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The ecological cost of land reclamation and its enlightenment to coast sustainable development in the northwestern Bohai Bay, China

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Abstract

Land has been widely reclaimed in large area in coastal zones all over the world to relieve the pressure of land shortage, promoting social development and economic growth. Asia has become a focus of land reclamation with the rapid industrialization and urbanization. From the Binhai New Area of Tianjin to the Caofeidian New Area of Tangshan, the undergoing project of land reclamation on the northwest coast of Bohai Bay, China, is the largest in the world. To clarify the environmental issues and benefit sustainable development of the coastal zone, we conducted both retrospective and predictive assessments of the ecological cost caused by land reclamation on the northwest coast of Bohai Bay, China. We calculated the ecological costs of ten aspects of the four ecosystem services, i.e., supply, regulation, support and culture, with the monetary estimate approach. The results indicate that the ecological cost of the new land reclamation is US$971.9 million from 2000 to 2010 and that the cost will be US$702.1 million from 2010 to 2020. The costs of gas regulation and marine food supply account for the greatest parts of the total value. Suggestions for land reclamation oriented to sustainable development in the study area are put forward, including a rational planning based on the comprehensive evaluation, reducing the amount of land reclamation area, optimizing the structure of the reclaimed land, reclaiming land with the concept of "low impact development" and implementing ecological compensation mechanisms, etc.

Key words: coastal zone, land reclamation, ecosystem service, cost valuation, Bohai Bay, China

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1 Introduction

Coastal zone is the transition zone where the land meets the ocean. It is abundant in natural and cultural resources as a result of this superior geographic location. The sustainability of coastal zone is of great significance for the earth system and human society. Recently there are numerous researches indicating that the influence of human activities becomes more and more important in the coastal zone. Barbier et al. (2014) discussed the strategy of vulnerable population protection and put forward the short-term emergency response and long adaptive strategy. Giosan et al. (2014) pointed out that the environment of coastal zone must be maintained; otherwise a heave price will be paid to restore the coastal zone after the collapse. Among all the human activities influencing the coastal system, land reclamation acts as one of the most important driving forces. The land from the sea reclamation brings in tremendous social and economic benefits. With the increasing land area, more industrial and agricultural projects that require huge tracts of land are conducted. More and larger ports are constructed, promoting the development of logistics. The increased coastal land also gives impetus to the development of the coastal zone and the inland (Hoeksema, 2007). On the other hand, land reclamation also causes some problems that perturb the balance of ecological condition in the coastal zone (Chen et al., 2010).

Currently, a number of important international research programs such as LOICZ, IGBP, IHDP, GLOBEC, GOOS, OSLR and IMBER are concerned about the environmental effects of land reclamation from sea (Ma et al., 2014; Aerts et al., 2014), especially in Asia. Ma et al. (2014) pointed out that thousands of miles of coastal wetlands in China have been closed by sea dikes and the reclaimed speed runs up to 60 000 hm^2 per year in the 2010s, resulting in the significant decrease of biodiversity and ecosystem services. He et al. (2014) found that the ecosystem of coastal zone is depredating along with the economic development in China, suggesting that more strict, systematic and strategic measures are needed to protect the coastal ecosystem in China. Koh (2014) reported that the Korean tidal flat system is transforming from land reclamation to wetland protection. Murray et al. (2013) found

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over 740 000 hm^2 of tidal flat are reclaimed in East Asia's Yellow Sea, which account for 65% of the total tidal flat from the 1950s; they also proposed that actions should be taken to conserve the tidal flats with the collaborative and properly planned development strategies.

The northwest coast of Bohai Bay, from Tianjin Binhai New Area to Caofeidian New Area, is one of the largest land reclamation areas in the world (Yang et al., 2011). The advantage of this area among the harbors of Bohai Sea and the regional economy has been taken by constructing the Caofeidian Harbor and Industrial Area, Dongjiang Harbor Zone and Tianjin Lingang Industrial Area. Reclaimed land in Caofeidian Harbor and industrial area amounts to 310 km^2, as the largest single project of land reclamation in the world (Zhu and Xu, 2012). According to the regional planning agency, there will be more land reclamation from tidal flat and inshore zone to expand the Caofeidian New Area of Tangshan and Binhai New Area of Tianjin. Simultaneously, the environment of the northwest coast of Bohai Bay has been changed dramatically, leading to numerous damages (Yang et al., 2011). Among such damages, ecological cost has been ignored for a long time (Zhang et al., 2010a). Now it deserves more attention. One consideration might be to implement quantitative and monetary evaluation, the results of which can be integrated into the economic analysis, planning, and decision-making of the coastal zone.

