Dynamic Response of Phragmites australis and Suaeda salsa to Climate Change in the Liaohe Delta Wetland

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ABSTRACT

Because of its unique geographical location and ecological function, the Liaohe Delta Wetland is important in maintaining regional ecological balance and security. Monitoring and evaluating changes in the wetland are therefore of great importance. We used medium- and high-resolution satellite data, meteorological station data, and site measurement data to analyze changes in the area and spatial distribution of Phragmites australis and Suaeda salsa in the Liaohe Delta Wetland from 1998 to 2017, as well as their growth response to the climate change. The results showed that during 1998–2017, the areas of both P. australis and S. salsa wetlands alternated through periods of decreasing, increasing, and then decreasing trends. The annual change in the area and spatial distribution range of S. salsa fluctuated more than that of P. australis. The annual variation of normalized difference vegetation index (NDVI) in P. australis wetland showed an upward trend from 1998 to 2017. The area of P. australis cover that was improved, unchanged, and decreased accounted for 81.8%, 12.3%, and 5.9%, respectively, of the total area; evaporation and wind speed were the main meteorological factors affecting the NDVI; and contribution rates of the climate change and human activities to the NDVI were 73.2% and 26.8%, respectively. The area with vegetation cover being mainly S. salsa that was improved, unchanged, and decreased accounted for 63.3%, 18.3%, and 18.4%, respectively, of the total area; and no meteorological factors significantly affected the NDVI of S. salsa in the region. The interaction between vegetation growth and meteorological factors may help to explain the increasing trend in vegetation cover. The improvement in wetland vegetation also led to carbon sequestration and an increase in sequestration capacity.

Key words: Liaohe Delta, wetland, Phragmites australis, Suaeda salsa, climate change

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1. Introduction

Wetlands are one of the earth’s three major ecosystems. They are highly vulnerable and sensitive, and more easily affected by the climate change than other terrestrial ecosystems (Johnson et al., 2016). The ecological function of wetlands helps to mitigate negative effects of the climate change (Ma and Zhang, 2015; Moomaw et al., 2018). In the context of climate change, wetlands are considered as one of the greatest unknowns in terms of the dynamics of elements and material flux in recent years (IPCC, 2001; Paul et al., 2006). Research has shown that the global area covered by wetlands is shrinking rapidly and is affected by the climate change and human activities such as the aquaculture, land reclamation, and urban expansion. Although many countries have set targets to restore the ecosystem, the negative trend is likely to continue (Leadley et al., 2014). Because the data...

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often change, it is difficult to determine global trends (CBD, 2014). There are complex interactions among the atmosphere, water, land, and plants in the wetland ecosystems. The wetland type and distribution, area and scope, and species distribution, constantly change (Song, 2003). Understanding the changes in the wetland type and distribution is of great significance for wetland protection and maintenance, as well as for future predictions.

Not only are wetland ecosystems sensitive to the climate change, but there are many uncertainties about how they may be affected by the climate change. Effects may be additive, antagonistic, or synergistic, and may interact with other influencing factors, causing these effects to be further complicated (Roberts et al., 2017). There are two main aspects of the effect of climate change on wetlands: the area of wetlands and their functions may decrease, and the geographic location of some types of wetlands may change (Erwin, 2009). The continuous increase in temperature and decrease in precipitation may result in a change in the wetland distribution and function, and even cause wetlands to shrink. Rising temperature will change the wetland water and soil temperature, and the decreasing precipitation will affect wetland water supply. This will lead to changes in wetland water quantity and quality, as well as a weakened and degraded wetland ecological function (Erwin, 2009; Xue et al., 2015; Huang et al., 2018). Sea level rise resulted from the climate change will reduce the area of coastal wetlands, and perhaps also lead to its severe salinization, resulting in changes in wetland vegetation communities (Stagg et al., 2017). Geographically, the species distribution is particularly sensitive to the climate change, and is vulnerable to wetland shrinkage, which increases the risk of extinction (Yasmeen et al., 2013).

