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Reclamation history and development intensity determine soil and vegetation characteristics on developed coasts

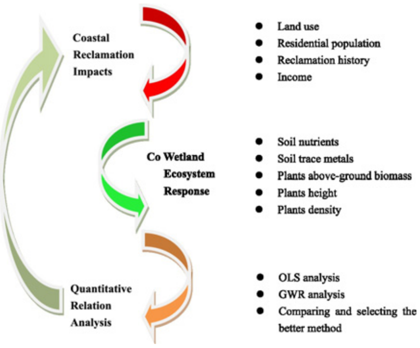
Shubo Fang [a,b,*], Xiaobo Jia [c], Qingteng Qian [a], Jun Cui [d], Grace Cagle [b], Aixin Hou [b]

[a] College of Fisheries and Life Science, Shanghai Ocean University, Shanghai 201306, PR China
[b] Department of Environmental Sciences, College of Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA
[c] Laboratory of Riverine Ecological Conservation and Technology, Chinese Research Academy of Environmental Sciences, Beijing 100012, PR China
[d] Jiangsu Provincial Key Laboratory for Bioresources of Coastal Saline Soils, Yancheng Teachers University, Yancheng, 224002, PR China

HIGHLIGHTS

- Soil and vegetation characteristics responded significantly to reclamation impacts.
- Human impact index was the most reliable variable reflecting reclamation impacts.
- Residential population was another better variable reflecting reclamation impacts.
- Coastal reclamation was highly spatial dependent in shaping the coastal ecosystems.
- Spatial explicit models should be further developed to research coastal reclamation.

GRAPHICAL ABSTRACT



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ABSTRACT

The question of where and how to carry out reclamation work in coastal areas is still not well addressed in coastal research. To answer the question, it is essential to quantify the impact of reclamation and the associated ecological and/or environmental responses. In this study, ordinary least square (OLS) analysis and geographical weighted regression (GWR) analysis were performed to identify the reclamation variables that affect soil and vegetation characteristics. Reclamation related variables, including residential population (RP), years of reclamation (YR), income per capita (IP), and land use-based human impact index (HII), were used to explain nitrate, ammonium, total phosphorous, and heavy metals in soil, and the height, density, and above-ground biomass of native hydrophytic vegetation. It was found that variables IP, RP, and HII could be used to explain the height of Scirpus and *Phragmites australis* as well as above-ground biomass with a R^2 value of no >0.55, and almost all the variables could explain the hydrophytic vegetation characteristics with a higher R^2 value. In comparison to OLS, GWR more reliably reflected the reclamation effects on soil and vegetation characteristics. By GWR analysis, total soil phosphorous, and nitrate and ammonium nitrogen could be explained by RP, YR, and HII, with the highest Ad-R^2 value of 0.496, 0.631 and 0.632, respectively. Both of the GWR and OLS analysis revealed that HII and RP were the better variables for explaining the soil and vegetation characteristics. This work demonstrated that coastal reclamation was

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* Corresponding author at: Department of Environmental Sciences, College of Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA.
E-mail address: sfang4@lsu.edu (S. Fang).

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highly spatial dependent, which sheds a light on the future development of spatial explicit and process-based models to guide coastal reclamation around the world.

1. Introduction

As an important countermeasure against lack of land resources, coastal wetlands reclamation has been carried out worldwide for centuries (An et al., 2007; IHDP, 2013; Zhang et al., 2013; Cui et al., 2016). Due to the negative impacts associated with coastal reclamation, how to balance coastal development and coastal wetlands conservation has become a focal issue for coastal areas (Mukai, 2010; Wolanski, 2013; Diop et al., 2014; Naser, 2014; Duan et al., 2016; Olewiler et al., 2016). Where and how to carry out the coastal reclamation project are urgent questions needed to be answered for coastal development, not only to governments and the coastal science community, but also to other coastal stakeholders (CAS, 2011; Cui et al., 2016). Also, managing human activities is the central task for conserving coastal natural resources (Mora et al., 2011; Loughland et al., 2012; Wang et al., 2013; Reyna et al., 2016). Quantifying human disturbances and the associated ecological responses, and identifying the possible thresholds with which coastal ecosystems respond to the human disturbances are still the pending questions for human activities management (Sun et al., 2011; Sun et al., 2012; Li et al., 2013).