When considering the ecological cost of land reclamation, people always focus on the short-term biomass loss rather than the permanent ecological cost. One reason is that the ecosystem services are viewed as public goods without a defined market price. They are provided by a complex and dynamic coastal ecological system and thus it is difficult to evaluate the ecological cost. It is impossible to precisely compare the ecosystem services cost to engineering, economic and financial evaluation (Chen et al., 1999). Nevertheless, after decades of development in the quantitative research of environmental resources and ecosystem services, quantities of methods for monetary evaluation of ecological cost from land reclamation have emerged, including direct market methods (market price method, productivity change method and human capital method, etc.), non-market methods (shadow engineering method, prevention cost method, recovery cost method, travel cost method and hedonic price method, etc.), investigation and evaluation methods and the results consultation methods (Zhang and Sun, 2009; Chen and Wang, 2009; Wang et al., 2009, 2010a).

Effective technical methods are needed to figure out the ecological loss caused by land reclamation from sea. Based on the ecosystem services evaluation method proposed by Costanza et al. (1997) and de Groot et al. (2002), some researchers evaluated the ecological cost from land reclamation in many coastal zones, including Haimen City, Lianyungang City, Nantong City of Jiangsu Province (Xiao et al., 2011; Zhang and Sun, 2009), Qingdao City of Shandong Province (Zhang, 2012), Xiamen City of Fujian Province (Peng et al., 2011) and so on. However, it has been rarely reported about the coast of the large-scale land reclamation in the Bohai Bay. The previous studies did not take the differences of the ecosystem services between the tidal zone and the ocean into account. This could lead to the loss of the precision in the evaluation. The depths of the seas that may affect ecosystem services have not been considered, either.

In this study, we estimated the value of the ecological cost of land reclamation from the tidal zone and inshore sea in both the past and the upcoming ten years on the northwest coast of Bohai Bay in China, presenting a measure to estimate the value of ecosystem services in the north coast of China.

2 Materials and methods

2.1 *Study area*

The northwest coast of Bohai Bay extends from Binhai New Area of Tianjin to Caofeidian New Area of Tangshan (Fig. 1). The Binhai New Area of Tianjin was established in 1993. It became a national planned special economic zone in 2006. Caofeidian became an industrial area in 2005, representing a newly developed district, integrated into the overall national plan in 2010. The Bohai Bay has some special features, including the low slopes, rich sediment sources and small coastline radian, all of which are in favor of the land reclamation in large scales. In the 21st Century, the demand for land resources has been intensified in the study area with the dual drivers of economic and political development, accelerating the process of land reclamation, which in turn leads to the permanent changes of the coastline and appropriation of oceanic resources.

Fig. 1. Location of the study area.

2.2 *Calculating the land reclamation area*

There are four steps to calculate the land reclamation area: (1) to obtain the 2000 and 2010 coastline of the study area using the supervised classification method integrated with artificial visual interpretation of the Landsat ETM+/TM images (track number is 122/33; acquisition time was June 10, 2000 and August 17, 2010), (2) to protract the coastline of 2020 based on the documents of the master plan of the Binhai New Area of Tianjin, the Caofeidian New City of Tangshan and the Tianjin Port, (3) to derive the new-built coastal dike, the occupied tidal and sea zone due to land reclamation for the past decade and the future decade by overlapping the coastline of 2000, 2010 and 2020 with an administrative boundary and sea charts, (4) to calculate the lost area and volume of the sea owing to the land reclamation during 2000–2010 and 2010–2020 with the base map of DEM.

2.3 *Evaluation model for ecological cost from land reclamation*

According to previous studies (Millennium Ecosystem Assessment, 2003; Costanza et al., 1997), the ecosystem services are divided into four categories and 20 detailed aspects. We selected ten kinds of ecosystem services of the four categories depending on the importance and local conditions in the study area (Table 1). We calculated the values of the ten selected ecosystem services of the land reclamation area with the market value method, shadow engineering method, replacement cost method and results consultation method, to constrain the total cost of the ecosystem services of the study area.

