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Restoration and Rational Use of Degraded Saline Reed Wetlands: A Case Study in Western Songnen Plain, China

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Abstract: The protection, restoration and sustainable use are key issues of all the wetlands worldwide. Ecological, agronomic, and engineering techniques have been integrated in the development of a structurally sound, ecologically beneficial engineering restoration method for restoring and utilizing a degraded saline wetland in the western Songnen Plain of China. Hydrological restoration was performed by developing a system of biannual irrigation and drainage using civil engineering measures to bring wetlands into contact with river water and improve the irrigation and drainage system in the wetlands. Agronomic measures such as plowing the reed fields, reed rhizome transplantation, and fertilization were used to restore the reed vegetation. Biological measures, including the release of crab and fish fry and natural proliferation, were used to restore the aquatic communities. The results of the restoration were clear and positive. By the year 2009, the reed yield had increased by 20.9 times. Remarkable ecological benefits occurred simultaneously. Vegetation primary-production capacity increased, local climate regulation and water purification enhanced, and biodiversity increased. This demonstration of engineering techniques illustrates the basic route for the restoration of degraded wetlands, that the biodiversity should be reconstructed by the comprehensive application of engineering, biological, and agronomic measures based on habitat restoration under the guidance of process-oriented strategies. The complex ecological system including reeds, fish and crabs is based on the biological principles of coexistence and material recycling and provides a reasonable ecological engineering model suitable for the sustainable utilization of degraded saline reed wetlands.

Keywords: degraded wetlands; reed; ecological restoration; ecological engineering; rational use

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1 Introduction

Wetlands constitute a distinctive type of ecological system characterized by the interaction of land and water. These ecological landscapes have the richest biodiversity in nature, and they represent one of the most important environments for humans. The functions and values of wetlands have been investigated by an increasing number of researchers (Shultz, 2000; Mitsch and Gosselink, 2007; Wu *et al.*, 2010; Yadav *et al.*, 2010; Zhang L *et al.*, 2010). In the past few centuries, the utilization of wetlands has mainly focused on drainage and cultivation (Zhang J Y *et al.*, 2010); this pattern of exploitation still exists in many regions. Increasing pressure on wetlands resulted from their decreased area; water-quality deterioration and biodiversity decline are the main processes leading to wetland degradation (Gibbs, 2000; Carubelli *et al.*, 2007; Gong *et al.*, 2010; Wang *et al.*, 2010; Zhang J Y *et al.*, 2010). The protection of existing natural wetlands, the restoration of degraded wetlands and the rational utilization of wetlands are the most effective means to develop these ecological

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systems in ways that yield ecological, social and economic benefits. The protection and sustainable utilization of wetlands are interconnected. The protection of wetlands requires the benefit of feedback from sustainable utilization, and sustainable utilization must be based on the protection of wetlands. The Ramsar Convention on Wetlands has reported that the potential for the sustainable utilization of wetlands is considered as the key criterion for determining whether a wetland area is designated as an internationally important wetland.

Researches on the restoration and reconstruction of important wetland functions have been conducted, both at home and abroad (Simenstad *et al.*, 2006; Jenkins and Greenway, 2007; Erwin, 2009; Qin and Mitsch, 2009). In the United States of America and in the southern Canada, the ecological restoration of marshes has mainly been associated with eutrophication as well as engineering and biological measures serving to control pollution and improve water quality and biodiversity (Mitsch and Wang, 2000; Miller and Fujii, 2010; Rodriguez and Lougheed, 2010). In Europe and in the northern Canada, the ecological restoration of marshes with oligotrophication has mainly been performed to increase the area of marshes and lake wetlands (Moss, 1990; White and Bayley, 1999). In China, studies of wetland ecological restoration and reconstruction were conducted slightly later but developed very quickly, especially in lake wetlands, river wetlands, urban wetlands, and coast wetlands in recent years (Wan *et al.*, 2001; Ji *et al.*, 2002; Li *et al.*, 2008; Wu *et al.*, 2008; Cui *et al.*, 2009). The technological models for restoration, reconstruction and sustainable utilization of wetland differ depending on the different environment, wetland type, the causes of degradation and restoration (Hopfensperger *et al.*, 2006; Moreno-Mateos and Comin, 2010).

The western Songnen Plain is an ecologically fragile zone in a semiarid region of China, however, there is concentrated distribution of saline wetlands. The total area of these wetlands is approximately 1.6×10^6 ha, all the wetlands are degraded to various degrees. The Niuxintaobao reed wetlands located in the Huolinhe River basin were very dry, and the average height of the reeds was < 1 m, and some of these wetlands have become alkali-saline patches without vegetation, therefore, there is no harvest here. From 2005 to 2010, ecological restoration was conducted in the reed wetland in Niuxintaobao to explore restoration and reasonable utilization technique based on a rational utilization design and appropriate engineering. The results of this study will provide an example useful for other types of wetland restoration and utilization.

2 Materials and Methods

2.1 Study area

The Niuxintaobao reed wetlands are located in the southwest of Da′an City, Jilin Province (45°13′–45°16′N, 123°15′–123°21′E) with the area of reed marshes being approximately 4000 ha (Fig. 1). This region is located in the Huolinhe River basin and has a monsoon climate with an average annual precipitation of 412.7 mm. In the rare high-flow years, the reed wetlands obtain their water supply from the flooding of the Huolinhe River; however, in average and low-flow years, they require water from Tao′erhe River to make up for the lack of water. There were seriously degraded reed wetlands in 2005. The degradation process of saline reed wetlands is often accompanied by severe salinization of soil and water, which, in turn, accelerates wetland degradation. The control of salinity and prevention of secondary salinization must be attached greater importance in the ecological restoration and reconstruction process.

In the study area, the main soil types were salinized peat soil and solonetzic soil, and soil quality before restoration in 2005 are shown in Table 1. The pH of the soils were higher than 10 except in the surface soil. The organic matter and total nitrogen contents of the wetland surface soil were higher with the values of 39.83 g/kg and 3621.40 mg/kg, respectively.