The Liaohe Delta Wetland plays an important role in the mitigation of climate change as well as in air purification for the surrounding areas (Tian et al., 2017). It also supplies a significant ecological service function in terms of the carbon sequestration, flood defense, climate regulation, and water purification (Xu et al., 2009). It is important to evaluate the vegetation distribution in the Liaohe Delta Wetland and the response of vegetation distribution to the climate change. We used satellite remote sensing data and meteorological data to analyze the distribution, growth dynamics, and response of Phragmites australis and Suaeda salsa to the climate change in the Liaohe Delta Wetland over a period of almost 20 years. We evaluated the characteristics of wetland vegetation types and the factors influencing them, and their variations in response to the climate change, to provide a basis for developing wetland environmental protection and policy management.

2. Data and methods

2.1 Study site

The Liaohe Delta Wetland covers about 80% of the area of Panjin City (Song et al., 2016). Panjin City (40°45′–41°27′N, 121°30′–122°31′E) is located in the center of the Liaohe Delta, extending from the mouth of the Daling River in the west to the mouth of the Daliao River in the east (Cheng and Zhou, 2018). The Shuangtai Estuary Wetland, located at the southern end of the Liaohe Delta, was listed as a wetland of international importance at the “Convention on Wetlands of International Importance Especially as Waterfowl Habitat” (Liang et al., 2016). The study site is in the warm temperate zone, with an annual mean temperature of 9.2°C and annual mean precipitation (predominantly during June–August) of 630 mm. The annual hours of sunshine are 2721 h, the annual mean wind speed is 4.3 m s⁻¹, and the frost-free period is 167–174 days (Liu et al., 2017). There are more than 20 rivers in Panjin, including the Daling, Liaohe, Raoyang, and Daliao rivers. They merge at the mouths of the Shuangtai and Daliao rivers and then flow into the sea, which are the main sources of water to the wetland. The dominant natural plant species are P. australis and S. salsa (Fig. 1). Soil types mainly include the saline, marsh, meadow, paddy, and wind-blown sand soils (Zhou et al., 2006). The landform types are predominantly flood plains and tidal flats in the lower reaches of the Liaohe River. The terrain is low and flat, with an elevation of 1.3–4.0 m (Jiang et al., 2018).

2.2 Data processing

2.2.1 Data sources

We used remote sensing images of Panjin City and surrounding areas from four sources as follows. (1) US NOAA, Moderate-resolution Imaging Spectroradiometer (MODIS), Fengyun-3 (FY-3), and other medium-resolution satellite data from 1998 to 2017, from the Institute of Atmospheric Environment in Shenyang of China Meteorological Administration, and Fengyun Satellite Remote Sensing Data Service Network (http://satellite.nsmc.org.cn/). (2) US Landsat satellite series data from 1998 to 2017, from the United States Geological Survey (USGS; http://glovis.usgs.gov/) and Geospatial Data Cloud (http://www.gscloud.cn/). (3) Gaofen-1 (GF-1) satellite data, from the Land Observation Satellite Data Service Platform of China Center for Resources Satellite Data and Application (http://218.247.138.119:7777/DSSPlatform/index.html), with data from 2013 to 2017. (4) Normalized difference vegetation index (NDVI) data for P. australis wetland in 1998–2017 from the Resources and Environmental Data Cloud Platform (http://www.
In addition, NDVI data for *S. salsa* wetland in 1998–2017 were calculated using the US Landsat satellite series data.

The meteorological data, which were from the Liaoning Meteorological Bureau [including 52 stations in Liaoning Province from 1998 to 2017 (two stations were located in Panjin City)], included the temperature, maximum temperature, and precipitation. Data of wetland water salinity and CO$_2$ were collected at the Panjin Wetland Field Observation Station (40°56′N, 121°57′E). This is a field science experimental base of the China Meteorological Administration, and is used for ecological and agricultural meteorology in northeastern China.

### 2.2.2 Data processing

Figure 2 shows the data processing flowchart of the remote sensing images. The areas and NDVI of *P. australis* and *S. salsa* wetlands were obtained from the downloaded satellite data and products. The specific methods are as follows.