Reclamation time and land use have been reported to affect the coastal soil desalination process (Kwak et al., 2008). Sun et al. studied the impacts of reclamation time and land use on soil properties in the Yangtze River Estuary, China (Sun et al., 2011). They found soil moisture, soil salinity, soil electric conductivity, and soil particle size decreased while soil organic matter increased with reclamation time (Sun et al., 2011). Farmlands contributed most to the soil function maturity process. Reclamation time and land use types were the main factors influencing soil physical and chemical properties in the reclamation area (Sun et al., 2011). In the coastal area of Jiangsu Province, East China, Yin et al. also found that soil salinity decreased with reclamation time and the land use conversion from tidal flats to fish ponds and then to agricultural lands could efficiently affect soil desalination process (Yin et al., 2016). Li et al. investigated the effects of land use intensity on soil nutrient distribution after reclamation in the Yangtze River Estuary (Li et al., 2013). They found that the spatial distribution of soil organic matter, available phosphorous, and nitrate nitrogen were the combined effects of reclamation time and land use type since reclamation (Li et al., 2013).By soil ^{15}N abundance analysis, Kwak analyzed soil nitrogen sources and dominant soil dynamic processes (Kwak et al., 2008). Not as expected, farming fertilizer inputs were not the main sources of soil nitrogen but atmospheric N_2 fixation and N deposition. Nitrification, not denitrification, was the dominant dynamic process that caused ^{15}N enrichment (Kwak et al., 2008). In Bay of Biscay, North coast of Spain, Fernandez et al. found that soil chemical and functional changes and soil horizons depended strongly on factors of tidal influence and land use (Fernandez et al., 2010).

Coastal reclamation also affects coastal plant and microbial community features. Sun et al. researched natural plant community distribution and impacting factors in the reclamation zones of Yangtze River Estuary (Sun et al., 2012). They found that species richness, species diversity, and above-ground biomass increased with reclamation years (Sun et al., 2012). With the increase of land use intensity, species richness and species diversity first increased and then decreased while dominant species decreased, but the above-ground vegetation biomass increased slightly (Sun et al., 2012). They concluded that factors including land use intensity, soil moisture, soil salinity, and reclamation time influenced plant community distribution in the reclamation areas (Sun et al., 2012). In southwestern coast of South Korea, Ihm et al. examined the relationships between vegetation and 12 edaphic factors (Ihm et al., 2007). By gradient analysis, Ihm et al. concluded the main gradients were soil-water relations and soil texture (Ihm et al., 2007). Min and Kim researched coastal plant succession and interaction between soil and plants after land reclamation on the West Coast of Korea (Min and Kim, 2000). First, soil salt leaching leaded to a vegetation shift, followed by an increase in soil organic matter, plant biomass, and total nitrogen, while soil bulk density and soil-available phosphorus decreased (Min and Kim, 2000). Zhang et al. assessed the difference in microbial taxa gradient distribution and compositional diversity between reclamation and non-reclamation areas (Zhang et al., 2016). They found bacterial relative abundance was affected by soil salinity, and in reclamation areas the bacterial abundance was lower than that in non-reclamation areas (Zhang et al., 2016).

Anthropogenic disturbances have direct impacts on coastal heavy metal (HM) accumulation processes (Fang et al., 2010; Xu et al., 2016). Human impact index (HII) was shown to be a robust indicator of human impacts on soil HM contents (Fang et al., 2010). Xu et al. (2016) found that reclamation increased the total amount of arsenic (As), copper (Cu), and zinc (Zn), as well as the pollution degrees of As, chromium (Cr), and Zn. The availability of Cu, lead (Pb), cadmium (Cd), and Cr can also be significantly affected by reclamation (Xu et al., 2016). Gao et al. (2016) reported that heavy metal accumulation in coastal areas was a joint effect of natural sedimentary process and anthropogenic activities. Quantification the impacts of human activities were found to be critical to the management of HM-associated ecological risk to coastal ecosystems (Fang et al., 2012).