For all the waters in the wetlands before restoration in 2005, pH were in the range of 8.0–8.5, the salinity was less than 1000 mg/L, and the total alkalinity was less than 10 mmol/L (Table 2). Although the total alkalinity is higher than that of normal freshwater for aquaculture (1–3 mmol/L), the saline waters were still suitable for breeding.

2.2 Experimental design

Following the ecosystem principles of species coexistence and material circulation, a production system with multistage material consumption was constructed. Depending on the natural state and self-organization capabilities of the wetland system, the indigenous plants, animals and microorganisms adapted to conditions changed by artificial and natural ways (mainly anthro-

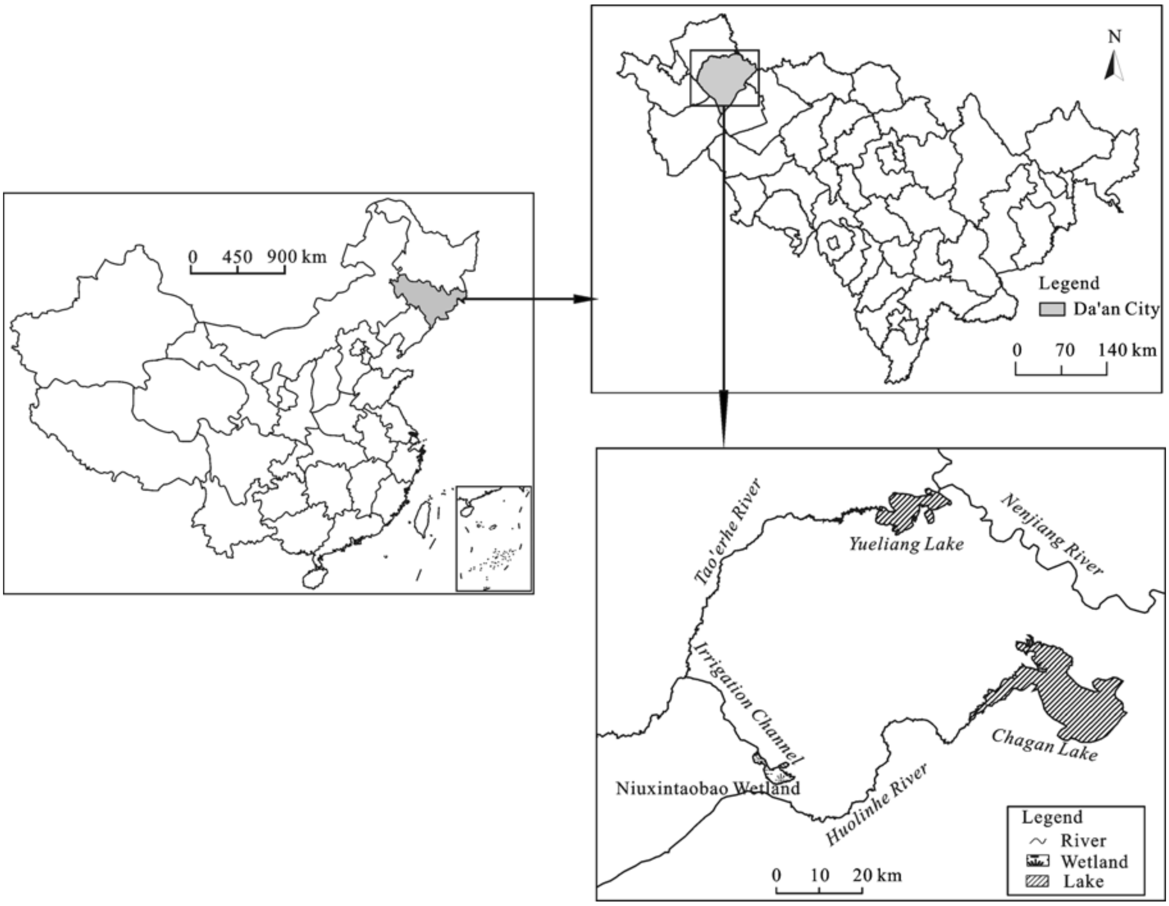


Fig. 1 Location of study area

Table 1 Soil quality in demonstration zone before restoration in 2005

Soil location	Layer (cm)	TN (mg/kg)	TP (mg/kg)	AN (mg/kg)	AP (mg/kg)	OM (g/kg)	pH	Salinity (g/kg)	Na^+ (mg/kg)	Ca^{2+} (mg/kg)	Cl^- (mg/kg)	CO_3^{2-} (mg/kg)	HCO_3^- (mg/kg)
Reed wetlands	0–5	3621.40	338.95	176.40	8.75	39.83	8.06	1.2	217.95	91.85	213.00	0.00	585.60
	5–30	1085.99	114.60	42.00	1.65	4.73	10.05	7.9	525.00	863.20	443.75	360.00	5124.00
	30–60	995.60	109.96	33.60	2.05	1.70	10.07	6.8	545.00	617.80	568.00	360.00	4392.00
	60–100	554.24	105.00	25.20	1.75	0.85	10.03	8.0	1194.00	802.90	656.75	360.00	4758.00
Alkali-saline patches	0–30	1121.76	224.14	33.60	9.80	3.67	10.34	16.0	2370.50	1787.50	1011.75	1044.00	9369.60
	30–75	984.68	111.78	33.60	4.25	2.37	10.01	10.7	1683.00	859.60	816.50	360.00	6588.00
	75–100	838.23	68.08	25.20	2.05	0.50	10.07	5.6	544.50	765.40	426.00	288.00	3294.00

Notes: TN, total nitrogen; TP, total phosphorus; AN, available nitrogen; AP, available phosphorus; OM, organic matter

Table 2 Water quality in demonstration zone before restoration in 2005

Source of water	pH	Salinity (mg/L)	Total alkalinity (mmol/L)	Ion concentration (mg/L)							
				Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	CO_3^{2-}	HCO_3^-	SO_4^{2-}
Wetland	8.5	996.4	8.08	37.07	29.79	3.06	208.23	106.50	6.12	603.90	1.76
Well	8.3	985.5	7.84	34.63	39.18	4.37	212.23	105.97	0	598.04	1.72
Huolinhe River	8.4	766.1	7.32	15.03	18.24	2.63	204.85	97.62	21.60	402.60	23.5

pogenic changes). These adaptations proceeded in combination with the optimum design methods included in system engineering.

