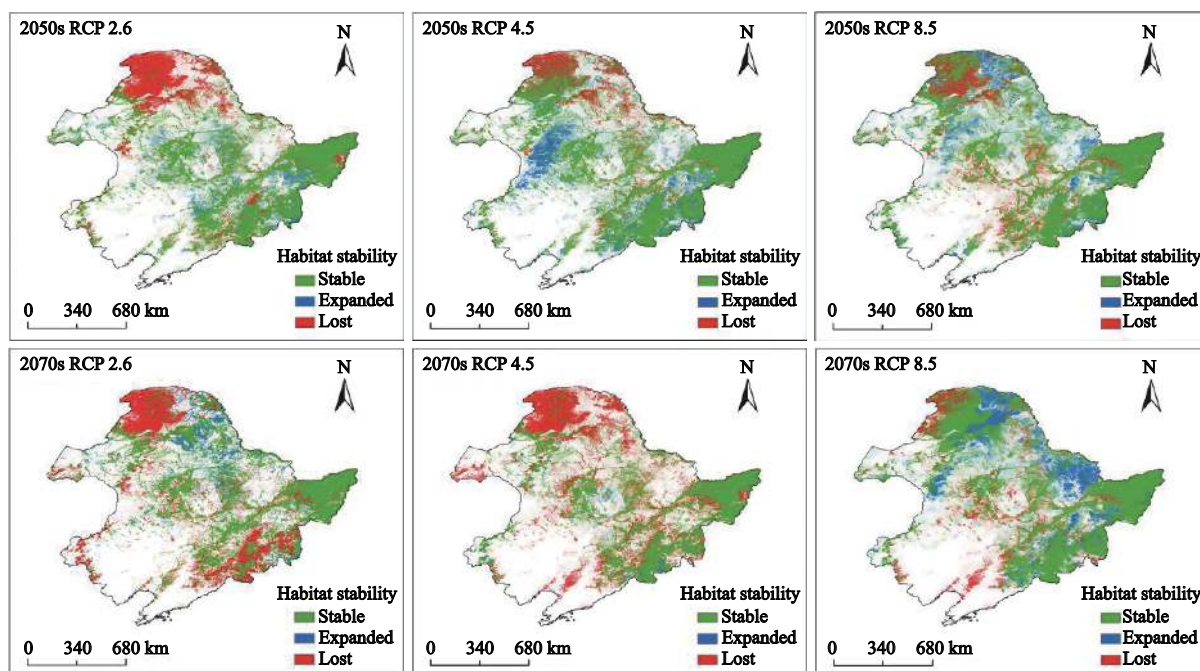
**Fig. 5** Response curves of main environment factors for occurrence probability of *Carex* tussock wetland in Northeast China. Bio3 is isothermality, Bio15 is precipitation seasonality (coefficient of variation).



**Fig. 6** Potential suitable habitats distribution of *Carex* tussock under future climate scenarios in Northeast China, RCP 2.6, 4.5 and 8.5 refer to radiative forcing reaches 2.6 W/m<sup>2</sup>, 4.5 W/m<sup>2</sup> and 8.5 W/m<sup>2</sup> by 2100, respectively



**Fig. 7** Percentage change of potential suitable habitats of *Carex* tussock under future climate scenarios in Northeast China, RCP 2.6, 4.5 and 8.5 refer to radiative forcing reaches 2.6 W/m<sup>2</sup>, 4.5 W/m<sup>2</sup> and 8.5 W/m<sup>2</sup> by 2100, respectively



**Fig. 8** Habitats stability of *Carex* tussock under future climate scenarios in Northeast China, RCP 2.6, 4.5 and 8.5 refer to radiative forcing reaches 2.6 W/m<sup>2</sup>, 4.5 W/m<sup>2</sup> and 8.5 W/m<sup>2</sup> by 2100, respectively