Although the response of soil characteristics and plant community diversity to reclamation time has been reported previously, quantitative research on the effect of reclamation time and intensity, income per capita and population size on soil characteristics, coastal native plant species' height, plant density, and above-ground biomass is needed. These characteristics are important soil and plant morphological indices linked to key coastal ecosystem services (Kremen, 2005). Demographic variables such as residential population in the reclamation area, income per capita, human impacts intensity reflected by land use, and reclamation time computed by local reclamation records are all useful indices to build quantitative models between anthropogenic disturbances and coastal soil and native plant characteristics. This study aims to answer (1) how soil nitrate and ammonium, native plants, and HM quantitatively respond to several human impact variables including residential population in the reclaimed area, income per capita, HII, and reclamation time, and (2) what kind of models best quantify these relationships.

2. Experimental section

2.1. The study site

The study site is located on the Yellow Sea coast at N 32°35′–34°28′, and E 119°37′–120°53′, lying in the north subtropical zone (Fig. 1). The annual average temperature is between 13.7 and 14.8 °C and the annual average precipitation is 1010 mm. Since the end of the late Pleistocene, the site has been a plain sedimentary geomorphology formed by the river fluvial and coastal sediment processes. The soils along the coast are grouped into three classes according to the formation process: Anthrosols, Fluvisols, and Cambisols (Fang et al., 2010). The vegetation community along the coast is distributed with a stratified pattern from the coast to inland. From the coast inland, past the bare tidal flats *Spartina alterniflora* dominates, followed by *Suaeda glauca Bge*, *Imperata cylindrica* (Linn.) *Beauv*., *Phragmites australis*, and other xeromorphic vegetation (Fang et al., 2010). Scirpus is mosaically