Information on wetland *P. australis* was obtained from NOAA, MODIS, FY-3, and other medium-resolution satellite data from late May to early June during
1998–2017, at a spatial resolution of 250 m. The unsupervised classification and NDVI index methods were used to extract wetland information. *S. salsa* wetland information was extracted from Landsat satellite data from late September to early October from 1998 to 2012, at a spatial resolution of 30 m. The object-oriented, supervised taxonomy, unsupervised classification, and other methods were used to extract wetland information. We mainly used the object-oriented method to extract *S. salsa* wetland information from GF-1 satellite data from 2013 to 2017 at a spatial resolution of 16 m. All satellite data were processed for orthorectification, radiometric calibration, and atmospheric correction.

The annual NDVI for regions occupied by *P. australis* was calculated from the mean value of each pixel from 1998 to 2017, by using ArcGIS 9.3 software (Environmental Systems Research Institute, Inc., USA).

The annual NDVI for regions occupied mostly by the *S. salsa* community was calculated from Landsat satellite series data. There was a large variation in the spatial distribution of the *S. salsa* community. However, in order to compare the variation in trend, we calculated the NDVI in a fixed region (Fig. 3). The region is the main area where the *S. salsa* community has been distributed over the past 20 years. The maximum value composites (MVC) method was used to calculate the NDVI value in the growing season. The results were tested and corrected with the downloaded NDVI product with data in this area. The corrected results were applied to the region in Fig. 3. The mean value of each pixel in the yellow line outlined region represents the mean NDVI of *S. salsa* wetland.

2.3 Methods

2.3.1 Trend analysis

The slope of mean annual NDVI of each pixel was calculated with the linear regression trend method, by using Eq. (1):

\[
\text{slope} = \frac{n \sum_{i=1}^{n} i \text{NDVI}_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} \text{NDVI}_i}{n \sum_{i=1}^{n} i^2 - \left( \sum_{i=1}^{n} i \right)^2}, \tag{1}
\]

where \(n\) is time series length and \(\text{NDVI}_i\) is the NDVI value in year \(i\). When slope \(> 0\), NDVI increases; when slope \(< 0\), NDVI decreases.

2.3.2 Rate of land use change

Equation (2) was used to calculate the rate of land use change:

\[
K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\%, \tag{2}
\]

where \(K\) is the rate of land use change; \(U_a\) and \(U_b\) are a certain land type at the beginning and end of the study, respectively; and \(T\) is the research period. The larger the
value of $K$, the greater the increase or decrease in the wetland area, and the faster the conversion rate between the wetland types.

2.3.3 Statistical analysis methods

The Pearson correlation method was used for the correlation analysis between NDVI and the meteorological factors. The main meteorological factors influencing the change of NDVI were analyzed by the stepwise regression method. The $T$-test method was used to test the significance of the NDVI variation trend. These analyses used IBM SPSS Statistics 25 software (International Business Machines Corporation, USA).

2.3.4 Stepwise regression residual analysis

The climate prediction value of NDVI was simulated by the stepwise regression analysis between the true value of NDVI and meteorological factors, by using Eq. (3):

$$\text{NDVI}_P = \sum_{i=1}^{n} (a_i \times F_i) + b,$$

where $\text{NDVI}_P$ is the predicted value of NDVI, $i$ is the number of meteorological factors, and $F_i$ is the meteorological factor selected by using the stepwise regression analysis, and $a_i$ and $b$ are the coefficients.

The predicted value represented the influence of climate on NDVI. The residual was the difference between the true and predicted values, and was used to represent the impact of human activities (Yang et al., 2014), by using Eq. (4):

$$\varepsilon = \text{NDVI}_T - \text{NDVI}_P,$$

where $\varepsilon$ is the residual; when $\varepsilon > 0$, human activity has a negative effect, and when $\varepsilon < 0$, human activity has a positive effect; and $\text{NDVI}_T$ is the true value of NDVI.