Table 1. The ecosystem services to be considered of the coastal zone

Category of ecological services	Content	Sub-service
Supply service	products gained from ecological system	food supply, genetic resources supply
Regulation service	benefits from regulation of ecological process	gas regulation, interference regulation, nutrient cycle function, self-purification capability
Support service	requisite support of other ecological system	primary production, biodiversity maintenance
Cultural service	non-material interests gained from ecological system	research & culture, leisure & tourism

Note: The classification and indices are derived from Millennium Ecosystem Assessment (2003) and Costanza et al. (1997).

2.3.1 *Cost of supply service*

(1) Food supply

Marine fishery resources are renewable resources. As long as being exploited reasonably, they can produce lasting benefits. Therefore, we applied the direct market method and estimated the cost of food supply service from land reclamation with the benefits of marine-culture and fishing (Wang, 2010b). The calculation formula is as follows:

$$F_1 = \frac{Y_f}{S_0} p\alpha S, \qquad (1)$$

where F_1 is the cost of food supply service caused by land reclamation (US\$/a), Y_f is the total production of marine fishery (t), S_0 is the area of marine fishery (km²), p is the mean market price of marine production (US\$/t), α is the mean profit rate of marine-culture, and S is the area of occupied marine fishery by land reclamation (km²).

(2) Genetic resource supply

Coastal ecological systems are important for marine fauna and flora that can supply genetic resources for human beings. The results consultation method is utilized, and the formula (Li and Fan, 2004) is as follows:

$$F_2 = gS, \qquad (2)$$

where F_2 is the value of lost genetic resource supply from land reclamation (US\$/a), g is the genetic resource supply value of per unit area of coastal zone (US\$/km²), and S is the area occupied by land reclamation.

2.3.2 *Cost of regulating service*

(1) Gas regulation

Phytoplankton and other plants in the coastal ecological systems absorb carbon dioxide and release oxygen to maintain the quality of air and regulate the climate. According to the photosynthesis formula, there are 1.63 g CO_2 being absorbed and 1.19 g O_2 being released to produce every 1 g dry matter. The primary productivity per unit area of occupied tidal zone and sea can be obtained through investigation to estimate the amount of CO_2 absorbed and O_2 released. The gas regulation value of coastal ecological system will be calculated from the cost of CO_2 fixation and O_2 production (Woodward and Wui, 2001). The formula is as follows:

$$F_3 = (1.63C_1 + 1.19C_2)(X_t S_t + X_h S_h), \qquad (3)$$

where F_3 is the value loss of gas regulation (US\$/a), X_t and X_h are the primary productivity (calculated by carbon, g/m²) per year of tidal zone and sea, S_t and S_h are the occupied area of tidal zone and sea (km²), and C_1 and C_2 are the cost of fixation of carbon dioxide and oxygen production.

(2) Interference regulation

As the first line of defense against storm surges and sea waves, the coastal zone can reduce the erosion risk for the nearshore areas. The human activities over newly reclaimed land will be safeguarded by constructed dikes. Accordingly, the ecological cost of land reclamation can be calculated with the shadow engineering method, namely, the construction and maintenance cost of the newly built dike that is used in land reclamation (Wang et al., 2009). The formula is as follows:

$$F_4 = Plw(h+d)(1+\rho n)/n, \qquad (4)$$

where F_4 is the interference regulation cost caused by land reclamation (US\$/a); P is the engineering cost per unit volume of dike (US\$/m³); l and w are the length and width of the newly built dike (m) respectively; h and d are the height of the newly built dike above and below sea (m) respectively; ρ is the proportion of the dike maintenance cost in total engineering cost per year; and n is service life of the dike.

(3) Nutrient cycle function

In a nutrient cycle, nutrients such as N and P circulate through the marine organisms, water and sediments, thus sustaining the coastal ecosystem. The tidal zone and sea mainly function as a sink in this cycle. If there were no marine ecosystems, human beings would have to remove the nutrients such as N and P from surface runoff artificially (Ou et al., 2006). Therefore, the value of the nutrient cycle cost of coastal zone can be estimated by calculating the cost of remaining N and P in the tidal zone and sea.

$$F_5 = (C_N X_{tN} + C_P X_{tP})S_t + (C_N X_{hN} + C_P X_{hP})S_h, \qquad (5)$$

where F_5 is the value lost by nutrient cycle function (US\$/a), C_N and C_P are the removal costs of N and P (US\$), X_{tN} and X_{tP} are the removal capacity per unit area of N and P of the tidal zone (t/km²), X_{hN} and X_{hP} are the removal capacity per unit of N and P of sea (t/km²), and S_t and S_h are the areas of occupied tidal zone and sea (km²).