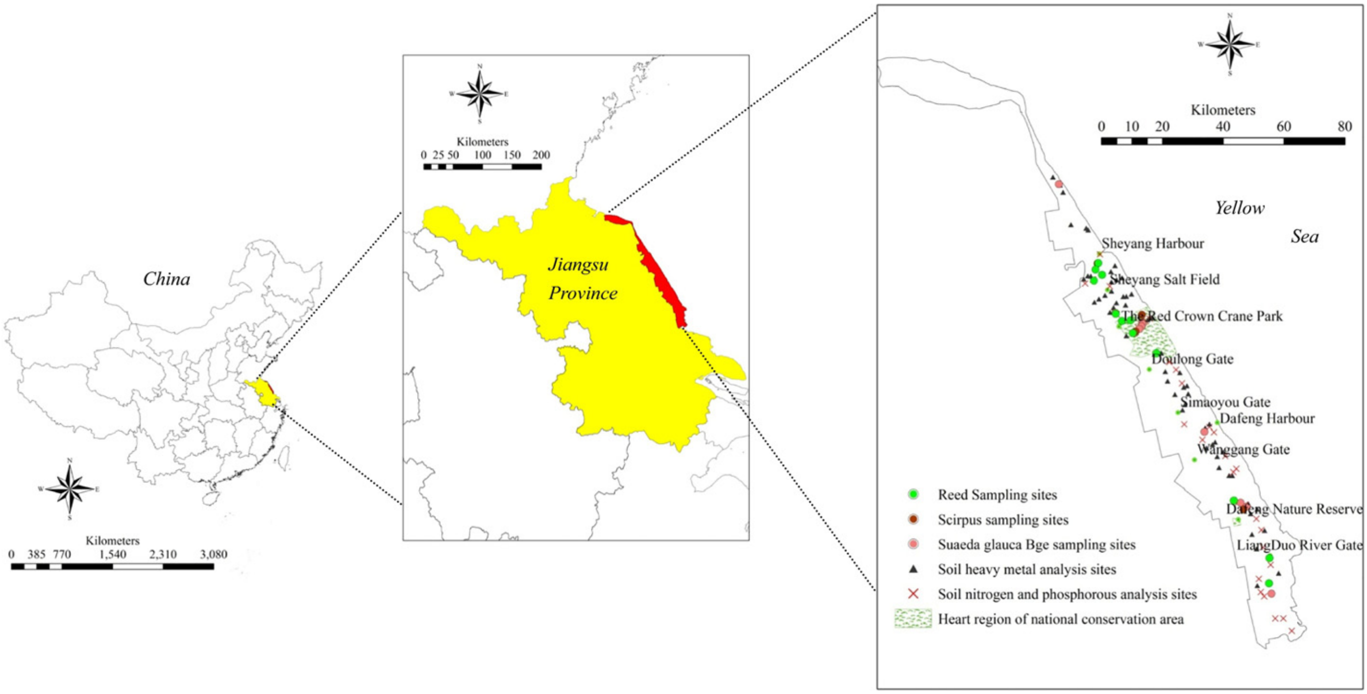

Fig. 1. One of the largest areas of coastal tidal flats in China, Jiangsu coast along the Yellow Sea had experienced large scale reclamation during the past decades, including aquaculture, agriculture and industry development. Samples of native hydrophytic vegetation including *Phragmites australis* (Reed), Scirpus, *Suaeda glauca Bge* and soils were collected to study the reclamation impacts. Height, density and above-ground biomass of the hydrophytic vegetation, soil heavy mental (HM) and soil nitrogen and phosphorous were analyzed. The coast was listed among the world important wetlands and two national natural reserved areas, the Red Crown Crane Park and Dafeng Natural Reserve areas located here.

distributed in the *Suaeda glauca Bge* community, *Imperata cylindrica* (Linn.) *Beauv*. community, and *Phragmites australis* community.

The core regions of two national natural reserved wetlands, the Red Crown Crane National Reserved Lands and the Dafeng Milu National Natural Reserve, are located on this coast. In 1992, Yancheng was listed in the world network of biosphere conservation (WNBP) by the United Nations. The area has become a hot spot of wetland research for its significance in biodiversity conservation (Fang et al., 2010).

2.2. Soil and vegetation sampling

The vegetation sampling was performed between August and October in 2007. Sample plots of native vegetation, including *Phragmites australis* (Reed), Scirpus, and *Suaeda glauca Bge*, were randomly selected with a 100 cm × 100 cm square. Vegetation height, density, and fresh above-ground biomass were measured at each sample plot (Fig. 1).The total number of samples collected for Reed, Scirpus, and *Suaeda glauca Bge* was 12, 9, and 18, respectively, with 3–5 replicates from each site.

The soil samples for soil nitrate and phosphorous analysis were collected in July 2014. The soil sampling and pre-processing methods were conducted as previously described (Fang et al., 2010). The total number of soil samples collected was 31, with 3–5 replicates from each site. Soil HM data were published in Fang et al. (2010), and HMs with higher potential ecological risks including Cr, Cd, Cu, Pb, and Zn were published in Fang et al. (2012).