The ratio of slopes of $\text{NDVI}_P$ and $\text{NDVI}_T$ represents the contribution rate of the climate change. The ratio of slopes of the residual and $\text{NDVI}_T$ represents the contribution rate of human activities (Jin et al., 2020), by using Eqs. (5) and (6):

$$C_c = \frac{\text{slope(NDVI}_P)}{\text{slope(NDVI}_T)},$$

$$C_h = \frac{\text{slope(NDVI}_P)}{\text{slope(NDVI}_T)},$$

where $C_c$ and $C_h$ are the contribution rates of climate change and human activities, respectively; and $\text{slope(NDVI}_P)$, $\text{slope(NDVI}_T)$, and $\text{slope(}\varepsilon)$ are the slopes of change rates in $\text{NDVI}_P$, $\text{NDVI}_T$, and residual, respectively. The detailed method was presented in Jin et al. (2020).

3. Results

3.1 Changes in $P. australis$ and $S. salsa$ wetland area and spatial distribution

3.1.1 $P. australis$ wetland area

From 1998 to 2017, the general area change in $P. australis$ wetland showed decreasing, increasing, and then decreasing trends (Fig. 4). Between 1998 and 2005, the area of $P. australis$ wetland decreased from 840 to 781 km$^2$. The main reason for this was human activities (such as the excessive reclamation), which led to a decline in wetland ecological function. Since 2005, when the Shuangtai Estuary Wetland first appeared in the list of wetlands of international importance, more attention has been paid to protecting it, and its area has been restored. During 2005–2014 (10 yr), $P. australis$ wetland in Panjin City increased from 781 km$^2$ in 2005 to 845 km$^2$ in 2014. Since 2008, its area has been maintained at above 800 km$^2$ (Fig. 4).

From 1998 to 2017, the rate of land change in $P. australis$ wetland was small, with a value of $-0.04\%$. It was $-0.88\%$, $0.74\%$, and $-0.33\%$, during 1998–2005, 2005–2014, and 2014–2017, respectively. The variation in $P. australis$ wetland can be divided into three stages:
sharp decrease (1998–2005), gradual recovery (2005–2014), and mild decrease (2014–2017).

3.1.2 S. salsa wetland area

The area of S. salsa wetland in the Shuangtai River estuary showed a fluctuating trend of decreasing, then increasing, and then decreasing from 1998 to 2017. The area decreased from 24.8 to 3.9 km² from 1998 to 2005, and the Red Beach (so named because it is covered with red S. salsa) was seriously degraded. The area increased from 3.9 km² in 2005 to 37.1 km² in 2014 as the Red Beach recovered. However, serious degradation of the S. salsa community reduced its area from 37.1 km² in 2014 to 12.1 km² in 2017 (Fig. 5).

Between 1998 and 2017, the rate of land change in S. salsa wetland was −2.6%. This was a small value in the general term, but larger from an interannual perspective. The rate of land change in S. salsa wetland was −10.5% from 1998 to 2005, 85.1% from 2005 to 2014, and −16.8% from 2014 to 2017. We divided the variation in S. salsa wetland into three stages: fluctuation reduction (1998–2005), recovery (2005–2014), and re-degradation (2014–2017).

3.1.3 Spatial distributions

The spatial coverage of P. australis wetland was similar in 1998, 2005, 2014, and 2017. The distribution of P. australis wetland in 2005 showed obvious shrinkage compared with other years, and the area of decrease was mainly at its northern edge. The area of shrinkage gradually recovered in 2014, when the wetland area was even slightly larger than that in 1998. The area decreased slightly in 2017, when some of the wetland was lost at the northern edge (Fig. 6).

The spatial coverage of S. salsa changed more than that of P. australis. S. salsa was mainly distributed near the beach, reservoir, and pond in 1998. The range of coastal breeding ponds on the western side of the Shuangtai River estuary continued to increase in 2005. A large number of S. salsa communities shrank and disappeared from the coastal flats on the eastern and western sides of the river as well as near the reservoirs and ponds. This resulted in serious degradation of the Red Beach. The tidal flat and breeding pond expanded further, but the area of S. salsa that was mainly distributed on the island (in the top of the river estuary) and near the beach showed the improved restoration. However, the Red Beach degraded again from 2014 to 2017, and a large area of S. salsa disappeared from the estuary beach and on both sides of the coast (Fig. 7).