(4) Self-purification capacity

Land reclamation undermines the self-purification capacity of seawater to degrade containments and to recover from degradation. Since there are only a few bays along the northwest coast of Bohai Bay, with little impact on the tide absorption ability, we primarily take into account the cost of biochemical removal due to reduced seawater. Given that the ecosystems' capacity to absorb N and P has been considered in nutrient cycle function, it is necessary to calculate the purification capacity of chemical oxygen demand (COD). The calculation formulas are as follows (modified from Chen and Wang (2009)):

$$F_6 = C_{\rm COD} \times X \times V \times 10^{-3}, \quad (6)$$

$$X = (C_0 - C_0 \times {\rm e}^{-kt}) \times 365 \times 10^{-3}, \quad (7)$$

where F_6 is the value of the cost of self-purification capacity of seawater (US$/a), $C_{\rm COD}$ is the processing cost of COD (US$/t), X is the degradation rate of seawater for COD (kg/m^3), V is the volume of seawater occupied by land reclamation (m^3), namely volume of reclaimed land, k is the degradation rate constant (d^{-1}), C_0 is the initial concentration of COD (mg/L), and t is the reaction time (d).

2.3.3 *Cost of support service*

(1) Primary production

The estimation is developed by transforming the relationship between primary productivity and mollusk, the weight relationship of mollusk and shellfish and the market price and profit rate of shellfish and so on (Xiao et al., 2011; Chen, 1994). The estimation formula is as follows:

$$F_7 = (\rho \frac{X_{\rm t} C}{\beta} S_{\rm t} + \rho \frac{X_{\rm h} C}{\beta} S_{\rm h}) p \times \alpha / 10, \quad (8)$$

where F_7 is the cost of the primary product (US$/a), ρ is the rate of gross weight of shellfish on weight of shellfish's flesh, β is the proportion of Carbon in shellfish, $X_{\rm t}$ and $X_{\rm h}$ are the primary productivity per unit area of tidal zone and inshore sea (g/(m^2·a)), $S_{\rm t}$ and $S_{\rm h}$ are the occupied area of tidal zone and inshore sea resulting from land reclamation (km^2), C is the efficiency of primary products transforming to mollusc (%), p is the market price of shellfish products (US$/kg), and α is the profit rate (%).

(2) Biodiversity maintenance

A natural coastal zone usually acts as significant spawning grounds, winter refuge and asylum fields for migrant birds, fish, and large mollusks, etc. Thus it plays a key role in maintaining the biodiversity. Under the pressure of the land reclamation in the large scale on the northwest coast of Bohai Bay, the migrant birds used to live through the winter in the mudflats of Tianjin have left away, and the biological communities of Tianjin coastal zone are on the verge of collapse (Yang et al., 2011). The estimation formula of value of biodiversity maintenance is as follows:

$$F_8 = E_{\rm h} S_{\rm h} + E_{\rm t} S_{\rm t}, \quad (9)$$

where F_8 is the cost of biodiversity maintenance from land reclamation (US$/a), $E_{\rm t}$ and $E_{\rm h}$ are the ecological cost of the tidal zone and inshore sea area per unit resulting from land reclamation (US$/km^2).

2.3.4 *Cultural function cost*

(1) Research and culture

The beaches and seas have always been a great inspiration for religion, literary creation, and the entertainment industry. They also provide scientists with a valuable location and rich contents to conduct researches. The result consultation method (Xiao et al., 2011) is used to calculate the research and culture cost of land reclamation in the coastal zone. The formula is shown as follows:

$$F_9 = r \times S, \quad (10)$$

where F_9 is the research and culture cost of ecological system caused by land reclamation (US$/a), r is the research and culture service value per unit area of coastal zone (US$/km^2), and S is the occupied area by land reclamation.

(2) Leisure and tourism

Thanks to its attractive sandy beaches, seawater and coastal wetlands, the ecological systems of the coastal zone are of significant leisure and tourism value. It offers a location for leisure, bird watching, photography, fishing and so on for tourists to enjoy themselves (Peng et al., 2005). The results consultation method is employed and the formula is as follows:

$$F_{10} = R_{\rm t} S_{\rm t} + R_{\rm h} S_{\rm h}, \quad (11)$$

where F_{10} is the leisure and tourism cost of ecological system caused by land reclamation (US$/a), $R_{\rm t}$ and $R_{\rm h}$ are the leisure and tourism cost per unit area of tidal zone and inshore sea caused by land reclamation (US$/km^2).