The design included the following major items: 1) River-diversion works and wells and dams within the wetlands to develop an irrigation and drainage system providing adequate water for reed growth; 2) plowing of reed fields, reed rhizome transplantation and fertilization to restore reed vegetation; 3) releasing crab and fish fry and allowing natural proliferation to construct a complex reed-crab/fish ecological system.

2.2.1 Hydrological scheme

Water plays a prominent role in the growth and development of reeds, and water demand varies in the different stages of reed growth. Furthermore, water conditions have direct impacts on soil temperature, salinity and fertility. Water regulation is therefore the key to achieving high reed yields.

(1) Water requirement of reed

Through a two-year reed water-requirement test, designed and implemented based on the findings of a preliminary investigation, the following results were achieved: shallow irrigation before the soil thaw in early spring could maintain soil moisture during reed germination, could increase soil temperature and meet the reeds′ demand for water and oxygen; additionally, this irrigation could wash out alkali. During the stages of reed growth, the water requirements of reeds increase as stem growth, leaf expansion, photosynthesis, respiration and transpiration increase. Therefore, sufficient water must be supplied to ensure the desired reed yield.

Reed height is the most important factor influencing reed yield. There are significant negative correlations among height, density and biomass (Table 3). The results of further research using a height-growth regression model indicated that the dates of the initiation of the height-growth peak, the peak period and the end of the growth peak were May 23, June 29 and July 26, respectively. These dates defined the most important demand period for water. Seasonal submergence of water favored an increase in the total number of rhizomes and fibrous roots, which caused an increase of reed yield. Long-term drought decreased the number of rhizomes and fibrous roots and resulted in gradual degradation of the reeds. In the presence of long-term flooding, rhizomes and fibrous roots concentrate on the soil surface, although the total number remains steady, and most buds likewise occur on the surface and exhibit poor resistance to environment. Finally, these factors lead to decreased reed yield (Fig. 2).

Table 3 Correlation between reed-yield component factors

	Height	Stem diameter	Biomass
Height		0.2045	0.5889**
Stem diameter			0.4321**
Density	–0.7140**	–0.1432	0.4765**

Note: ** represents statistically significant at the level of 0.01

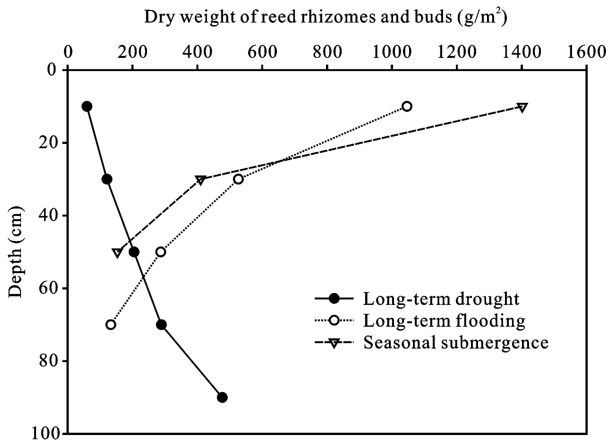


Fig. 2 Distribution of reed rhizomes and buds with different water-submergence patterns

(2) Irrigation and drainage system

A system of biannual irrigation and drainage was designed on the basis of the seasonal pattern of water demand by the reeds (Table 4). The irrigation quota for each growing season was 9000–1 2000 m^3/ha. In the saline reed wetlands experiencing serious water shortage and drought in the spring, the drainage after mid-August was omitted so as to maintain a natural infiltration of water. Subsequent freezing in winter, followed by thawing in the spring of the next year, diminished the alkali levels and supplied the water needed for seedling growth.

2.2.2 Plant-propagation

(1) Plowing and reed rhizome transplantation

In the degraded reed wetlands, reed rhizomes and fibrous roots were concentrated on the soil surface, the soil was compacted and poorly aerated, the activity of aerobic soil microorganisms was low, soil fertility was poor, and the reeds were short and produced low yields. Plowing or raking can improve soil structure and aeration conditions, restore fertility, and subsequently aid in

Table 4 Arrangement of times and water depths for irrigation and drainage

Month	April			May			June			July			August			September.		
	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
Development stage	Pre-emergence			Seeding				Growth peak				Earing and blooming				Maturity		
Water level control	Spring irrigation (5–8 cm)		First drainage		Summer irrigation (10–15 cm)									Second drainage				

Notes: Spring irrigation, to improve soil surface temperature, promote soil thaw and accelerate reed germination; first drainage, to expose field to sunlight to help break down soil organic matter and suppress marsh weed growth; summer irrigation, to promote growth during the reed growth peak; second drainage, to accelerate maturing of the mature reed stems and improve fiber quality and yield

rejuvenation, thereby promoting productivity and improving yield.

Alkali-saline patches of different sizes occurred within the degraded reed wetlands, exhibiting little reed growth; they were therefore initially restored by reed rhizome transplantation. The results of preliminary experiments showed that an effective approach for restoration is to select robust and pest-free reed seedlings (approximately 15 cm long) with rhizomes and transplant these seedlings in early May into holes (spaced 1 m apart) dug in the alkali-saline patches, transplantation is followed by compaction of the soil and irrigation. These measures can restore the reed vegetation in alkali-saline patches and can increase their survival rate to as high as 100%.