2.2.1. Soil nitrate nitrogen analysis

A zinc-cadmium reduction method was used to test soil nitrate nitrogen. 20 g of 4 °C-stored fresh soil was placed into 250 mL Erlenmeyer flasks with 100 mL of 2 M NaCl, and shaken for 2 h at 25 °C at 200 rpm. The samples were allowed to settle, and then filtered with four layers qualitative filter paper into an Erlenmeyer flask, and the filtrate was stored at 4 °C for further analysis. A nitrate nitrogen standard solution was prepared as follows: 0.7218 g of analytically pure potassium nitrate was brought to a constant volume of 1000 mL and diluted 10 times to10 ppm. Standard solutions (0.0, 0.1, 0.2, 0.3, 0.5, and 0.8 mL) of potassium nitrate were placed into 50 mL cuvettes with 1 mL 2 M NaCl, and brought to a volume of 50 mL (with DI water). Next, 1 mL filtrate was placed into a 50 mL cuvette and brought to a volume of 50 mL. A zinc circular coil and 1 mL of $CdCl_2$ (20 g/L) was added to each cuvette, and they were placed on a vibrator for 10 min, followed by standing for 5 min, then adding 0.5 mL sulfanilamide (10 g/L), standing for 5 min, adding 0.5 mL hydrochloride ethylenediamine (1 g/L), and standing for 15 min. Lastly, the solution was mixed and colored for 30 min, and the absorbance at 543 nm was detected with a visible spectrophotometer (SP-722E).

2.2.2. Soil ammonium analysis

A reagent colorimetric method was used to test soil ammonium nitrogen. The ammonium nitrogen standard solution was prepared as follows: 1.91 g NH_4Cl, was dried at 90 °C, 1 mL chloroform was added, and the volume was brought to 1000 mL, producing a standard solution of 500 ppm. 20 mL of standard solution was brought to a volume of 500 mL, producing a standard solution of 20 ppm. Standards of 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0 mL solution of 20 ppm solution were placed into 25 mL cuvettes, 2 mL of 2 M NaCl was added to each and the volume was brought to 20 mL. 2 mL of filtrate was added to a 25 mL cuvette and the volume was brought to 20 mL. 1.0 mL of seignette salt (25%) was placed in all the cuvettes, followed by standing for 5 min, then adding five drops gum arabic and shaking while adding 1 mL of the colorimetric reagent. The volume was brought to 25 mL in all the cuvettes, the solution colored for 20 min, and then the absorbanceat 490 nm was detected using a visible spectrophotometer (SP-722E).

2.2.3. Soil phosphorous analysis

The preparation of the standard curve was as follows: 1.9174 g of analytical pure potassium dehydrant phosphate was dried at 45 °C for 4–8 h, then mixed with 5 mL concentrated sulfuric acid and diluted to 1000 mL, producing a dilution of 1000 ppm. Next, 5 mL of the dilution was placed into a 100 mL volumetric flask with 3 mL of 3 M sulfuric acid and the volume was brought to 100 mL, taking 10 mL of which