**Table 2** The shifts of potential suitable habitats of *Carex* tussock under future climate scenarios

Climate scenarios	Year	Area /10 <sup>4</sup> km <sup>2</sup>			Proportion of area / %		
		Stable	Lost	Expanded	Stable	Lost	Expanded
RCP 2.6	2050s	36.24	13.27	4.25	29.2	10.7	3.4
	2070s	32.45	17.06	4.36	26.1	13.7	3.5
RCP4.5	2050s	41.75	7.76	8.97	33.6	6.2	7.2
	2070s	29.98	19.53	1.10	24.1	15.7	0.9
RCP 8.5	2050s	40.77	8.74	7.70	32.8	7.0	6.2
	2070s	41.23	8.29	11.84	33.2	6.7	9.5

Notes: RCP 2.6, 4.5 and 8.5 refer to radiative forcing reaches 2.6 W/m<sup>2</sup>, 4.5 W/m<sup>2</sup> and 8.5 W/m<sup>2</sup> by 2100, respectively

model shows that isothermality, seasonal precipitation variation and elevation are the main environmental factors affecting the distribution of *Carex* tussock (Fig. 4). The presence probability of *Carex* tussock exhibited decreasing trend with the increase of isothermal and seasonal precipitation variation. This was consistent with the research of Yao et al. (2011) and Hu et al. (2020), who reported that the temperature affected the distribution of wetland plant the most, and rainfall could determine its succession. The vertical redistribution of water-heat conditions and the effect of altitude on water availability of wetland plants affect the distribution pattern of plants. However, in costal wetland, salt and nitrogen are the main factors affect the dominance spe-

cies distribution (Zong et al., 2017). *Carex* is typical freshwater wetland plant and its growth and distribution are influenced by wetland water conditions (Lawrence and Zedler et al., 2011; Zhang, 2017). The function characters, physiological processes and element contents of *Carex* are significantly different under fluctuation or stable hydrological conditions (Zhang et al., 2019a; 2021). Compared with long-term drought, flooding and water fluctuation are beneficial to the formation of *Carex* tussock (Lawrence and Zedler et al., 2011). Precipitation supplied freshwater and decreased salinity (Hu et al., 2020) and was therefore improved soil water conditions, which could increase the feasibility of restoration of degraded *Carex* tussock wetlands in semiar-



id areas (Wang et al., 2019c).

Generally, methods of plant distribution modeling mainly use climate, topography and soil variables in regional scale studies (Koncki et al., 2015; Cao et al., 2020; Hu et al., 2020). However, the distributions of wetland plant species are also affected by microtopography, water depth and distance to open water surface in wetland ecosystems (Riis et al., 2001; Gosejohan et al., 2017; Lou et al., 2018). According to the study of Lou et al. (2018), due to the different optima and niche width, wetland plant species show different distribution patterns according to the hydrological conditions.

Water level and hydrological fluctuation period are important ecological factors affecting the formation and development of *Carex* tussock (Zhang et al., 2019a), however in the regional study, it is hardly to use the changes of water level (centimeter precision) as an important environmental factor in the construction of the model since the grid resolution is usually in the range of meters to kilometers. Besides, in this study, three groups of environmental factors were integrated during modeling, including bioclimate, soil properties and topography, but did not consider the influence of human disturbance on the spatial distribution of *Carex* tussock. In the past 30 to 50 yr, human disturbance including farmland, reclamation, grazing, cutting and burning has led to a large area of *Carex* tussock wetlands degraded or disappeared in Northeast China (Pan et al., 2006; Mao et al., 2018; Zou et al., 2018), and ditches and roads blocked the hydrological connectivity of wetlands, resulting in the decline of ecological functions (Tong et al., 2008). The destruction of hydrological connectivity caused by human activities is the main reason that affects the spatial distribution of *Grus leucogeranus* (Liu, 2020). Therefore, in the study of small-scale wetland species distribution, it would be significant to take the hydrological characteristic and human activity into consideration during modeling.