3.2 Quality of P. australis community growth and its response to climate change

We calculated the variation slope (based on the area of P. australis wetland in 1998) by each pixel of annual maximum NDVI in the period of our study. Figure 8 shows the spatial distribution of the annual maximum NDVI slope change of P. australis wetland from 1998 to 2017, where NDVI was used to represent the vegetation cover. Most vegetation cover had improved (slope > 0.002), which accounted for 81.8% of the total area of P. australis wetland area in 1998. The area that remained nearly unchanged (−0.002 ≤ slope ≤ 0.002) accounted for 12.3%, and the obviously decreased area of variation (slope < −0.002) accounted for 5.9%. Compared with 1998, the vegetation cover of P. australis improved significantly between 2008 and 2017, but it deteriorated in a small region.

The annual change in NDVI and meteorological factors were analyzed by using a Pearson correlation coefficient and stepwise regression method for P. australis wetland. The correlation coefficients between NDVI and

![Fig. 5. Annual variation of the area of S. salsa wetland in the Shuangtai River estuary from 1998 to 2017.](image-url)
meteorological factors are shown in Table 1. The results show that the annual sunshine hours, annual evaporation, annual mean wind speed, and mean wind speed in the growing season had good consistency with NDVI. The other factors had no significant correlation with NDVI. We found that the annual mean wind speed and evaporation in the growing season were the major factors affecting NDVI, and may explain 60.8% of the NDVI change (Table 2).

There was an upward trend in annual variation of NDVI (regional mean value) for *P. australis* wetland from 1998 to 2017. Water surface evaporation and wind speed showed significant downward trends during the same period (Fig. 9). The T-test results showed that NDVI experienced a significant increasing trend in the past 20 years. The decrease in wind speed (Fig. 9b) might have caused a decrease in water surface evaporation (Fig. 9a), which represented the atmospheric evaporative forcing. The evaporative forcing has been decreasing for almost 20 years, so the actual evapotranspiration would
have been increasing. The actual evapotranspiration of *P. australis* wetland was influenced not only by meteorological factors, but also by its own physiological and ecological changes. These include the plant height and leaf area index, which strongly affects evapotranspiration (Yu et al., 2008).

### 3.3 Quality of *S. salsa* community growth and its response to climate change

In contrast to *P. australis* wetland, *S. salsa* was mainly distributed on the coastal beach. The change in its spatial coverage and area was relatively larger from 1998 to 2017, and NDVI was not suitable for use to make comparisons in frequently changing areas. For this reason, we calculated the variation slope by each pixel of the annual maximum NDVI in a fixed region in the Shuangtai River estuary (the region outlined by the yellow line in Fig. 3).

Figure 10 shows the spatial distribution of the annual maximum NDVI slope change in the study area from 1998 to 2017. Most vegetation cover had improved (slope > 0.002), which accounted for 63.3% of the total
area. The area that remained nearly unchanged (−0.002 ≤ slope ≤ 0.002) accounted for 18.3% and the obviously decreased area of variation (slope < −0.002) accounted for 18.4%. There was an upward trend in the annual NDVI variation from 1998 to 2017 in the Shuangtai River estuary. The T-test results showed that there has been a significant increasing trend in the NDVI change in the past 20 years (Fig. 11).

The study area included, however, not only the S. salsa community. It also contained a small amount of other types of wetland vegetation and farmland that were the original wetland vegetation or tidal flats. The reason for vegetation cover improvement was mainly that S. salsa and tidal flats were transformed into other wetland vegetation type (such as P. australis) or farmland (such as for growing rice). The main reason for vegetation cover decrease was that S. salsa and tidal flats were transformed into non-vegetated areas (such as the bare beach, pond, or salt pan).

We analyzed the correlation and regression between NDVI and meteorological factors in S. salsa wetland. The correlation result showed that the meteorological factors had no significant correlation with NDVI (Table 3). The stepwise regression analysis showed that no meteorological factor had a major influence on NDVI.

4. Discussion

4.1 Effects of climate change and human activities on NDVI

The climate prediction values of NDVI for P. australis wetland were obtained by using the stepwise regression analysis results and Eq. (3), and the residuals were calculated by using Eq. (4). In the past 20 years, the contribution rates of human activities were in the range of −0.03 to 0.03 (Fig. 12). The results showed that the positive and negative effects of human activities all occurred for over 10 years. The positive and negative effects mainly occurred before and after 2008, respectively.

