Science of the Total Environment 569–570 (2016) 1077–1086

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Developing and sustainably utilize the coastal mudflat areas in China

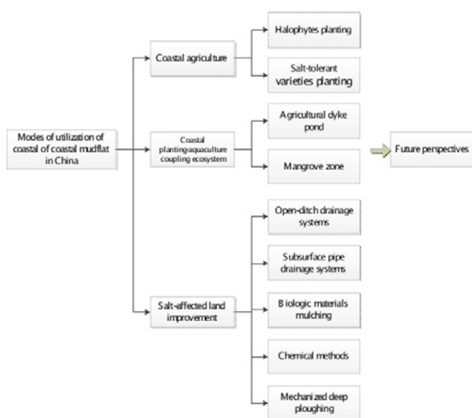
Xiao-hua Long [a,*,1], Li-ping Liu [a,b,1], Tian-yun Shao [a], Hong-bo Shao [c,d], Zhao-pu Liu [a]

[a] College of Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing 210095, China
[b] Shandong Provincial Key Laboratory of Marine Environment and Geological Engineering, College of Environmental Science and Engineering, Ocean University of China, Qingdao 266100, China
[c] Institute of Agro-biotechnology, Jiangsu, Academy of Agricultural Sciences, Nanjing 210014,China
[d] Yantai Institute of Coastal Zone Research,Chinese Academy of Sciences,Yantai264003,China

HIGHLIGHTS

- Coastal mudflat areas are as the important reserve land resource in China
- Exploitation of mudflat can relieve the stress of inadequate land resources
- Aquaculture and agriculture are the primary modes of utilization of mudflats
- In the exploitation of mudflats, environmental problems have arisen
- We offer some suggestions for the sustainable development of mudflat areas

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 14 June 2016
Accepted 20 June 2016
Available online 7 July 2016

Editor: Gang Xu

Keywords:
Coastal mudflat areas
Crop-aquaculture ecological system
Planting-aquaculture ecological coupling system
Salt-soil utilization with efficiency

ABSTRACT

Coastal mudflat areas are regarded as the important reserve land resource in China. Rational exploitation and development of the mudflat areas can relieve the stress of inadequate land resources. Probing into the developing models of resource exploitation of coastal tidal mudflats is one of the important components of achieving the sustainable development in the coastal areas. Therefore, the development history of coastal mudflats after 1950s in China is briefly introduced in this paper. Then, the status in quo of the modes of development and utilization of coastal mudflat in China the paper is reviewed with a special attention payed to the agricultural use of coastal resource, especially halophytes and improved salt-tolerant varieties planting, agricultural dyke pond and coastal saline-alkali soil remediation. Based on related research frontier, sustainable developmental prospects of these coastal areas are presented as well.

1. Introduction

Coastal mudflat areas, in a narrow sense, refer to the coastal zone flooded periodically by seawater, the so called intertidal zone (Svenja et al., 2016; Andreu et al., 2016). However, in a broad sense, they include

* Corresponding author.
E-mail addresses: longxiaohua@njau.edu.cn (X. Long), shaohongbochu@126.com (H. Shao).

[1] These authors are the co-first author because of equal contribution.

http://dx.doi.org/10.1016/j.scitotenv.2016.06.170
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not only the intertidal zones, but the supra-tidal and sub-tidal areas that can be developed and utilized.

China coastline extends over a length of 32,000 km, with the coastal zone covering a total area of 2.17×10^6 ha out of which 95% is in an intertidal belt (Table 1). Jiangsu province has the largest area of coastal tideland in China, accounting for 6.53×10^5 ha, almost 1/4 that of the whole China. Other tideland is in Yellow River Delta in Shandong province, 2.07×10^5 ha, then the Pearl River Delta, 7.3×10^4 ha (Zhang and Zhang, 2009). The coastal tidal flat, as a typical location in the intersection between sea and land, is a multifunctional and complex ecosystem which shows continuous distribution. The offshore areas are vital habitats for a wide range of commercial species(Liu et al., 2016; Portman et al., 2012). The translation zones can also protect human from lots of ocean disasters which is regard as the key areas of exploitation and utilization among all reserved land resources in China. Moreover, coastal mudflat areas which have substantial sediment sources are undergoing an increase in area. Researchers estimate that new tidal mudflat areas are increasing by approximately 30,000 ha per year due to sediment transport. (Chen et al., 2000).

Based on the landscape ecology principles, mud flatlands are divided into four types including mud flats, sand beaches, benches, and biologic flats (Peng and Wang, 2000). Mud flats are characterized by a gentle slope, which are formed with successive soil developments, and have fine texture and high content of organic matter suited for agricultural reclamation. Sand beaches, with beautiful landscapes and diversity of dwelling species have a high value both in academic research and tourist development. Biologic flats are rich in biological resources, typically including coral reef and mangrove swamp beaches. Among the six types of reserved land resources (including barren mountain land, slope wasteland, unused grassland, and alkali land), the coastal mudflat areas are regarded as the land with the largest potential for improvement (Wei et al., 2010).

Currently, in China, utilization rate of coastal tourism resources is less than 1/3 (and without in-depth development), the coastal aquaculture areas utilization is less than 60%, and utilization of shallow beach areas above the depth of 15 m is less than 2% (Yang, 2014). Apparently, due to the effects of human activities, the coastal ecosystem productivity is closely related to the modes of development and utilization. Therefore, while reviewing the development history of coastal mudflats in China, the paper analyzed the status in quo of the modes of development and utilization of coastal mudflat in China with a special attention payed to the agricultural use of coastal resource. In addition, by referring to the research frontier both at domestic and abroad, sustainable developmental prospects of these coastal areas are discussed in the closing section.