(2) Fertilization in the degraded area

Based on soil fertility background, a three-year reed fertilization experiment (1000 m^2 per plot) designed with two factors (nitrogen and phosphorus) and three levels was implemented in the study area. The results demonstrated a linear positive correlation of nitrogen application with reed height, density and yield over a given range of nitrogen values. The proposed optimal fertilization regime for the steady overproduction of reeds was determined to be the application of nitrogen (N) at 297.0 kg/ha and phosphate (P_2O_5) at 66.6 kg/ha. All fertilizer should be used as basal nutriment with long-lasting coating in deep soil.

2.2.3 Reed-crab/fish compound system

Reed wetlands can provide food resources for fish and crabs. Conversely, fish and crabs can help to control pests and weeds vying for space with reeds. The feces of fish and crabs also serve as fertilizer, and their feeding activity can loosen soil, promoting reed rhizome development. Many kinds of submerged plants can also furnish good breeding sites for fish and crabs and provide shelter from predators.

(1) Breeding crabs in reed wetland

Stocking design: Based on the natural abundance of food in the reed wetland, the initial crab stocking level was determined under the assumption of no additional bait. The estimated production potential of the crabs in reed wetland was approximately 340 kg/ha, and the target yield was set at 120 kg/ha. Crab-seeding density was set at 13 kg/ha, with an average initial weight of approximately 7 g per crab.

Acclimation to enhance crab viability: To facilitate their survival in the carbonate-rich water in the study area, crabs were placed into nylon bags with little holes, set on the shore and then gradually moved to deeper water. Approximately six hours later, the crabs were slowly released into the water. A plastic wall was erected to prevent their escape.

(2) Breeding fishes in reed wetland

Ring ditches, fishways and ponds were created for fish habitat and overwintering. Ring ditches around the reed wetland played three roles: First, they expanded the space for fish activity, feeding and habitat and helped improve water temperature and increase dissolved oxygen, promoting the proliferation of their natural food; second, they allowed for the early release of fish and thereby extended their growing time; third, they increased water storage and thereby avoided a shortage of water and oxygen in early spring. Fish-overwintering pools were excavated at the end of the ring ditches to provide habitat for fish after the autumn drainage.

Structural design for fish fry release: 1) Natural proliferation: fish fry were introduced with the irrigation water from the Tao′erhe and Huolinhe rivers to restore these aquatic communities; 2) Release according to a designed scheme: Following natural recovery, a design for fry release increased the recovery rate of fish stocks in reed wetlands and thus promoted efficiently optimized aquatic communities. The polyculture of a variety of fishes that feed on plankton, suspended microorganisms, organic debris and other natural bait and do not compete with crabs for food can help prevent an over-abundance of plankton and can also purify the water. However, fishes that compete with crabs for benthos should not be bred, e.g., carp (*Cyprinus carpio*), crucian carp (*Carassius auratus*), and herring (*Mylopharyngodon piceus*). The fishes released into the restored reed wetlands (RRW) included silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Aristichthys nobilis*), scherzeri (*Siniperca scherzeri Steindacher*), catfish (*Silurus asotus*), grass carp (*Ctenopharyngodon idellus*), and others. The average amount of fry released was approximately 20 kg/ha. The size of the fry released was 100–150 g per fish. Grass carp can not be bred in excessively large numbers because they undermine reed growth.

2.2.4 Ecosystem monitoring

To better understand the improvement of the restored reed wetlands on condition regulation, water purification, primary productivity and biodiversity, ecosystem monitoring in the restored reed wetlands and alkali-saline patches was performed as follows:

(1) Temperature and humidity

Soil temperature at different depths, air temperature and relative humidity at several heights were monitored every 3 hours over a continuous 24 hours period in the restored reed wetlands and alkali-saline patches from 9 to 10 June, 2006, 25 to 26 August, 2006, and 7 to 9 August, 2007. Equipments used included psychrometers (DHM2, China), maximum-minimum thermometers (WQG-13, WQY-18, China), curved soil thermometers (WQG-16, China), stemmed earth thermometers (WQG-14, China) and remote-measuring thermohygrographes (FYTH2, China).

(2) Evapotranspiration of reed wetland

Evapotranspiration monitoring can help to analyze the water need of reed. During the reed growth period from June to October, cylinders (1 m × 1 m) were transplanted into reed beds, and these cylinders were different in the amount of vegetation coverage. The cylinders were set up in restored wetland, and the water level was monitored daily to calculate the evapotranspiration rate.

(3) Water-quality of restored reed wetlands

Water quality monitoring was performed monthly at the entrance, center and outlet of the wetland during the reed growth period from June to October, 2010.

(4) Determination of reed photosynthetic capacity

In August, 2010, the LI-6400XT (LED red and blue light (800 μmol/(m^2·s)); Licor, USA) photosynthesis system was used to monitor the net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs) and intercellular CO_2 concentration (Ci) of reeds in the restored reed wetlands and alkali-saline patches.

(5) Biodiversity in reed wetland

The diversity of aquatic animals was investigated when fishes and crabs were harvested in the autumn from 2006 to 2009. A species-diversity index (the Shannon-Weaver index) was used for assessing biodiversity (Shannon, 1948). The Jaccard similarity coefficient was used to compare the biodiversity before and after restoration. Simultaneously, the monitoring for migratory birds was performed.

2.2.5 Experimental site construction

In accordance with the overall design, the engineering, agronomic and biological measures were implemented step by step. A 21-km irrigation diversion channel and its supporting subengineering infrastructure were constructed under a regional water-resource-management policy that included reservoirs, rivers and wetlands. The reed wetlands were divided into four districts according to their terrain, and four sluices and three wells (50–60 t/h output) were built in the wetlands to improve the irrigation and drainage system. Ring channels (10.0 m wide, 1.5 m deep, with a total length of 3400 m) were dug around the reed wetlands for fish culture, and a water pond (6000 m^2 and 3.0 m deep) was dug at the intersection of the channels to hold overwintering fish. After the engineering construction was performed, the reed fertilization, reed water-requirement tests, vegetation-restoration tests and rational stocking of fishes and crabs were implemented.