The trends in variation of the true NDVI, predicted NDVI, and residual were analyzed for P. australis wetland from 1998 to 2017. The trend rates were 0.0041, 0.003, and 0.0011 yr⁻¹, respectively. The T-test results showed that the three data series all had significant increasing trends in the past 20 years (Fig. 13). The climate change mainly promoted the increasing trend in NDVI, and human activities mainly inhibited it. The impacts of climate change and human activities on NDVI were identified by using Eqs. (5) and (6). The results showed that the contribution rates of climate change and human activities were 73.2% and 26.8%, respectively.

| Table 1. The correlation between meteorological factors and NDVI in P. australis wetland from 1998 to 2017 |
| --- | --- |
| Factor | Correlation coefficient |
| Annual mean temperature | 0.023 |
| Annual highest temperature | 0.035 |
| Annual precipitation | 0.020 |
| Annual precipitation in the preceding year | 0.290 |
| Annual sunshine hours | −0.452* |
| Annual mean relative humidity | −0.446* |
| Annual evaporation | −0.644* |
| Mean temperature of growing season | −0.422 |
| Precipitation of growing season | 0.053 |
| Sunlight hours of growing season | −0.439 |
| Mean relative humidity of growing season | −0.626** |

Note: * denotes significant correlation at the P < 0.01 level; ** denotes significant correlation at the P < 0.05 level.

| Table 2. The regression analysis of meteorological factors and NDVI in P. australis wetland from 1998 to 2017 |
| --- | --- | --- | --- |
| Factor | $R$ | $R^2$ | $F$ | Sig. |
| Evaporation of growing season and wind speed | 0.779 | 0.608 | 13.157 | 0.000353 |

Notes: correlation coefficient—$R$, determination coefficient—$R^2$, significance—$F$, significance probability—Sig.
As there was no significant correlation between NDVI and meteorological factors in *S. salsa* wetland, it was impossible to predict NDVI with meteorological factors. Because of the lack of human activity data, it was also difficult to calculate the contributions from human activities and meteorological factors. The key factor in the growth of *S. salsa* was the level of salt. The level higher or lower than 15‰ may cause the *S. salsa* degeneration; and once damaged, it recovers naturally with difficulty because of its weak regeneration ability (Wang and Li, 2006). Although the general trend in precipitation in the past 20 years showed an increase, there was a great fluctuation in its interannual variation. It is possible that, in a low-precipitation year, the salinity of tidal flats increased, resulting in *S. salsa* degeneration. The direct impact of meteorological factors, however, cannot explain the effect of climate change on the wetland ecosystem. Indirect meteorological factors should also be taken into account. For example, the change in evaporation caused by rising temperatures, extreme precipitation events lead-
ing to rises in wetland water levels, or extreme drought events, might result in a reduction in the wetland area (Meng et al., 2016). Continuous insufficient precipitation and freshwater supplies led to the increased salinization of coastal beaches from 1998 to 2005. Human activities such as the oil exploitation and crab breeding in the ponds near the beach also seriously affected conditions in the S. salsa habitat (Luo et al., 2011). Rising temperatures led to increased evaporation, and a reduction in precipitation led to a decrease in runoff to the sea and in freshwater resources; thus, the salinity of the beach increased, and excessive salinity destroyed the growing environment of S. salsa, which resulted in its wilting or death (Hao et al., 2017).

Table 3. The correlation between the meteorological factors and NDVI in S. salsa wetland from 1998 to 2017

| Factor                              | Correlation coefficient |
|-------------------------------------|-------------------------|
| Annual mean temperature             | -0.399                  |
| Annual highest temperature          | -0.102                  |
| Annual precipitation                | 0.083                   |
| Annual precipitation in the preceding year | 0.176               |
| Annual sunshine hours               | -0.174                  |
| Annual mean relative humidity       | 0.222                   |
| Annual evaporation                  | -0.299                  |
| Annual mean wind speed              | 0.134                   |
| Mean temperature of growing season  | -0.341                  |
| Precipitation of growing season     | 0.077                   |
| Sunshine hours of growing season    | -0.037                  |
| Mean relative humidity of growing season | 0.117              |
| Evaporation of growing season       | -0.146                  |
| Mean wind speed of growing season   | -0.051                  |