2. Development process of coastal mudflat areas utilization

The main modes of coastal areas of western countries at present include: operation of large-scale coastal mechanized farmlands; restoration of coastal natural ecological environment and building of coastal natural conservation areas; salt producing in coastal salt field; development of seaside tourism; construction of port towns (Wei et al., 2010). In Asian and African areas, it mainly focused on developing large-scale and low-level mechanized coastal agriculture and building port towns (Ng et al., 2014). Moreover, it started to construct the coastal natural conservation area to protect the coastal habitat (Qiu and Jiang, 2005).

Because of difference on politics, economy, society and culture of different countries, the utilization and management of coastal lands varies. The Netherlands is a typical country with exploitation of coastal areas which include coastal sand dune, seawall and barrier islands. Its sediment supply is from the floor of the North Sea. The Netherlands always focuses on development of tideland reclamation and livestock breeding along its coasts (Raats, 2015). Brazil is one of countries with the longest coastline and has a range of varied coastal ecosystems. Brazil began to carry out environmental protection of coastal areas from 1970s (Bockstael et al., 2016). The main mode of exploitation and utilization of coastal resources of Japan is mudflat aquaculture under the precondition of environmental protection (Wei et al., 2010). Coastal aquaculture based on coastal tourism and entertainment industry is the main exploitation mode of New Zealand (Bremer and Glavovic, 2013). Many countries have explored lots of models of exploration and management on coastal areas which apply to their local conditions of coastal lands, which is of great value for reference to us.

Before the establishment of new China, tideland reclamation was organized spontaneously by the locals for use in agriculture and salt production. Hence, the development scale was small and a standard of reclamation was low. During the 30 years after the country founding, the reclamation reached the peak (Li et al., 2014). The ecological investigations were conducted in several typical intertidal zones including Yellow Sea and Bohai Sea area in northern China, the Zhoushan islands of the East China Sea and Hainan Island of the South China Sea. Early in 1960s, in some areas beach-making land projects started under local government coordination. Meanwhile, fauna and flora resources and biological investigations were carried out in offshore areas and the intertidal belt (especially in Xisha and Zhongsha Islands) (Peng and Wang, 2000). From the mid 60′s to late 70′s, reclamation in coastal areas progressed from reclaiming land in the high intertidal zones to silt-promoting engineering in the mid and low intertidal zones, from embankment works in estuarine and coastal areas to sea-closure engineering (Yang et al., 1997). The Comprehensive Survey of China's Coastal

Table 1
Coastal shoreline resources distribution in China (He et al., 2005).

Coast	Total area/$\times 10^4$ hm^2		Proportion%	Components %		
				Coastal beach	Marsh	Flood land
Total		217.09	100.0	80.6	14.5	4.9
Bohai Seacoast area	Subtotal	68.04	31.3	75.1	17.5	7.4
	Liaoning section	24.18	35.5	70.7	29.3	
	Hebei section	11.00	16.2	70.2	26.0	3.8
	Tianjin section	5.87	8.6	63.7	23.5	12.7
	Northern Shandong	26.99	39.7	83.7	1.9	14.4
South Yellow Seacoast area	Subtotal	58.20	26.8	79.3	20.4	0.3
	Eastern Shandong	6.88	11.8	92.1	5.9	2.0
	Jiangsu section	51.32	88.2	77.6	22.4	
East Seacoast area	Subtotal	55.49	25.6	84.5	6.3	9.2
	Shanghai section	6.15	11.1	72.7	27.3	
	Zhejiang section	28.86	52.0	79.7	5.0	15.3
	Fujian section	20.49	36.9	94.8	1.8	3.4
South China Seacoast area	Subtotal	35.36	16.3	86.8	12.3	0.9
	Guangdong section	20.42	57.8	89.8	9.6	0.6
	Hainan section	4.89	13.8	80.8	15.1	4.1
	Guangxi section	10.05	28.4	83.7	16.3	

Zones and Tideland Resources, which was carried out from 1979 to 1986, accumulated abundant information regarding further work to be done in the coastal areas. Tidal flat development in this phase emphasized coastal resources and environmental background surveys. After the 1980s, a new period of exploitation of coastal mudflat areas concentrated on referring to the advanced foreign experience as well as theoretical research, especially including the construction of irrigation facilities (He et al., 2005). The reclamation of tidal flats transformed from a spotted single development to a comprehensive pluralistic direction including aquaculture, coastal town construction, building of ports and docks, and tourism business along the coast. Some eco-environmental problems caused by poor management attracted attention in practice. Moreover, this stage also began to consider the principle of public participation.

3. Modes of exploration of coastal mudflat areas in China

Development and utilization of coastal mudflat resources comprises the following types: aquaculture, planting, salt manufacturing, tourism, port and dock, coastal town construction and industrial portfolio (Wei et al., 2010). The supra-tidal and intertidal zones mainly promote farming development including rice, forage grasses, bulrush, spartina, etc. In the intertidal zones, coastal algae, shellfish as well as ecological tourism are mainly promoted, whereas agriculture is mainly in the sub-tidal zone. In short, aquaculture and agricultural planting are the primary modes of utilization of coastal mudflats at present China. The main modes of exploration of coastal mudflat areas were showed in Fig. 1.

4. Agriculture in coastal mudflat areas

Agricultural planting in coastal areas is a traditional mode of exploitation, especially in tideland reclamation, which promotes the traditional industry bases such as salt, fishery, cotton industry and is of importance for the dynamic equilibrium of the total cultivated land and mitigate the shortage of land resources.

4.1. Planting halophytes

Salinization of coastal soils is an important factor limiting agricultural planting. In some coastal areas with no significant improvement of saline-alkali soil, planting of salt-tolerant plants is one of the effective measures for using and exploiting the coastal land resources.