2.4 *Parameters of ecological cost model*

As shown in Table 2, the parameters are selected from the statistical material and relative studies in the study area and nearby.

3 Results and analyses

3.1 *Process analyses of land reclamation*

As displayed in Fig. 2, the newly built dikes of 2000–2010 and newly planned dikes of 2010–2020 are protracted with the correlation analysis using ArcGIS. Between 2000 and 2020, about 608 km sea dikes respectively were already built or will be built along the northwest coastline of the Bohai Bay. The area of land reclamation from tidal zone and sea will reach 950 km^2 while the volume of land reclamation will increase to 1.19×10^9 m^3 (Table 3). The land reclamation and the dikes constructed in the first decade account for two-thirds of the twenty-year project, in terms of both the length and area. These new dikes and reclaimed land are mostly located in the tidal zone. By contrast, more lands are reclaimed on the occupied inshore sea area during the second decade, reaching 57% in terms of area. The area of newly reclaimed land, length of new dikes and volume of occupied sea derived above will be used to calculate the ecological cost caused by land reclamation.

3.2 *Ecological cost from land reclamation*

We developed the ten formulas for evaluating the ecological cost of land reclamation, to estimate the total ecological cost resulting from land reclamation in the study area. According to the results, the estimated ecosystem services cost by newly added land reclamation in the past decade (2000–2010) and future decade (2010–2020) are US$176.7×10^6 in 2010 and US$127.7×10^6 in 2020, respectively. If the land reclamation projects are conducted evenly in the decade, the ecological cost by newly added land reclamation in the past decade and future decade are 5.5 times of the ecological cost per year, i.e., US$971.9×10^6 and US$702.1×10^6 respectively. The calculated values of ecological costs are shown in Fig. 3. Calculated estimates are about 161×10^3 US$/km^2 during 2000–2010 per year or 202×10^3 US$/km^2 during 2010–2020 per year, which are similar to the estimates in other regions,

Table 2. Sources of parameters of ecological cost evaluation

Formula number	Value of parameters	Note
(1)	Y_f=181 634 t (for 2000–2010) or 176 328 t (for 2010–2020), S_0=3 593 km² (for 2000–2010) or 3 246 km² (for 2010–2020), P=4.3×10³ US$/t, α=25%	Y_f, S_0 are data of 2000 (for 2000–2010) or 2010 (for 2010–2020) obtained from Statistical Yearbook of Tianjin and Tangshan.
(2)	g=5.9×10³ US$/(km²·a)	Genetic resource value per unit area of ecological system is 6–112 US$/hm²; and the average value is taken from Li and Fan (2004).
(3)	X_t=54.75 g/(m²·a), X_h=564.39 g/ (m²·a), C_1= 150 US$/t, C_2=57 US$/t	X_c is taken from Li and Fan (2004), X_h is taken from Tan and Shi (2006), C_1 is taken from Woodward and Wui (2001), C_2 is taken from Board of Biodiversity Research Report of China (1998).
(4)	P=13.1 US$/(m³·a), h=7 m, w=12 m, ρ=2%, n=100	P is taken from Nantonghexin Construction Survey and Design Institute Limited (2008); h is selected according to recurrence period of one hundred year (Li et al., 2009); w is selected according to standard of project design of dike protection (GB50286-1998) and the example of Caofeidian; ρ is taken from Wang et al. (2010b).
(5)	C_N=714 US$/t, C_P=14.3×10³ US$/t, X_{tN}=0.038 5 t/(km²·a), X_{tP}=0.004 2 t/(km²·a), X_{hN}=16.7 t/(km²·a), X_{hP}=3.25 t/(km²·a)	C_N, C_P are taken from Wang (2006); X_{tN}, X_{tP} are taken from Ou et al. (2006); X_{hN}, X_{hP} are taken from Zhang and Sun (2009).
(6)	C_{COD}=614 US$/t	The COD-treat cost is selected according to the data used in setting standard of national sea area usage fee.
(7)	k=0.047 d⁻¹, C_0=3 mg/L	k is derived from Ji et al. (1999); C_0 is estimated based on marine environmental quality bulletin of Bohai area in 2008 and standard of national sea-water quality (GB 3097-1997).
(8)	C=10%, β=8.33%, ρ=5.52:1	C is taken from Tait and Dipper (1998); β, ρ are taken from Lu et al. (1999).
(9)	E_t=16.9×10³ US$/(km²·a), E_h=13.1×10³ US$/(km²·a)	E_t and E_h area derived from Costanza et al. (1997).
(10)	r=7×10³ US$/(km²·a)	r is taken from Costanza et al. (1997).
(11)	R_t=65.8×10³ US$/(km²·a), R_h=8.2×10³ US$/(km²·a)	R_t and R_h are taken from Costanza et al. (1997).