#### 4.2 Potential distribution and habitat stability of *Carex* tussock under climate change

Climate change is expected to have a profound impact on species distribution, richness and diversity (Pecl et al., 2017; Tilman et al., 2017). The impact of global warming on species habitats is uncertain. Some of researches have indicated that with the rise of global tem-

perature, the decreased of species suitable habitats will lead to an increase in risk of species extinction (Pearson et al., 2014; Urban, 2015). However, the study of endangered wetland species distribution in low latitude shows that species habitat shifts have the trends of increase and unstable (Cao et al., 2020). In this study, the stable habitat is generally consistent with current spatial distribution pattern (Fig. 8), and the stable habitat in the future climate is significantly larger than the lost habitat and expanded habitat (Table 2). Furthermore, the lost/expanded habitat is mainly the low suitable habitat, while the moderate and high suitable habitats fluctuate in a small range (Fig. 7), indicating that the *Carex* tussock habitat is relatively stable. This may result from the differences in ecological amplitude of species in different latitudes, many studies have confirmed that plant in high latitudes and high elevations are more sensitive to temperature rise (Liu et al., 2017; Thakur and Chawla, 2019), resulting in differences in response of species habitat stability to climate warming.

Numerous evidences have suggested that species adapt to global warming by adjusting their physiological and ecological characteristic (Walther et al., 2002; Menzel et al., 2006; Shen et al., 2015) or migrating to high latitudes or high elevations (Du et al., 2018; Vetter et al., 2018), especially in alpine-plateau ecosystems and polar-subpolar ecosystems. The loss and expansion of *Carex* tussock wetland in high altitude and high latitude is the response of plant distribution to global warming, which is consistent with previous studies (Beckage et al., 2008; Rabasa et al., 2013; Jin et al., 2018). The *Carex* tussock habitats have an obviously trend of shrinks under RCP 2.6 and RCP 4.5, and the lost habitats are mainly distributed in north of Da Hinggan Mountains and Xiao Hinggan Mountains and Changbai Mountains (Fig. 8). Additionally, the expansion of *Carex* tussock is more prominent in medium and high emission scenarios, and expanded habitats are mainly distributed in Da Hinggan Mountains and Xiao Hinggan Mountains, which indicates that the *Carex* tussock wetlands in high latitude and high altitude are more sensitive to climate change.

#### 4.3 *Carex* tussock wetland conservation

In recent years, with the strengthening of wetland protection in China, the State Forest Administration, the

National Development and Reform Commission and the Ministry of Finance jointly issued the ‘National Wetland Protection 13th five-year Plan’ to open up the comprehensive protection of wetlands ([http://www.gov.cn/xinwen/2017-04/20/content\\_5187584.htm](http://www.gov.cn/xinwen/2017-04/20/content_5187584.htm)). In addition, with the improvement of public awareness of environmental protection and the strengthening of scientific research, wetlands protection and restoration are gradually deepening. At present, wetland conservation teams have developed a series of restoration techniques for *Carex* tussock wetland, including seed bank technology (Wang et al., 2013; 2015), hydro-regulatory techniques (Wang et al., 2019b; Zhang et al., 2019a) and rhizome clonal propagation technology (Qi et al., 2021), which is of great significance for *Carex* tussock habitat protection and restoration. And the guidance of national policy will help us to actively deal with the impact of climate change on wetland plant species in the future.

## 5 Conclusions

Current potential suitable habitat of *Carex* tussock is about  $49.4 \times 10^4$  km<sup>2</sup> in Northeast China, which is mainly distributed in the Sanjiang Plain, Songnen Plain, Changbai Mountains and Hinggan Mountains. High suitable habitat of *Carex* tussock is about  $5.7 \times 10^4$  km<sup>2</sup>, concentrated in the Sanjiang Plain, Changbai Mountains and along the rivers in the Songnen Plain, and sporadically distributed in Da Hinggan Mountains. Under future climatic scenarios, the spatial distribution pattern is generally consistent with current, the moderate and high suitable habitats are also concentrated in the Sanjiang Plain, while the low suitable habitat shifts greatly. Under the future climate scenario, the area of high, moderate and low suitable habitats are mainly reduced. Isothermality, seasonal precipitation variability and altitude are the main environmental factors affecting the distribution of *Carex* tussock wetland. The area of stable habitat is obviously higher than that of the lost and expanded habitat. And the lost and expanded habitats mainly occur in Da Hinggan Mountains, Xiao Hinggan Mountains and Changbai Mountains, indicating that *Carex* tussock wetlands at high altitude and high latitude are more sensitive to climate change. Therefore, more attention should be invested in the habitat protection of *Carex* tussock at high latitude and high altitude. This study revealed the potential distribution and ecolog-

ical stability under climate change, which is reference that could be applied to sustainable tussock wetland management.

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