In 1963, *Spartina anglica Hubb* was introduced successfully from Britain to coastal mudflat areas for seashore stabilization and salt-affected soil mitigation (Chung, 2006). *Spartina alterniflora* Loisel was then introduced successfully from America to the lower high-tide zone and the upper mid-tide zone in China in 1979 (An et al., 2007). To date, three species: *S. anglica*, *S. patens*, and *S. alterniflora* are frequently being planted along the Chinese coastal areas. Although these three species were successfully introduced, in particularly, *S. anglica* and *S. alterniflora* have been mainly planted along the China's coast. However, due to the niche competition, the latter were widely expanded (Zuo et al., 2012). These species showed a well-developed root system, adaptation to the natural environment of Chinese coastal soils which have already affected the habitats of native coastal communities and mainly is reflected in lower diversity index. But equally important is that the species show great ecological merits of both creating land with silt and protecting seashore when reasonably planted and managed.

Previous studies focused on the results of silt promotion, levees protection and effects of forest operation on biological diversity (Netto and Lana, 1997). Since successful introduction at the coast of Jiangsu province, the amount of soil sediment deposition along the *Spartina anglica* growth belt has increased by 3.8×10^7 m^3 (Tang and Zhang, 2003). The *Spartina alterniflora* salt marshes expanded in Jiangsu coastal areas since initial planting in 1982. By interpreting the remote sensing pictures of TM in years of 1985, 1988, 1933, 1995,1997 and 1999 combining with the field investigation in 1999 and 2000, the average annual expansion rate was 23% in the early period, 89% in the mid period, and 48% in the later period (Shen et al., 2002).

The image fusion technique was used in vegetation classification of the inter-tidal wetlands of Chongming, in Shanghai (Guan and Zhang, 2008). It was concluded that the role of salt marshes in deposition promotion and maintenance of the health of coastal environment was irreplaceable. In addition, soil properties, such as the organic matter and soil fertility, were improved by residue deposition and degradation of *S. anglica* in coastal soils, and increased with the years of planting. Aboveground plant N and soil inorganic N pools in *S. alterniflora* plantings were increased by 24% and 38% respectively, compared with the native common reed marshes (Peng et al., 2011). Soil organic carbon (SOC) and N content in 1–10 cm depth of *S. alterniflora* land *S. anglica* plantings increased 3.7–4.9 g C/kg soil, and 0.31–0.39 g N/kg soil, respectively

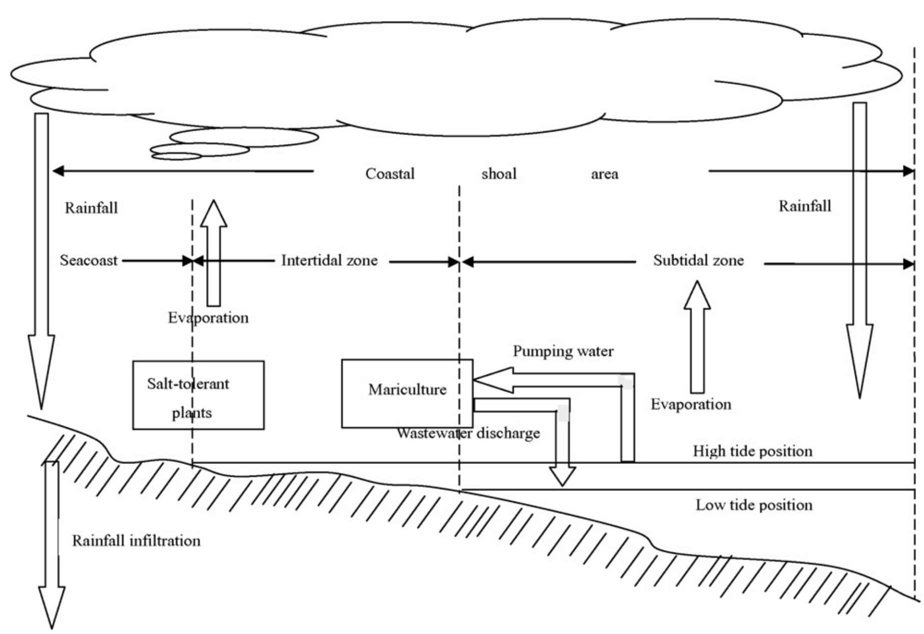

Fig. 1. Modes of exploitation of coastal mudflat areas (Wei et al., 2010).

(Zhang et al., 2010a). As a strongly salt-secreting plant, *S. anglica* can accumulate high concentration of salts in the roots (Chung, 2006). *S. anglica* also plays a role in preventing and remedying pollution, especially nutrient enrichment of near-coastal waters caused by sea farming (Yan et al., 2006). *S. anglica* has a strong capacity to accumulate mercury. The absorption of mercury can be up to 43% of the amount in solution with concentration of 1 mg/L (Zhong and Qin, 1983). A research (Zhang et al., 2014) on found the contents of Pb, Cd, As, Hg, Cr, Cu, Ni, Zn in *Spartina alterniflora* salt-marsh wetland were higher than those associated with the adjacent bare flat areas, in Rudong, Jiangsu province. *S. anglica* and *S. alterniflora* are important factors to accumulate heavy metal in coastal mudflats which can prevent metals from entering the open sea directly.

Salicornia europaea L. can tolerate high NaCl concentration of 5% (*w*/w) and survive seawater irrigation. It is rich in essential microelements for humans, including carotene, vitamins and proteins. A research (Zhang et al., 2003a) showed oil content in *Salicornia europaea* seed can reach about 26–33% (*w*/w), more than in other oil seeds such as soybean. Seed cake after squeezing contained 40% *w*/w crude protein and 7.6% (*w*/w) crude fiber and can be utilized as a feed supplement (Wu, 2007). *Salicornia europaea* can absorb large amounts of carbon dioxide from the atmosphere (Josh et al., 2011), equivalent of about 5 t of carbon per hectare. In addition, it can remove heavy metals and pollutants from the mariculture areas due to complexation with root exudates (Pan et al., 2012; Pan et al., 2011).