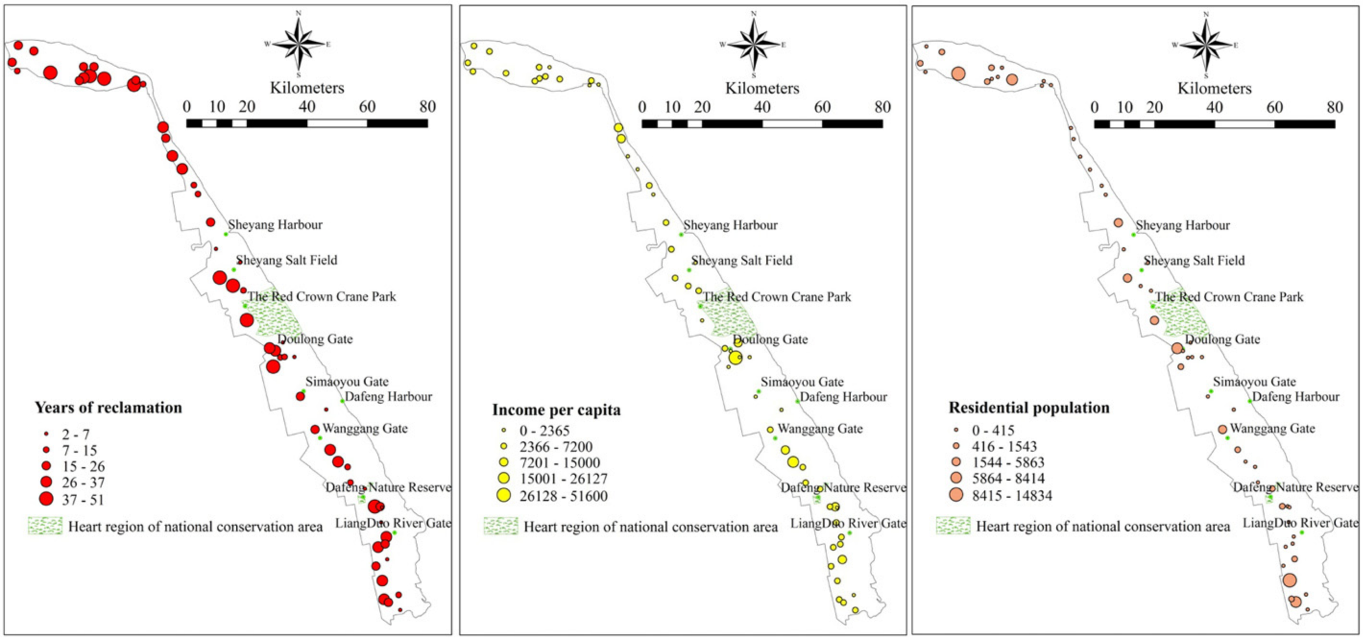

Fig. 2. Spatial heterogeneity of the reclamation variables including years of reclamation (unit: Year), income per capita (unit: Yuan), and residential population (unit: Person). Analysis revealed that the longer the reclamation time, the larger the residential population. But income per capita was not so clearly related to reclamation time or residential population. In areas around Doulong Gate and Wanggang Gate the income per capita were higher than other areas. At the landward and northern area, reclamation time and residential population were longer and larger compared with the seaward and Southern area. The correlation analysis between the reclamation variables also showed these results (Table 1).

into 100 mL volumetric flask and making the volume to 100 mL, which was phosphorus pent oxide standard solution of 5 ppm. Next, taking 0, 1, 2, 4, 6, and 8 mL of the phosphorus pent oxide standard solution of 5 ppm was added to 25 mL cuvettes with 5 mL sulfuric acid molybdenum antimony, and the volume was brought to 25 mL. The solution was then colored for 30 min and the absorbance at 660 nm was detected using a visible spectrophotometer (SP-722E).

Samples were processed as follows: 0.2 g air-dried,100 mesh-sieved soil was placed into a 100 mL conical flask, 3 mL concentrated sulfuric acid and 10 drops of perchloric acid were added, and the flask was placed onto a heating plate at 350 °C and heated until almost no smoke was released. After cooling, the remnants were leached into a 50 mL cuvette, and the volume was brought to 50 mL. After the solution was allowed to settle for 24 h, 2.5 mL of the top layer was placed into a 25 mL conical flask with10 mL pure water and one drop 2, 6-Dinitrophenel. The flask was shaken and 2.5 mL chromomeric reagent was added when gas production ceased. The solution was then colored for 30 min and the absorbance at 660 nm was detected using a visible spectrophotometer (SP-722E).

2.3. Land use and coastal reclamation data

Coastal reclamation data, including the residential population in every reclamation area, income per capita (IP), reclamation time (years of reclamation, YR), and residential populations (RP) were referenced from Zhang et al. (2013) and other recorded atlas data (Jiangsu Agricultural Resources Development Agency, 1999).

Land-use data were published and described previously (Fang et al., 2010, 2012). For vegetation and HM analysis, the land-use map of 2006 was used, and variables of income per capita, reclamation time, and residential population were also referenced from 2006. For soil nitrate and phosphorous analysis, the land-use map of 2013 was used, and variables of income per capita, reclamation time, and residential population were referenced from 2010. Land use-based HII was used to reflect human disturbance from the land use data (Fang et al., 2010). The spatial scale, i.e. the radius of the circle, was 1 km (Fang et al., 2010).