Note: Due to exchange rate fluctuation between RMB and US dollar from 6–8 approximately in the recent ten years, so 7:1 is chosen as the fix rate where the exchange is needed.

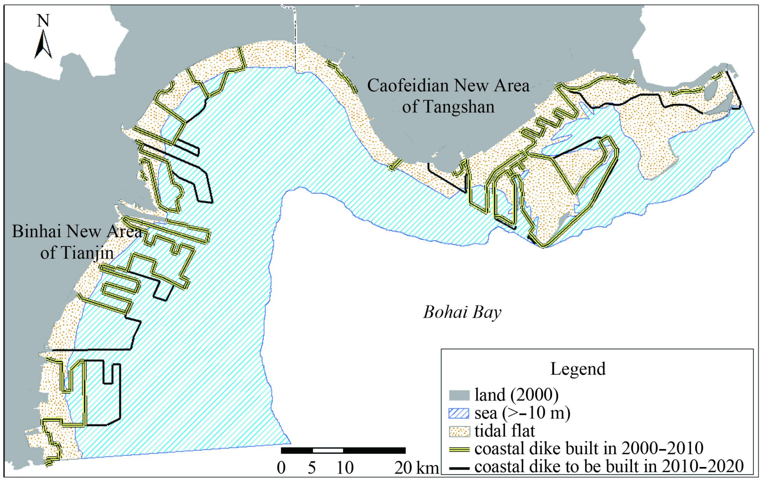

Fig. 2. Sketch map of land reclamation along the northwest coast of Bohai Bay during 2000–2020.

Table 3. Statistical table of land reclamation along the northwest coast of Bohai Bay during 2000–2020

	Area reclaimed from the sea/km²		Length of new-built coastal dike/km		Volume reclaimed from the sea/m³		Volume of newly built dike/m³	
Time period	2000–2010	2010–2020	2000–2010	2010–2020	2000–2010	2010–2020	2000–2010	2010–2020
Reclaimed area	603	347	400	208	7.06×10⁸	4.82×10⁸	3.19×10⁶	6.74×10⁶
Tidal flat of reclaimed	400	150						
Sea of reclaimed	203	197						

China. For example, the ecosystem services of Jiaozhou Bay are estimated to be 2 260 US$/hm² per year (Zheng et al., 2012), and the wetland value of China was around 2 957 US$/hm² per year (Xie et al., 2008).

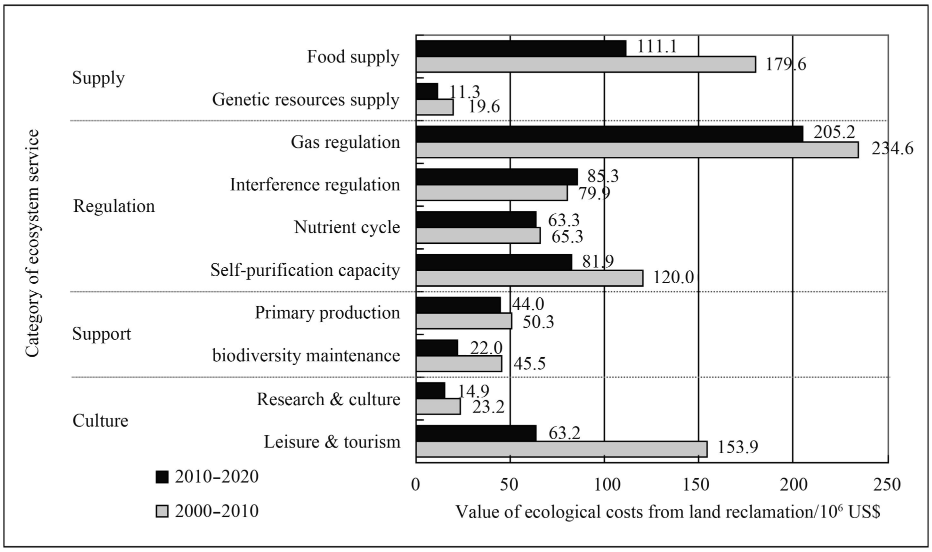

Fig. 3. Classified value of ecological costs from land reclamation on the northwest coast of Bohai Bay.