Suaeda glauca Bunge is another halophyte growing on mudflats. The *Suaeda glauca* can tolerate brine with about 25 g/kg NaCl concentration and limit is 35 g/kg according to a brine-soaking experiment (Zhang et al., 2007). Three years after planting soil desalinization rate reached 27%. The soil organic matter content, total N, available P and available K increased by 56%, 167%, 194% and 38%, respectively (Zhang et al., 2003b).

Oil sunflower, as one of the four major oilseed crops, has the strong resistance to cold, drought and saline-alkaline soils, and is one of the main crops growing on semi-arid areas as well as slightly saline and alkaline soils. Based on salt tolerance, genotypes G101B and DK1 (early- and mid- maturing, respectively) can grow well in saline-alkali soils along the coastal areas in Jiangsu province (Wang et al., 2008). Experiments with seawater irrigation of oil sunflower, carried out in Laizhou, Shandong province, by Liu et al. (2008a), showed that for the seed yields of oleic sunflower (G101B), 6.2 t seed/ha at 20% and 5.9 t seed/ha at 40% seawater irrigation can be achieved per year, respectively. A 4-year trial with oil sunflower showed that salt leaching by drip irrigation may change the very strongly salt-affected soil into moderately saline soil (Ye et al., 2014). Besides, sunflower was effective in extracting organic chlorine pesticides from the soil (Wan et al., 2013).

4.2. Improved salt-tolerant varieties for planting on coastal saline soils

Research on salt tolerance mechanisms in plants has always been popular (Flowers et al., 1977; Zhu, 2002). Selecting salt-tolerant cash species that can be planted on the coastal mudflat areas is essential to reduce soil erosion and accelerate the process of soil maturation.

Jerusalem artichoke is one of the most promising non-food biofuel crops due to its wide adaptability, high resistance, high biomass production, extensive use and environmental friendliness. In addition, it can tolerate 7–10 g salt/kg soil in coastal mudflat areas (Hu et al., 2012). Tubers of Jerusalem artichoke have high inulin content accounting for about 80% of dry tuber weight. The content of synanthrin is 8.5 to 15 t /ha/year, which is similar to sugar beet. If converting sugar into ethanol, Jerusalem artichoke can produce 3.5 to 6.8 t ethanol/ha, which is about double the yield of Chinese corn. The Key Lab of Marine Biology of Jiangsu province studied the introduction, selection and breeding of energy crops in Laizhou, Shandong province, and Dafeng, Jiangsu province, and screened out Jerusalem artichoke Nanyu1 and Nanyu2 genotypes that have high seawater tolerance, substantial biomass production and high energy density (Long et al., 2007).

A significant amount of research work was done on the salt-tolerance mechanisms in cotton (Xu et al., 2013; Mai et al., 2013; Zhang et al., 2013). The soil with 0.2% (*w*/w) salt content can improve seedling emergence, growth as well as yield and quality of salt-tolerant cotton. However, 0.3% (*w*/w) salt and above may be harmful to cotton growth. Some new cotton varieties with salinity tolerance were identified. And they were extensively planted in the salt-affected soil according to local conditions. In Putian, Fujian province, 70 ha of salt-tolerant cotton were planted on desalted reclaimed areas for 3 years in the high- and mid-tide flats, finally yielding 55 t lint (Zhang, 2001). Some research focused on increasing cotton salt tolerance to 0.3–0.35% (*w*/w) or more as an adaptation to the saline-alkali soils in the coastal mudflat areas in Jiangsu province. A cotton growing area in Yancheng, Jiangsu province, amounts to $1.7–1.9 \times 10^5$ ha.

Salt stress is one of the major causes of rice yield loss. Research on drought and salt resistance and breeding of salt-tolerant rice is an effective and valuable economic way to enable planting on coastal saline-alkali soils. It is also useful for decreasing soil salt content due to rice cultivation and salt wash-down. Chinese researches on salt-tolerant rice mainly focus on the tolerance mechanisms (Zhao et al., 2013; Gao et al., 2007). The rice salt tolerance at the seedling stage is representative of that at the later growth stages. Soil salt content below 2.0 g/kg soil was favorable for rice growth, and the irrigation water salinity should not exceed 2.0 g salt/L, and is even better if below 1.5 g salt/L (Yang and Li, 2011). Moreover, lots of research was carried out on breeding and screening rice germplasm tolerant to salt stress, which was an effective means of enabling planting on salt land. In particular, due to the salt-water intrusion caused by hurricanes in coastal rice fields, it is essential to consider salt-tolerant rice varieties for ensuring high and stable yield. Hybrid rice XIEYOU 46 grew well with Cl^- concentration in water below 1250 mg/L in rice seedling bed in Taizhou, Zhejiang (Zhang and Peng, 1999).

Breeding salt-tolerant rice varieties based on phenotypic selection is difficult and low efficiency. Much researches have been done on QTLs mapping of salt-tolerant rice (Cheng et al., 2012), salt-tolerant genes cloning and expression (Jiang et al., 2012). Hu et al. (2010) reviewed the progress of domestic research on salt-tolerant rice germplasm resources, mapping QTLs conferring salt-tolerance, cloning salt-tolerant genes and breeding salt-tolerant rice varieties. Some molecular biology methods, such as mutagenesis, somatic mutation screening and genetic engineering (referring to introducing target genes into varieties with desirable agronomic traits) may be helpful.

Soybean, as an important oil crop in China, can endure salt stress of 5.0 dS/m, having medium salt tolerance (Berstein and Ogata, 1966). Research on salt-tolerant soybean mainly focused on the mechanisms of salt tolerance (Phang et al., 2008). Molecular markers of genes associated with salt tolerance were characterized in soybean (An et al., 2014). It is necessary to screen wild germplasm resources and improve salt tolerance of soybean by molecular biology techniques, which would be the focus of future research.