3 Results and Analyses

3.1 Economic efficiency

With the implementation of engineering techniques, agronomic and biological measures, the actual reed yield in the study area increased significantly. Reed basal diameter and height almost doubled with the spring irrigation, and the reed yield increased by 3.8 times in 2006 (Table 5). Reed production was up to 11 188.5–12 501.0 kg/ha in the area with fertilization, and yield increased by 79.2% with the application of nitrogen (N) and 100.2% with phosphrous fertilization (P_2O_5) in 2006 (Fig. 3). The input/output ratio of nitrogen and phosphrous fertilization were 1 ∶ 10.8 and 1 ∶ 8.3. The overall yield of reeds in the restored wetland increased by 20.9 times, from 0–350 t/yr (before degradation) to 7000 t/yr (after restoration for a year) in 2009 (Table 6).

The breeding of fish and crabs significantly improved the economic benefits (Table 7). In October, 2006, the average weight of crabs was up to 120 g, and the total crab production was 9500 kg, with a corresponding economic benefit of 154 000 yuan (RMB). In 2007, the production of crabs was improved by additional production, because some local farmers started to breed crabs in the restored reed wetland with the technique popularization, the total crab yield increased to 47 200 kg, with the economic benefit of 434 000 yuan. In 2008, the general benefit of crabs increased to 247 000 yuan. In addition, fish yield was up to 6000 kg in 2006, and the economic benefit is 54 000 yuan.

3.2 Vegetation productive capacity

As shown in Table 8, the density, height, basal diameter and other morphological indicators of reed growth in the wetland significantly increased after 2005. The fiber content and length reached or exceeded the characterization of reed before degradation. In 2008, the reed coverage in the demonstration area was almost up to 100%, and the reed density in the alkali-saline patches that previously lacked vegetation had recovered to 30–60 plant/m^2.

Determination of photosynthetic capacity also further demonstrated the superiority of reed growth potential in restored reed wetlands (Fig. 4). In the restored reed wetland, the net photosynthetic rate, stomatal conductivity, intercellular CO_2 concentration and transpiration rate of reed all were better, while in the alkali-saline patches, the reed growth potential was lower for the worse ecological environment, with the values of 48.9%, 29.1%, 83.1% and 39.9% of those in the restored reed wetland, respectively.

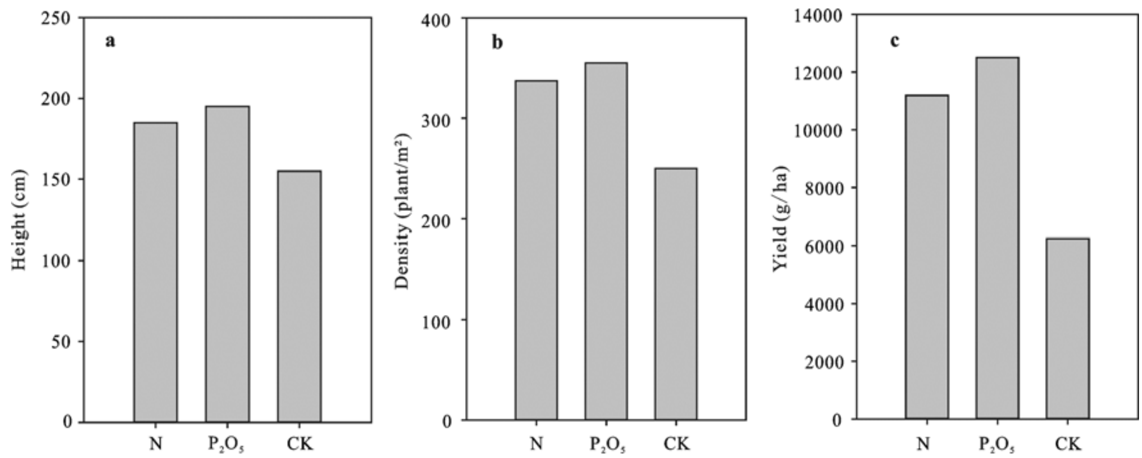
3.3 Functional recovery of local climate regulation

The results of several successive monitoring showed that the temperature of the restored reed wetlands was lower than that of the alkali-saline patches during the day, owing to the regulation of water and the covering of lush vegetation, and the maximum ground temperature was lower than the dry alkali-saline patches by 13.8℃, but the temperature was slightly higher than the alkali-saline patches temperature during the night, the minimum ground temperature was higher than the alkali-saline patches temperature by 1.7℃. The daily average temperature of ground surface and soil at different depths in the restored reed wetlands was lower than the values of alkali-saline patches by 1.7–3.7℃(Table 9).

The air temperature near the ground surface depends

Table 5 Growth and yield of wetland reeds with irrigation in 2006

	Density (plant/m^2)	Basal diameter (mm)	Height (cm)	Dry biomass (g/m^2)	Yield (kg/ha)
Irrigation	272	3–6	150–200	792	7912.5
CK	153	2–3	70–115	207	2068.5



N: nitrogen fertilization; P_2O_5: phosphrous fertilization; CK: control check

Fig. 3 Growth and yield of wetland reeds with fertilization in 2006

Table 6 Economic-benefit of reed crop in 2009

Yield (t)	Selling price (yuan/t)	Input (yuan/t)	Total output (10^6 yuan)	Net benefit (10^6 yuan)
7300	480.0	220.0	3.504	1.898

Note: Input includes the cost of irrigation, harvest, packing, transportation, *etc*.