4.2 Effects of climate change and human activities on wetland distribution

Wetland ecosystems are affected by both the climate change and human activities, and the strong impact of human activities on wetlands may often mask the effect of climate change (Davis and Froend, 1999; Xue et al., 2015). In addition, human activities constantly try to slow down wetland degradation, and it is difficult to distinguish between the wetland adaptation to the climate change and non-climatic driving factors. Researchers

Fig. 12. The trend in annual variation of the NDVI residual in P. australis wetland from 1998 to 2017.

Fig. 13. Trends in the predicted NDVI, true NDVI, and residual in P. australis wetland from 1998 to 2017.
have used the correlation method to analyze the climate change and wetlands, and found that wetland changes were mainly influenced by human activities in a long time series. According to Xue et al. (2015), non-meteorological factors played a leading role in the Sanjiang Wetland, and the contribution rates of the climate change effect on the wetland distribution were 5.21% and 4.33% during 1951–1980 and 1981–2010, respectively. Zhang et al. (2015) reported that the climate change contributed 17%–30% to variations in the wetland area on the Sanjiang Plain. They also stated that the climate change was beneficial to the increase in the wetland area, but non-meteorological factors led to the loss of wetlands.

This study used correlation and regression analyses of meteorological factors with respect to the areas occupied by P. australis and S. salsa communities. It showed that the influence of meteorological factors on the area change was not significant, and the wetland distribution was mainly affected by human activities. There was an increasing trend in the area change of P. australis wetland, but variation in the spatial distribution was minor. We found that with respect to the change on the coastal beach, the distribution of S. salsa fluctuated considerably and was affected by both natural factors and human activities. On the one hand, the S. salsa community was degraded because there were less precipitation and increasing salinity; and on the other hand, it recovered and its distribution was changed by artificial planting.

The climate change had a certain influence on vegetation cover of P. australis and S. salsa in the Liaohe Delta, but the climate change action was masked by intense human activities. Economic development and population growth resulted in excessive exploitation and pollution in the wetland, which led to its shrinkage (Song et al., 2016). However, at the same time, human activities played a significant role in its restoration. In the early stage, urbanization and agricultural expansion were the most important driving factors in wetland loss, while human restoration was the main driving factor for the increase in P. australis and S. salsa coverage. We found it difficult to quantify the effects of climate change and high levels of interference from human activities.

4.3 Interaction between vegetation cover in wetland and climate change

There were three reasons for the change in P. australis cover: (1) change in land use type, (2) climate change, and (3) irrigation quantity or quality. In this study, the area of land use type change was minor and irrigation was sufficient. The change in quality of P. australis growth was also related to water salinity. If precipitation decreased, river inflow also decreased, allowing sea water to flow back. This led to an increase in the salinity of wetland water and degradation of P. australis near the river estuary. The Liaohe Delta Wetland was covered with irrigation water from May to September in the growing season, and the water mainly came from rivers and precipitation. Studies showed that the salt tolerance of P. australis was large, ranging from 0.2% to 0.8%. Salinity lower than 0.2% allowed the growth of a mass of Typha orientalis. When the salinity was higher than 0.8%, P. australis germination was inhibited (Li et al., 2015; Jia, 2018). Owing to the lack of long-term observation data on the freshwater environment, only the moisture and salinity changes in the wetland were observed and analyzed at the field station (40°56′N, 121°57′E) during the growing season from 2013 to 2017. The results showed that the monthly mean salinity of wetland water was in the range of 0.2%–0.8% (Fig. 14). In our study period, precipitation in Panjin Wetland had been increasing. We inferred from this that the freshwater environment had not deteriorated.