5. Integrated technologies and modes of agricultural exploitation of coastal resources

5.1. Agricultural dyke pond

Agricultural Dyke Pond, also called agriculture-fishery system, refers to digging a pond in saline-alkali land for fish, shrimp and crab production, with soil dug out used to construct platform fields for planting grain, cotton or vegetables and for livestock breeding. The land is excavated 1.6–2.2 m deep, with water depth measured at about 3 m and ridge at about 30 cm on the platform. Salt from a plough layer (about 20 cm) of the platform can be leached into a drainage canal. During the dry season, salt in soil can rise with the capillary water, but the critical height of soil salinization can be maintained at 2 m below the surface of the platform fields, effectively decreasing salt content in the plough layer. This system can fundamentally improve saline land and ensure crops grow normally. The agricultural dyke ponds have the characteristics of combining land-based and freshwater ecosystems in which planting, livestock and fish farming tend to work in synergy with each other (Fig. 2).

Due to the silty tidal flat with feature of high salt content and low fertility, there are some problems such as large capital investment, long development cycle, and low profits by cultivation of reclaimed dry salt-effected land. Our group established a highly effective model of agricultural utilization of coastal salt-affected lands under which the development process of soil environment salinization happened: coastal saline soil → strong soil salinization → moderate soil salinization → mild soil salinization (Table 2).

The model of exploiting mudflats, with accumulation of fresh water in enclosed land in which fish was raised, could fully utilize the rainwater resources. Soil desalting period can be shortened by up to 2/3 (Table 3) (Liu et al., 1992). Soil was cultivated for 3 years after applying this ecological model. It was also an effective and sustainable mode of improving soil fertility. During the experimental 3-year period, an increase in soil organic carbon (0–40 cm) in mixed cultivation of sesbania grew in waterlogged soils with fish culture was about 22 to 70%. The content of available phosphorus in soil was increased by 29% compared with that of cultivating sesbania in uplands. An increase in total nitrogen in the mixed cultivation was three or five times the content of the single culture (cultivating sesbania in uplands or single fish culture) (Liu et al., 1999).

Yellow River Delta is in the warm-temperate zone with semi-humid monsoon climate, four seasons and plenty of sunshine, and is therefore well-suited to temperate freshwater fish farming. In addition, Yellow River and impounding reservoirs are a reliable water source. However, shallow groundwater and high soil salt content may cause problems in agricultural production. Modern agricultural measures such as biological control and the agricultural dyke ponds can achieve desirable agricultural efficiency and generate considerable social and economic benefits.

Fig. 3 (Li, 2002; Zhang, 2007) showed typical patterns of the agricultural dyke pond in Yellow River Delta and the present value of net benefits. According to the total present value of net benefits, the order was Orchard-dyke-fish-pond (III) > Livestock-dyke-fish-pond (I) > Agriculture-dyke-fish-pond (II) > Paddy field (IV). It showed that orchard land-pool farming possessed the highest value. However, its yield was inferior to others at the beginning, but improved per year during the 30 years of land contract in China, surpassing crop land-pool farming first and then the livestock. From the economic net present value, the order was I > III > II > IV (Fig. 3). Initially, the net value of orchard land-pool farming showed lower yield than crop land-pool farming, but exceeded crop land-pool farming during the 30 years. From the present value of environment benefits, the order was III > II > I > IV (Fig. 3). Agricultural Dyke Ponds can combine fishery utilization and agricultural planting in saline-alkali land which is an effective stereo ecological agriculture system that can add areas for fresh-water fisheries and cultivation, as well as achieve efficient use of water resources in saline land of Yellow River Delta (Fig. 4).

5.2. Mangrove planting-aquaculture ecological coupling system

Aquatic plants can purify water. Mangrove is the only woody plant community that can survive in the intertidal zones. Researchers showed that sea areas with mangroves can achieve higher yield than those without because mangroves provide habitat for marine organisms. The cropping-breeding coupled system in the ecological transition zone between mangroves areas and shore seawater is a new circulating artificial ecosystem that can promote growth of organisms in the system as well as the marine aquaculture production. The system can significantly purify water and is a new sustainable development pattern. According to Liu et al. (2008b), the content of metals and metalloids in crab *Scylla serrata* from mangrove planting-agriculture systems in the coastal shore areas can be high, with Cd slightly above the limit (<0.5 mg/kg, wet weight) for edible oysters in China (but, concentration of Hg and As was below the critical limit).

6. Integrated technology of efficient agricultural utilization of salt-affected lands

China has a total area of saline-alkali soils of 3.6×10^6 ha, including 1×10^6 ha of coastal salt-alkali soils located mainly in Bohai coastal region and along Jiangsu coast, with the rest in the coastal areas of Zhejiang, Fujian and Guangdong (Yang, 2008). Some fundamental research on soil salinization was carried out in China, including properties and evolution of secondary saline soils in different regions and under variable natural conditions, basic characteristics and regional distribution of different saline soils (She et al., 2014), saline soil classification (Zeng, 1985), anthropogenic impacts on soil salinization (Liu et al., 2013) and the saline-alkali soil survey and mapping (Tao et al., 2013). The following section elaborates the improvement technologies and the measures for salt-affected soil in the coastal areas of China.