Table 7 Economic benefit of fish and crab breeding in restored reed wetlands in study area

Year	Main product	Area (ha)	Total yield (kg)	Total benefit (10^6 yuan)
2006	Fish	60	6000	5.4
	Crab	100	9500	15.4
2007	Crab	420 (320*)	47200	43.4
2008	Crab	640 (540*)	39000	24.7

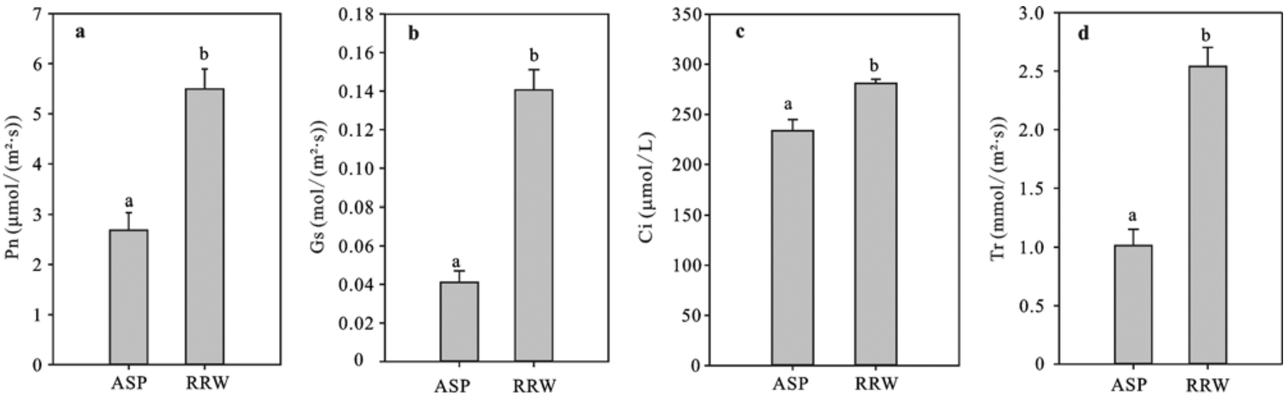
Note: *, the area turning experiment achievements into mass production

on the radiation balance, surface temperature, evapotranspiration and turbulent exchange intensity. Due to the shallow water cover, solar radiation reduction by vegetation, and large amount of evaporative heat loss, the air temperature above the restored reed wetlands was lower than that over the alkali-saline patches. As shown in Fig. 5(a), in June 9–10, the air temperature at 150 cm above ground in the restored reed wetlands was 20.2℃, lower than that in the alkali-saline patches 3.3℃ at 14:00. However, in night, the air temperature at 20 cm above ground in the restored reed wetlands was 15.6℃, higher than that in the alkali-saline patches 1.2℃ at 2:00.

The average relative air humidity in restored reed wetlands was higher than that in the alkali-saline patches

Table 8 Reed characteristic in wetland before and after restoration

Year	Density (plant/m^2)	Height (cm)	Basal diameter (mm)	Dry weight (g/plant)	Fiber content (%)	Fiber length (mm)
2001	44	37	1.9	2.8	27.6	1.04
2006	78	118	4.3	14.1	43.7	1.27
2007	88	149	4.7	13.7	42.2	1.34
2008	97	173	3.9	13.2	39.8	1.30



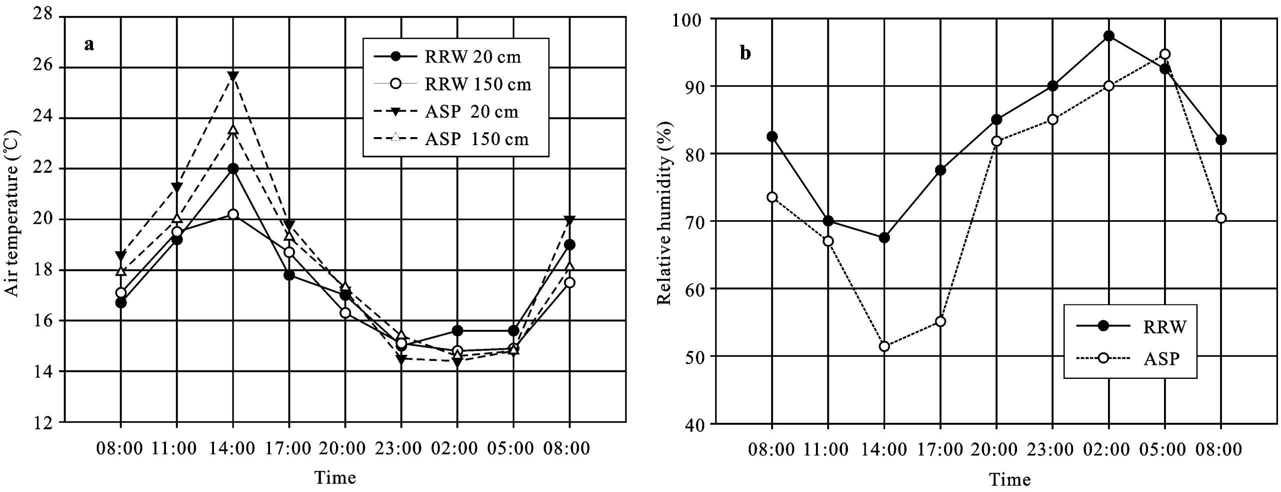
ASP: alkali-saline patches; RRW: restored reed wetlands; different letters in insets indicate significant differences ($P < 0.05$) among habitats

Fig. 4 Net photosynthetic rate (Pn) (a), stomatal conductance (Gs) (b), intercellular CO_2 concentration (Ci) (c) and transpiration rate (Tr) (d) of reeds in restored reed wetlands and alkali-saline patches

Table 9 Soil temperature at different depths in restored reed wetlands and alkali-saline patches (℃)

	Restored reed wetlands			Alkali-saline patches		
	0 cm	10 cm	20 cm	0 cm	10 cm	20 cm
Temperature at 5:00	15.5	16.1	15.9	15.7	16.6	17.5
Temperature at 14:00	26.5	17.6	16.7	36.5	23.0	18.9
Daily average temperature	19.1	16.9	16.4	22.8	19.1	18.1
Maximum ground temperature	27.7			41.5		
Minimum ground temperature	13.8			12.1		

Notes: Monitoring time is June 9–10, 2006; the depth of water in the reed wetlands is 30 cm



RRW: restored reed wetlands; ASP: alkali-saline patches

Fig. 5 Air temperature (a) and relative humidity (b) at different heights in restored reed wetlands and alkali-saline patches

in the most time of one day (Fig. 5b), especially in the diurnal hours with sunlight, the air above the alkali-saline patches was drier, the relative air humidity was lower than restored reed wetlands 16.1% at 14:00 and 22.4% at 17:00. The variation range of average relative air humidity in restored reed wetlands also was smaller.