P. australis wetland ecosystems have a strong carbon storage and sequestration capacity. The carbon sequestration of P. australis wetland in the Liaohe Delta was 13.32 t hm$^{-2}$ in 2005 (Wang et al., 2006), which might have reduced the concentration of greenhouse gases in the atmosphere. From 1984 to 2013, the average carbon sequestration capacity of Panjin Wetland was 1.50 kg m$^{-2}$, showing a fluctuating and increasing trend. Carbon sequestration increased by 73 g CO$_2$ m$^{-2}$ yr$^{-1}$ every 10 years, and CO$_2$ content increased from 344.3 to 395.8 ppm, at an increasing rate of 17.2 ppm (10 yr)$^{-1}$ (Jia, 2018). The maximum CO$_2$ absorption rate at the field
station in this study (generally appearing in late June or early July) showed an increasing trend from 2012 to 2017 (Fig. 15). We might infer that an increasing trend in *P. australis* cover contributed to the growing capacity of wetlands to sequester carbon.

The improvement or deterioration in *P. australis* wetland resulted from the interaction between changes in the irrigation quantity and quality, climate change, and human activities. Because irrigation water data were lacking, we found it difficult to compare the meteorological factors and irrigation water quantity. A regression analysis of meteorological factors indicated that the combined effect of evaporation and wind speed may explain 49.7% of the NDVI variation. With the weakening atmospheric evaporation and increasing actual evapotranspiration in response to the climate change, the quality of *P. australis* growth has increased over the study period. Better vegetation cover would, however, lead to an increase in actual evapotranspiration, and thus reducing atmospheric evaporation. The interaction between the quality of growth and actual evapotranspiration also helped explain why *P. australis* cover showed an increasing trend.

5. Summary

We used the medium- and high-resolution satellite data, and meteorological station data, to analyze changes in the spatial distribution of *P. australis* and *S. salsa* in the Liaohe Delta Wetland, as well as the growth response of vegetation to the climate change. The general trends in the area change in both *P. australis* and *S. salsa* wetlands from 1998 to 2017 were decreasing, increasing, and then decreasing again. We divided the variation in *P. australis* wetland into three stages: sharp decrease (1998–2005), gradual recovery (2005–2014), and mild decrease (2014–2017). The variation in *S. salsa* wetland was divided into three stages: fluctuation reduction (1998–2005), recovery (2005–2014), and re-degradation (2014–2017).

There was an upward trend in the annual NDVI variation in *P. australis* wetland from 1998 to 2017, indicating that the vegetation cover had improved significantly. The area of improved *P. australis* cover accounted for 81.8% of the total area, and the area either unchanged or obviously decreased accounted for 12.3% and 5.9%, respectively. The trend in vegetation cover was influenced by evaporation during the growing season and by annual wind speed, which might explain 60.8% of the NDVI change. The change in the spatial distribution range and area of *S. salsa* was larger than that of *P. australis*. On its own, the NDVI of *S. salsa* was not suitable for making comparisons. The annual variation in NDVI on the coastal beach where *S. salsa* grew also showed an upward trend from 1998 to 2017. The area of vegetation cover improved, and accounted for 63.3% of the total area. The area unchanged and obviously decreased accounted for 18.3% and 18.4%, respectively. No meteorological factor was a major factor of the NDVI on the coastal beach.

The climate change mainly promoted the increasing trend of NDVI in *P. australis* cover, and human activities mainly inhibited it. Contribution rates of the climate change and human activities on NDVI were 73.2% and 26.8%, respectively. The climate change and vegetation cover interacted, with the interaction between the quality of growth and actual evapotranspiration further explaining the variation in *P. australis* cover. Suitable salinity and sufficient freshwater irrigation were also important factors in explaining the increasing trend of *P. australis* cover. Excessive salinity caused by increasing temperature or decreasing precipitation might have been the main natural factor affecting *S. salsa* growth. The main reason for improvements in vegetation cover on the coastal beach was that *S. salsa* and the tidal flats were transformed into other wetland vegetation or into farmland. The main reason for the decrease in vegetation cover was the transformation of *S. salsa* and tidal flats into non-vegetated areas.

In general, the climate change had an influence on vegetation cover of *P. australis* and *S. salsa* in the Liaohe Delta, but it was difficult to quantify the effect of climate change and high levels of interference from human activities. In addition, because of the lack of irrigation...
water and its related environmental data, the wetland assessment is not comprehensive and needs further study.

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