Between 2000 and 2010, the cost caused by land reclamation in gas regulation, food supply, leisure and tourism and self-purification capacity is tremendous, reaching US$234.6×$10^6$, US$179.6×10^6, US$153.9×$10^6$ and US$120.0×$10^6$ respectively. Between 2010 and 2020, the cost of gas regulation, food supply, interference regulation and self-purification capacity resulting from land reclamation will be large as well, reaching US$205.2×$10^6$, US$111.1×10^6, US$85.3×$10^6$ and US$81.9×$10^6$, respectively. Although in the future decade, the area of land reclamation is only 57.5 percent of that in the past decade, the ecological cost is 72.2 percent of that in the past decade. The cost in some specific aspects is even higher than in the past decade. For example, as land reclamation occupies more offshore sea areas, there will be higher project fees per unit area of the dike, resulting in more regulation services and thus increasing costs of the occupied area.

Furthermore, even if land reclamation projects were stopped in 2020, there would still be an ecological cost as high as US$27.8×$10^9$ on the northwest coast of Bohai Bay as a result of the land reclamation in the 21st Century. These environmental costs should be taken into account together with other costs of land reclamation, such as engineering and construction costs. All these costs should be taken into account when evaluating the land reclamation project with the cost-effective analysis, which could also serve as a guide for the land reclamation projects in the future.

4 Discussion

4.1 *The experience of land reclamation from sea in the world*

In Holland, a quantity of coastal wetlands and estuaries were reclaimed to agricultural and industrial lands through the three tides of land reclamation since 16th Century, one third of which is below sea level now (Hoeksema, 2007). Large-scale land reclamation projects were also implemented in the Tokyo Bay and Atsumi Bay of Japan, Nile Delta of Egypt and Saemangeum of South Korea (Hayashi and Miyakoshi, 2009; Sohma et al., 2009; El Banna and Frihy, 2009; Song et al., 2013).

We summarized the following three points about the reclamation by analyzing the history of land reclamation from sea. (1) Land reclamations are mainly conducted in Asia while rarely implemented in America and Europe with some individual exceptions such as Holland. This is related to the lower population densities and lower demand for land whereas the rising demands for protecting social and environmental value in post-industrial era in the American and European countries. (2) The land reclamation of all relative countries generally peaked during the period of rapid industrialization. After industrialization and urbanization, land reclamation was slowed down owing to the increasing public awareness of environment protection and the more comprehensive government policies. Meanwhile, the services-oriented economies increase the demand for higher quality land in the seaside than those depend on the primary and secondary industries. Most countries have abandoned the large-scale land reclamation projects. (3) Generally, the coastline where reclamation occurs has gone through the stages of "farmland (including fishery and salt pond) -traffic hub (including harbor and airport) - industry/urban - tourism". Shorelines changes reflect the evolution of land reclamation from primary industry to secondary industry and finally to tertiary industry.

As a massive human intervention, land reclamation from sea brings in great ecological damage to the coastal zone. In order to balance the regional development and environment protection in the coastal zone, some measures are taken and proved to be effective in other regions. These measures include: controlling the scale of land reclamation strictly, raising the efficiency of land use in reclaimed area, optimizing the process of land reclamation, and adjusting the location and geometric construction of reclaimed land according to environment conditions, etc. Our nation is now in a key period of rapid industrialization and urbanization, demanding for a quantity of affordable lands. It is necessary to learn lessons of land reclamation from other regions, pay more attention to the ecological and environmental influences, and adjust and control activities of land reclamation, so as to ensure the sustainability of coastal zone.

4.2 *Suggestions for land reclamation oriented to sustainable development in the northwestern Bohai Bay*

From the 1970s, many projects of land reclamation from sea were implemented in the northwest coast of Bohai Bay successively, and therefore this region becomes the largest zone of artificial land reclamation from sea in China at present. To minimize the environmental impacts from land reclamation is the key issue to achieve more sustainable development of this region. Three aspects of advice are put forward as below.