Leaching treatment, irrigation mode and drain pipe system are important measures of water conservation for improvement of coastal

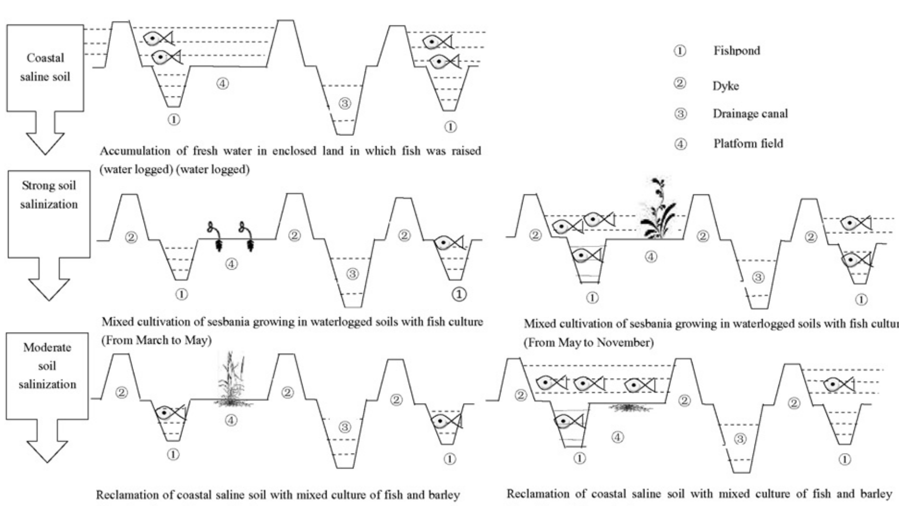

Fig. 2. A highly effective model of exploitation and utilization of coastal mudflat resources (Liu et al., 2003).

Table 2
Models of the highly efficient utilization of coastal land in humid zone in China (Liu et al., 2003).

Soil development regulation	Strong soil salinization	moderate soil salinization	mild soil salinization.
Models	Accumulation of fresh water in enclosed land in which fish was raised (waterlogged)	Mixed cultivation of sesbania growing in waterlogged soils with fish culture	Reclamation of coastal saline soil with mixed culture of fish and barley
Operating Procedures	The temperatures for fish growth should be above 12 °C. In October, filter-feeding fish such as silver carp and bighead carp was released for overwintering. In May of the following year, during the rainy season, the water level was about 1 m above the platform. Average grain output could reach 6000 kg/ha.	In October predatory fish such as carp and crucian carp was released for overwintering. In March of the following year, sesbania seed was planted on the entire platform. The rain water started to rise up to the platform during the growth period of sesbania after May. At the end of July, height of sesbania was up to 2 m. The water level was 1 m above the platform. The system utilized the symbiosis between fish and sesbania.	In October, filter-feeding and predatory fish were released according to a certain proportion for overwintering. At the same time, barley was sown on the platform with no tillage. On 20th May of the following year, the water lever rose up to 1 m above the platform after barley harvest. In October, water was drained off and the platform emerged. Then, fish was harvested and barley sown.
Ecological and economic benefits	This system can yield 45,000–60,000 yuan /ha. Soil desalting period can be shortened by up to 2/3. The content of soil organic carbon was increased by 1.2 g/kg per year. The yield of fish can achieve 6000 kg/ha, worth about 22,500 yuan /ha.	The soil organic carbon was increased by 1.3 g/kg soil, total nitrogen by 0.17 g/kg. The yield of sesbania seed reached 1500 kg /ha. Predatory fish could yield 5250 kg/ha, worth 24,000 yuan /ha.	4500 kg/ha barley and 6000 kg/ha fish were yield. Lots of residual roots under anaerobic condition were useful for organic matter accumulation and phosphorus and nitrogen cycling in soil.

saline soil. Irrigation and drainage systems can leach salt, discharge the surface water and partly the groundwater, decreasing salt content in soils in coastal areas. Discharging groundwater can lower the groundwater table that can decrease evaporation and capture more rainwater to enhance the effectiveness of salt leaching. Drainage by open channels is suitable for areas with abundant rainfall and large infiltration. Soils can be leached repeatedly to maintain lower salt content during the rainy season, followed by enhanced control of salt accumulation in the surface soil and secondary salinization. Lu et al. (2010) reviewed the ecological function of agricultural drainage ditches and found that open-ditch drainage was an important measure for preventing waterlogging, reducing soil salt content and promoting crop growth in coastal saline areas. In seasons with shortage of rain, water in ditches could complement the irrigation resources.

Technology of subsurface pipe drainage refers to placing underground a paralleled-pipe network for removing salt. It can utilize rainwater and irrigation water to leach salt from soil above the subsurface pipes and keep the saline water table under the critical depth. Soil salinization can be fundamentally ameliorated after 2 to 3 years. This technology originally appeared in the Netherlands and was introduced into China in 2000. In order to control the improvement effect of drainage, save water and land resources and reduce cost, it is essential to fix the irrigation and drainage parameters according to the local conditions, such as leaching quota and the optimal space and depth of subsurface drainage tubes. Researchers have carried out some experiments on determining engineering technical parameters. Wang and Qu (2008) discussed the calculation method of field drain spacing, considering the influence of evaporation and desalinization requirements in northern China.

Yu et al. (2012) reviewed the mechanisms of subsurface pipe drainage in saline-alkali soil improvement in agro-ecosystems. Constructing the raised platform field in Bohai coastal region could significantly accelerate water drainage and desalination (Zhang et al., 2010b). Salt leaching was more significant in slightly saline-alkali soils during rainy season (June to September) than in severely affected soils. Therefore, irrigation should be considered to supplement rainfall to enhance desalination. Subsurface pipes had the advantages of effective desalination, long usage time, and applicability in large areas in Hekou area of Dongying, Shandong (Wang and Jiang, 2005). The effects of subsurface drainage on saline soil improvement were also determined in Dayuzhang irrigation areas in Shandong (Zhang, 1988). In coastal salt-affected land of Tianjin, the main reason behind a significant improvement in soil fertility and a decrease in soil salinity and pH was construction of shallow and dense underground pipes and fertilization according to original local soil conditions (Zou et al., 2010a).