3.4 Functional recovery of water purification

The water-purification capacity of reed wetlands has been confirmed by many studies, and the results show that the flow of water containing toxins and impurities slows down in wetlands and that pollutants, suspended solids and nutrients are adsorbed, degraded and precipitated so that potential contaminants become resources (Albuquerque *et al.*, 2009; Yi *et al.*, 2010). The water-purification capacity of restored wetland ecosystems is an important indicator of wetland restoration. For July 2010, the results of water-quality monitoring at the water entrance, center and outfall in the restored reed wetlands showed that the restored reed wetlands could remove impurities with high efficiency (Table 10). The removal rates of total nitrogen (TN) and total phosphorus (TP) increased more than 75%, and that of CODcr was up to 86%. The salinity reduction was also very significant. The removal rates of Na^+ and Cl^- were more than 85%, and the removal rate of HCO_3^- was 68.48%. The water-purification capacity of wetland depends on the size, the type and number of wetland organisms. The increase of wetland vegetation cover and soil microbial numbers and activity resulting from wetland restoration can thus improve the water-purification capacity of the wetland.

3.5 Biodiversity

A survey in autumn and winter of 2008 showed that the wetland was once again occupied by all naturally occurring fish (except for variegated minnow (*Phoxinus czekanowski* Dybowski), dog-head minnow (*Gobio cynocephalus* Dybowski) and Amur weatherfish (*Misgurnus mohoity*)), and three kinds of shrimp. The community-similarity index was used to compare the shrimp and fish communities before and after the restoration in the degraded reed wetlands. The Jaccard similarity coefficient of the shrimp populations was 1.00, and the population-similarity coefficient for the fish was 0.69. The population density of aquatic communities increased in the restored reed wetlands. It indicated that

Table 10 Water quality in restored reed wetlands (mg/L)

Sample site	TN	TP	NO_3^--N	NH_4^+-N	CODcr	Na^+	SO_4^{2-}	CO_3^{2-}	HCO_3^-	Cl^-
Entrance	6.32	0.10	0.09	0.54	139.55	781.37	60.39	86.40	1077.50	862.22
Center	1.11	0.01	0.11	0.11	38.50	82.29	3.41	0.00	304.51	100.54
Outfall	1.35	0.02	0.10	0.07	43.31	84.73	5.23	0.00	339.65	126.10
Removal rate (%)	78.64	76.77	–20.00	86.37	68.96	89.16	91.33	100.00	68.48	85.37

community structure had been optimized. The restored reed wetlands was occupied by 18 species of fishes (13 of these species were natural fishes) belonging to three orders, six families, and seventeen genus. The Shannon-Weaver index of fish increased to 5.48. and the Shannon-Weaver index of shrimp was up to 3.71.

In addition, in the recovery area, the size of the reed wetland and the diversity of vegetation increased, so that birds had adequate food and the conditions of the bird habitats were likewise improved. Some rare and endangered bird species can also be found in the region. The most prominent species found were red-crowned cranes (*Grus japonensis*), grey cranes (*Grus grus*), black-winged stilt (*Himantopus himantopus*), grey-headed lapwing (*Vanellus cinereus*), black-browed reed warbler (*Acrocephalus bistrigiceps*), common pochard (*Aythya ferina*), and others. The species and numbers of birds in the wetland both increased significantly. In contrast, no birds remained in the unrecovered alkali-saline patches for long periods.

4 Conclusions

Ecological restoration and ecological engineering were applied to design and restore a degraded saline wetland in the western Songnen Plain of China with the aim of sustainable utilization. The improvement of water, soil and other nonbiological environmental components is important for achieving degraded saline wetland restoration and reconstruction. The perfect surface-water exchange system can fully eliminate salt and reduce alkalinity, high fertility and good soil physical and chemical properties can ensure the success of vegetation restoration, and manual transplantation and breeding promotion can improve the recovery of vegetation, so the combination of engineering and agricultural practices is an effective way to restore degraded wetland.

The complex reed-fish/crab ecological system is an ecologically based, environmentally friendly and highly efficient approach for restoring and making rational use of degraded saline wetlands. This approach is suitable for various restored reed wetlands in the Songnen Plain and provides an example useful for other wetland restoration and utilization.