(1) Before implementation of the land reclamation project, the several principles below should be followed and always kept in mind: to consider fully the complexity of the land and sea, the integrity of nature, society and economy; to coordinate the people-land relationships to achieve maximum economic, social and ecological benefits; to reestablish a dynamic balance between the reclamation region and nearby regions as soon as possible; and to fully consider the geographical, ecological and social conditions to make appropriate allocations and land use planning. The benefits and costs of the planned land reclamation project should be calculated. With all the above principles followed, the project can be considered to carry out, and further research and planning will be needed to determine the location and the scale of land reclamation.

(2) During the implementation of the land reclamation project, some suggestions may be beneficial, including to reduce the amount of land reclamation area in Tianjin Binhai New Area, to optimize the structure of Caofeidian Port and Tianjin New Port, to maintain the natural system functions of the northwest coast of Bohai Bay, to strengthen the supervision and administration by the government, to apply the concept of "low impact development" to accelerate ecological system reconstruction and improve the environment in the reclaimed zone.

(3) After implementation of the land reclamation project, ecological compensation mechanisms are needed. The cost of land reclamation includes not only the economic cost but also the external social, environmental and ecological cost. However, the ecological cost has long been ignored because it is not expressed in the objective terms to decision makers, producers and developers who prefer the economic terms (Häyhä and Franzese, 2014). "Eco-compensation" is clearly going to be a contribution made by Chinese researchers' effort (Zhang et al., 2010b) and this study contributes to the evaluation of ecological cost based on the ecological system services of China. The internalization of the ecosystem service will help address the environmental problems in the process of coastal zone development. They may finally facilitate the sustainable development strategy in decision-making, planning, implementation and development of land reclamation.

5 Conclusions

The cost of land reclamation includes not only the economic cost, but also the external environmental costs. However, because of the dual pressure of market economics and regional policies, attention to the ecological cost has been long ignored or dismissed. Decision-makers, producers and developers have a preference for economic benefits rather than social or environmental benefits and they reluctantly include ecological cost resulting from land reclamation in their considerations. Based on the theories and methods of ecological services and market and nonmarket valuation using the benefit transfer methods, this research studied land reclamation from tidal zone and inshore sea of the northwest coast of Bohai Bay in the past and future decades to evaluate ecological cost in terms of provision, regulation, support and culture.

This study calculated the ecological cost caused by land reclamation from 2000 to 2010 in the northwest coast of Bohai Bay. The results indicate that the total ecological cost is about US$971.9 million, among which the most severe cost comes from gas regulation, food supply, leisure and tourism, and self-purification capacity. According to the reclamation plan, the ecological cost of land reclamation is about US$702.1 million from 2010 to 2020, among which the most severe cost comes from gas regulation, food supply, interference regulation and self-purification capacity. The ecosystem services lost per unit area of reclaimed area is estimated to be 0.16 US$/m^2 in the period from 2000 to 2010, while in the period from 2010 to 2020 the cost per unit area of newly reclaimed area is estimated to be 0.2 US$/m^2 per year. The results are consistent with the previous researchers' estimates. According to the recent charge standard of sea area utilization in China, the charge of the reclaimed land from sea of the study area is 15–19 US$/m^2, which could only offset the ecological cost from land reclamation within four or five decades. In addition, there may be other cost that has not been calculated yet may cause future costs, such as subsidence, flooding, weed invasion, algal blooms and contamination. It is thus likely to be an underestimate of the ecological cost from land reclamation of the study area. Therefore, we should take into account the local ecosystem services cost in policy-making process, consider higher charges for sea area utilization and invest more to rebuild the ecological systems of the study area.

As a social and economic hotspot as well as an ecologically fragile zone that is subject to sea level rising, the land reclamation on the northwest coastline of Bohai Bay has caused permanent changes to coastal land-use types and environment, leading to problems in resources, environment and human-land relationships. The monetary estimate of ecological cost caused by land reclamation will be helpful to find the environmental issues and benefit sustainable development of the coastal zone. It should be noted that, due to the limitations of the methods and data, the results are involved with some uncertainties, thus the sensitivity testing of the estimates and the static time assumptions should be analyzed for point-in-time estimates in the future studies.

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