Mechanized deep ploughing and scarification cultivation treatment also play an important role in improving the heavy saline land. Deep ploughing in autumn can decrease farmland soil evaporation in winter and spring, as well as minimize salt accumulation in the topsoil. The pest in ploughed soil can be killed after drying in spring and winter. Besides, drying also can accelerate the process of maturity of soil. It is also important to adjust seedbed preparation and sowing based on water and salt transport under local conditions.

Many domestic scholars have studied in detail the spatial distribution and rates of water transport in some typical saline soils in China, including transfer balance in arid areas, especially under irrigation, water and salt movement under irrigation with saline or brackish water (Pang et al., 2010), transport of water and salt under freeze-thaw conditions (Bing and He, 2011), distribution of water and salt under drip irrigation (Min et al., 2014), numerical simulation modeling of water, heat and salt movement in soil (Han et al., 2001), as well as applying genetic algorithm and neural network to the salt and water transport (Zou et al., 2010b). In addition, modern technologies, such as EM31 and EM38 electromagnetic soil conductivity meters, GIS and high precision GPS, have been used widely in monitoring, assessment and early warning of salinization with improved accuracy and efficiency (Fang et al., 2005; Li et al., 2007).

Using biologic materials or plastic film mulching can reduce evaporation and accumulation of salt in topsoil, as well as increase soil organic matter accumulation. The soil bulk density was reduced, especially at

Table 3
Desalinization rate under different models (Liu et al., 1992).

Year	Waterlogged	Reclaiming cultivation in dry land	Idle cultivated land under natural condition
Desalinization in the second year	55.3	13.0	/
Desalinization in the third year	63.1	29.0	14.9

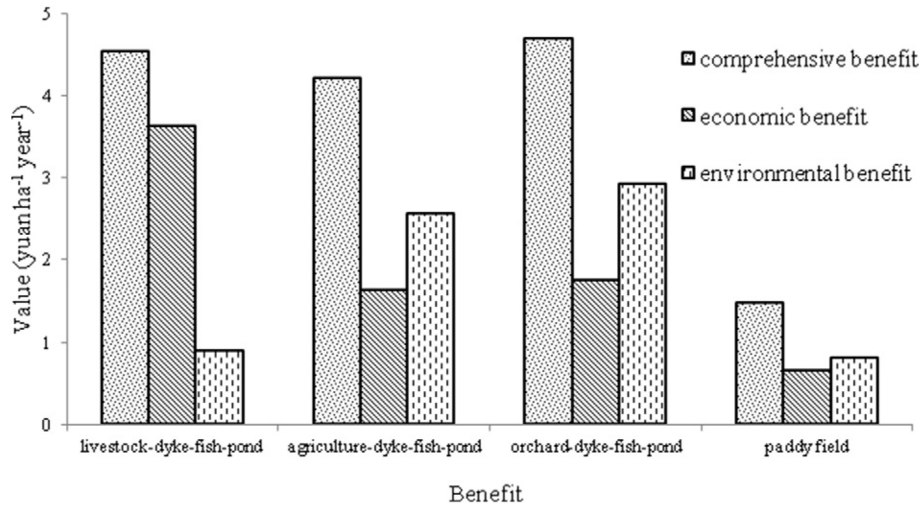

Fig. 3. Net Present Value (NPV) of four agricultural exploitation patterns. (Calculations were made on the basis of the 30-year duration of rural land contracting and management in China).

depths of 20–60 cm, whereas soil organic matter and moisture increased due to the effect of the combining measure of plastic film mulching and straw buried. Effects of farmyard manure, polyethylene film mulch and straw mulch and their combinations on coastal tidal flat soil were evaluated in northern Jiangsu province (Zhao et al., 2009). All treatments had a positive effect on soil water, salinity and crop growth. It was considered that the combination treatment of farmyard manure and straw mulch were better than plastic film mulching for soil water-salt control and crop growth promotion. Plastic film cover had significant effects on maintaining soil water content and decreasing salinity. The straw cover could retain rainwater, hinder the runoff and evaporation, and protect soil from secondary salinization.

Adoption of chemical methods to improve saline alkali soils in coastal mudflat areas is wide-spread. Soil amendments are effective in softening soil, holding soil moisture and improving soil chemical and physical properties, as well as enhancing crop yield. Main types of salt-affected soil include mineral materials, such as gypsum and vermiculite; water-soluble natural or synthesized polymer materials, such as agricultural residues; synthetic polymers, such as sodium polyacrylate, biological products from beneficial microorganisms and feces of livestock and poultry, etc.

Great achievements have got in domestic researches on soil salinity treatment and improvement in coastal China. Improvement experiment was carried out on coastal saline land in Tianjin (Shao et al., 2010). Compared with control, soil bulk density decreased by 2.3%–11.9% and the bulk porosity of soil, capillary porosity and corn yield increased, respectively by 0.2%–10.5%, 6.3%–26% and 10.2%–31%. The combination of straw, desulfurized gypsum, pig manure, humic acid and $FeSO_4$ was the best treatment for saline-alkali soil in Cangzhou, Hebei province (Liu et al., 2014). Frozen saline water irrigation could significantly enhance growth of Chinese tamarisk in the coastal salt land in Tianjin, and the best treatment was the combination of 1350 m^3 frozen saline water and 7500 kg phosphogypsum per hectare (Lian et al., 2011). Application of desulfurized gypsum supplemented with natural organic materials during irrigation could achieve effective desalting and preventing alkalization in saline lands (Shao et al., 2009). In coastal mudflat areas of Jiangsu province, Wang et al. (2013) tested five amendments to improve saline soil and found humic acid had the best effect. Yield of corn and rape in the humic acid treatment increased by 105% and 42%, respectively. In Yellow River Delta, the optimum combination for improving soil properties was gypsum (6.7 t/ha), cow dung (51 t/ha), straw (0), and water retention (0.64 t/ha) (Wang et al., 2012). Compared with the control, soil organic matter, available P, available N and available K of the best treatment increased by 114%, 828%, 1014% and 265%, respectively. Besides, soil pH and SAR decreased by 4.7% and 33%, respectively.