References

Albuquerque A, Arendacz M, Gajewska M *et al*., 2009. Removal of organic matter and nitrogen in an horizontal subsurface flow (HSSF) constructed wetland under transient loads. *Water Science and Technology*, 60(7): 1677–1682. doi: 10.2166/wst.2009.548

Carubelli G, Fanelli R, Mariam G *et al*., 2007. PCB contamination in farmed and wild sea bass (*Dicentrarchus labrax* L.) from a coastal wetland area in central Italy. *Chemosphere*, 68(9): 1630–1635. doi: 10.1016/j.chemosphere.2007.04.004

Cui B S, Yang Q C, Yang Z F *et al*., 2009. Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. *Ecological Engineering*, 35(7): 1090–1103. doi: 10.1016/j.ecoleng.2009.03.022

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

Gibbs J P, 2000. Wetland loss and biodiversity conservation. *Conservation Biology*, 14(1): 314–317. doi: 10.1046/j.1523-1739.2000.98608.x

Gong P, Niu Z G, Cheng X *et al*., 2010. China′s wetland change (1990–2000) determined by remote sensing. *Science China-Earth Sciences*, 53(7): 1036–1042. doi: 10.1007/s11430-010-4002-3

Hopfensperger K N, Engelhardt K A M, Seagle S W, 2006. The use of case studies in establishing feasibility for wetland restoration. *Restoration Ecology*, 14(4): 578–586. doi: 10.1111/j.1526-100X.2006.00169.x

Jenkins G A, Greenway M, 2007. Restoration of a constructed stormwater wetland to improve its ecological and hydrological performance. *Water Science and Technology*, 56(11): 109–116. doi: 10.2166/Wst.2007.754

Ji G D, Sun T, Zhou Q X *et al*., 2002. Constructed subsurface flow wetland for treating heavy oil-produced water of the Liaohe Oilfield in China. *Ecological Engineering*, 18(4): 459–465. doi: 10.1016/S0925-8574(01)00106-9

Li E H, Liu G H, Li W *et al*., 2008. The seed-bank of a lakeshore wetland in Lake Honghu: Implications for restoration. *Plant Ecology*, 195(1): 69–76. doi: 10.1007/s11258-007-9299-4

Miller R L, Fujii R, 2010. Plant community, primary productivity, and environmental conditions following wetland re-establishment in the Sacramento-San Joaquin Delta, California. *Wetlands Ecology and Management*, 18(1): 1–16. doi: 10.1007/s11273-009-9143-9

Mitsch W J, Gosselink J G, 2007. *Wetlands* (*4th ed.*). New York, USA: John Wiley & Sons, Inc.

Mitsch W J, Wang N M, 2000. Large-scale coastal wetland restoration on the Laurentian Great Lakes: Determining the potential for water quality improvement. *Ecological Engineering*, 15(3–4): 267–282. doi: 10.1016/S0925-8574(00)00081-1

Moreno-Mateos D, Comin F A, 2010. Integrating objectives and scales for planning and implementing wetland restoration and creation in agricultural landscapes. *Journal of Environmental Management*, 91(11): 2087–2095. doi: 10.1016/j.jenvman.2010.

06.002

Moss B, 1990. Engineering and biological approaches to the restoration from eutrophication of shallow lakes in which aquatic plant-communities are important components. *Hydrobiologia*, 200: 367–377. doi: 10.1007/BF02530354

Qin P, Mitsch W J, 2009. Wetland restoration and ecological engineering: International conference of wetland restoration and ecological engineering. *Ecological Engineering*, 35(4): 437–441. doi: 10.1016/j.ecoleng.2008.12.001

Rodriguez R, Lougheed V L, 2010. The potential to improve water quality in the middle Rio Grande through effective wetland restoration. *Water Science and Technology*, 62(3): 501–509. doi: 10.2166/Wst.2010.323

Shannon C E, 1948. A mathematical theory of communication. *Bell System Technical Journal*, 27(3): 379–423, 623–656.

Shultz S, 2000. Wetland storage to reduce flood damages in the Red River. In: *Land Stewardship in the 21st Century*: *The Contributions of Watershed Management*, *Conference Proceedings*, (13): 363–366.

Simenstad C, Reed D, Ford M, 2006. When is restoration not? Incorporating landscape-scale processes to restore self-sustaining ecosystems in coastal wetland restoration. *Ecological Engineering*, 26(1): 27–39. doi: 10.1016/j.ecoleng.2005.09.007

Wan S W, Qin P, Li Y *et al*., 2001. Wetland creation for rare waterfowl conservation: A project designed according to the principles of ecological succession. *Ecological Engineering*, 18(1): 115–120. doi: 10.1016/S0925-8574(01)00062-3

Wang X Y, Feng J, Zhao J M, 2010. Effects of crude oil residuals on soil chemical properties in oil sites, Momoge Wetland, China. *Environmental Monitoring and Assessment*, 161(1–4): 271–280. doi: 10.1007/s10661-008-0744-1

White J S, Bayley S E, 1999. Restoration of a Canadian prairie wetland with agricultural and municipal wastewater. *Environmental Management*, 24(1): 25–37. doi: 10.1007/s002679900212

Wu C Y, Kao C M, Lin C E *et al*., 2010. Using a constructed wetland for non-point source pollution control and river water quality purification: A case study in Taiwan. *Water Science and Technology*, 61(10): 2549–2555. doi: 10.2166/Wst.2010.175

Wu Y, Chung A, Tam N F Y *et al*., 2008. Constructed mangrove wetland as secondary treatment system for municipal wastewater. *Ecological Engineering*, 34(2): 137–146. doi: 10.1016/j.ecoleng.2008.07.010

Yadav A K, Kumar N, Sreekrishnan T R *et al*., 2010. Removal of chromium and nickel from aqueous solution in constructed wetland: Mass balance, adsorption-desorption and FTIR study. *Chemical Engineering Journal*, 160(1): 122–128. doi: 10.1016/j.cej.2010.03.019

Yi Q T, Yu J H, Kim Y, 2010. Removal patterns of particulate and dissolved forms of pollutants in a stormwater wetland. *Water Science and Technology*, 61(8): 2083–2096. doi: 10.2166/wst.2010.159

Zhang J Y, Ma K M, Fu B J, 2010. Wetland loss under the impact of agricultural development in the Sanjiang Plain, Northeast China. *Environmental Monitoring and Assessment*, 166(1–4): 139–148. doi: 10.1007/s10661-009-0990-x

Zhang L, Wang M H, Hu J *et al*., 2010. A review of published wetland research, 1991–2008: Ecological engineering and ecosystem restoration. *Ecological Engineering*, 36(8): 973–980. doi: 10.1016/j.ecoleng.2010.04.029