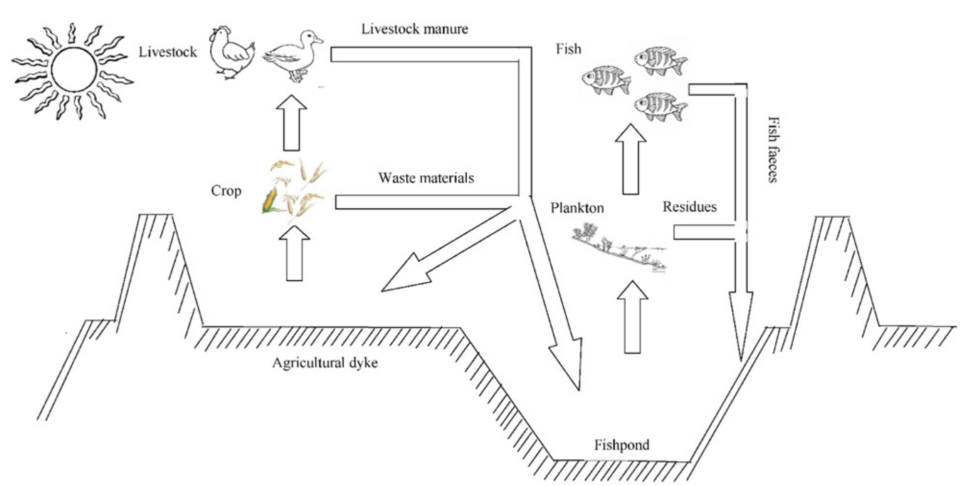

Fig. 4. Agricultural-dyke-fish-pond:An artificial ecosystem formed by interaction between land and water.

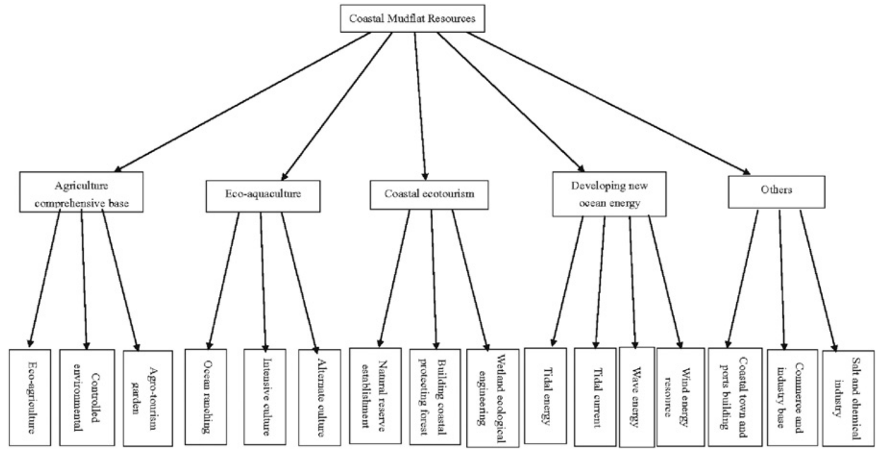

Fig. 5. Sustainable exploitation and development opinions for coastal mudflat areas.

7. Future perspectives and conclusion

Agricultural utilization is regard as the most traditional way on exploration of coastal shoal areas. However, now in the world it tends to apply the comprehensive patterns. In agriculture, it is necessary to build comprehensive development zones and construct green agricultural industries, such as eco-agriculture and ecological touring-agriculture. In aquaculture, the intensive aquaculture, industrialized operation is essential to be promoted. Soil in coastal shoal areas, boasting superior condition of high salt content, especially the chlorine salt, is very applicable for salt production. Yancheng city is located in Jiangsu province and is one of main salt production bases in China. In recent years, it has realized industrial restructuring including transformation into sea-bordering industries, sea or fresh water aquaculture, harbor and coastal town construction in some coastal areas with soil of sandy texture and unfavorable climatic. In terms of developing ecological tourism, construction of nature reserve is the most effective measure to protect the biodiversity and rare species in coastal wetland. It is essential to enhance the protective coastal forest and wetland natural preservation zones. Ocean energy, including tidal energy, tidal current energy and wave energy, as well as biological resources in coastal shoal areas will be developed vigorously. Coastal town and coastal port, important bases among commerce, town and industry, will be built under reasonable programming according to local condition. Meanwhile, it will increase the conservation for coastal wetland and resources conservation. In Fig. 5 we reviewed the sustainable exploration and development options for coastal mudflats.

Exploitation of coastal mudflat areas has significance internationally. For example, Yellow River Delta has the most complete, widest and youngest wetland ecology system in the temperate zone of China, and is a temporary habitat for migratory birds from East Asia, Australia, Pacific Rim and Northeast Asia. In order to realize the goal of wetland conservation in the "China's agenda 2 l" as soon as possible, the principles of green and sustainable development should be implemented during the whole process of exploitation of the coastal mudflat areas for comprehensive improvement of social capital, economic efficiency and ecological benefits.

Acknowledgements

The authors are grateful for the financial support of the National Key Project of Scientific and Technical Supporting Programs funded by Jiangsu Agricultural Science and Technology Independent Innovation Fund Project [No. CX(15)1005 and CX(12)1005-1], Ministry of Science & Technology of Jiangsu Province (Nos. BE2014374 and BY2015071-03),the Fundamental Research Funds for the Central University (KYZ201623 and YZ2016-1),Shuangchuang Talent Plan of Jiangsu Province and the National Major Basic Research Program of China (2013CB430403).

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