2.4. Statistical analysis

Two kinds of statistical methods were applied to quantify the soil and vegetation characteristics with reclamation related variables including HII, income per capita, residential population, and reclamation time. The ordinary least square (OLS) method, i.e., curve estimation analysis by SPSS 19.0, and the geographical weighted regression (GWR) analysis by ArcGIS 9.3 were used to quantify the relationships. The OLS method considers non-spatial information, taking all the variables as spatial independent, while the GWR method considers spatial information (Su et al., 2014; Fang et al., 2015).

Only when the characteristics are distributed with spatial correlation, GWR analysis is reasonable (Su et al., 2014). Before GWR analysis, spatial isotropic semivariogram analysis of soil and vegetation characteristics was performed by GS+ for windows.

Values of R^2, square root of the normalized residual sum of squares (Sigma), and corrected Akaike Information Criterion (AICc) were analyzed to compare the efficiency of the two kinds of methods (Fang et al., 2015). The bigger the R^2 value, the smaller the AICc and Sigma value, the better the models (Fang et al., 2015).

Table 1
Correlations between the reclamation variables.

	IP	RP	YR	HII
Income per capita (IP)	1			
Residential population (RP)	−0.095	1		
Years of reclamation (YR)	−0.133	0.434**	1	
Human impact index (HII)	0.252*	0.201*	0.357**	1

* Correlation is significant at the 0.05 level (1-tailed).
** Correlation is significant at the 0.01 level (1-tailed).

Table 2
OLS analysis between variables and soil or vegetation characters ($^{*}p < 0.05$, $^{**}p < 0.01$).

Independent	Dependent	Equation	Ad_R^2	F	Parameter estimates	
					Constant	b1
Scirpus H	IP	Linear	0.432	7.087*	0.719	3.23E-05
	RP	Linear	0.555	10.980*	0.911	0
Reed H	HII	Linear	0.306	5.856*	2.907	−2.277
Reed B	HII	Logistic	0.354	7.018*	0.249	26.625

Estimated coefficients and ANOVA of the linear regression analysis

	R^2	F	Equation
Cr	0.116	2.556*	$y = 52.66 + 0.03 \ast YR + 0.001 \ast IP\text{-}7.50 \ast HII$
Cu	0.216	5.365**	$y = 12.06 + 0.208 \ast YR + 0.002 \ast IP\text{-}6.301 \ast HII\text{-}0.002 \ast RP$
Cd	0.111	4.971**	$Y = 2.81 - 0.001 \ast RP + 0.052 \ast YR$

Note: H, height; B, Biomass; IP, income per capita; HII, human impact index; RP, residential population (RP); YR, years of reclamation.

3. Results

3.1. The spatial distribution of reclamation variables

The spatial distribution of reclamation time, income per capita, and residential population in 2010 was illustrated. Reclamation time was longer in the northern part, north of the Dafeng Harbor, than in the southern part. As an important solar salt production base, areas in the far northern part and in the Sheyang Salt Field had a coastal reclamation time of over 50 years (Fig. 2). In the southern part, only parts of the areas, i.e., the area around Liangduo River Gate was developed for >50 years (Fig. 2). Comparing seaward with landward, the areas of landward were developed earlier and longer (Fig. 2).As income per capita was concerned, the highest value was in the middle area of the study site, around Doulong Gate. The value of income per capita in the middle-south part was higher than that of the northern part (Fig. 2). For residential population, it was found that the longer the reclamation time, the larger the residential population. The highest value of the residential population was located in the far northern part of the study area. Compared with seaward area, the value of residential population was higher in the landward area (Fig. 2).

Based on correlation analysis, income per capita was positively correlated with HII (Table 1, $p < 0.05$), e.g., the higher the HII, the higher the income per capita. HII was also positively correlated with all of the other variables, indicating that HII was a useful surrogate reflecting human disturbances. Residential population was also positively correlated with reclamation time, demonstrating that a longer reclamation time is correlated with a larger residential population.

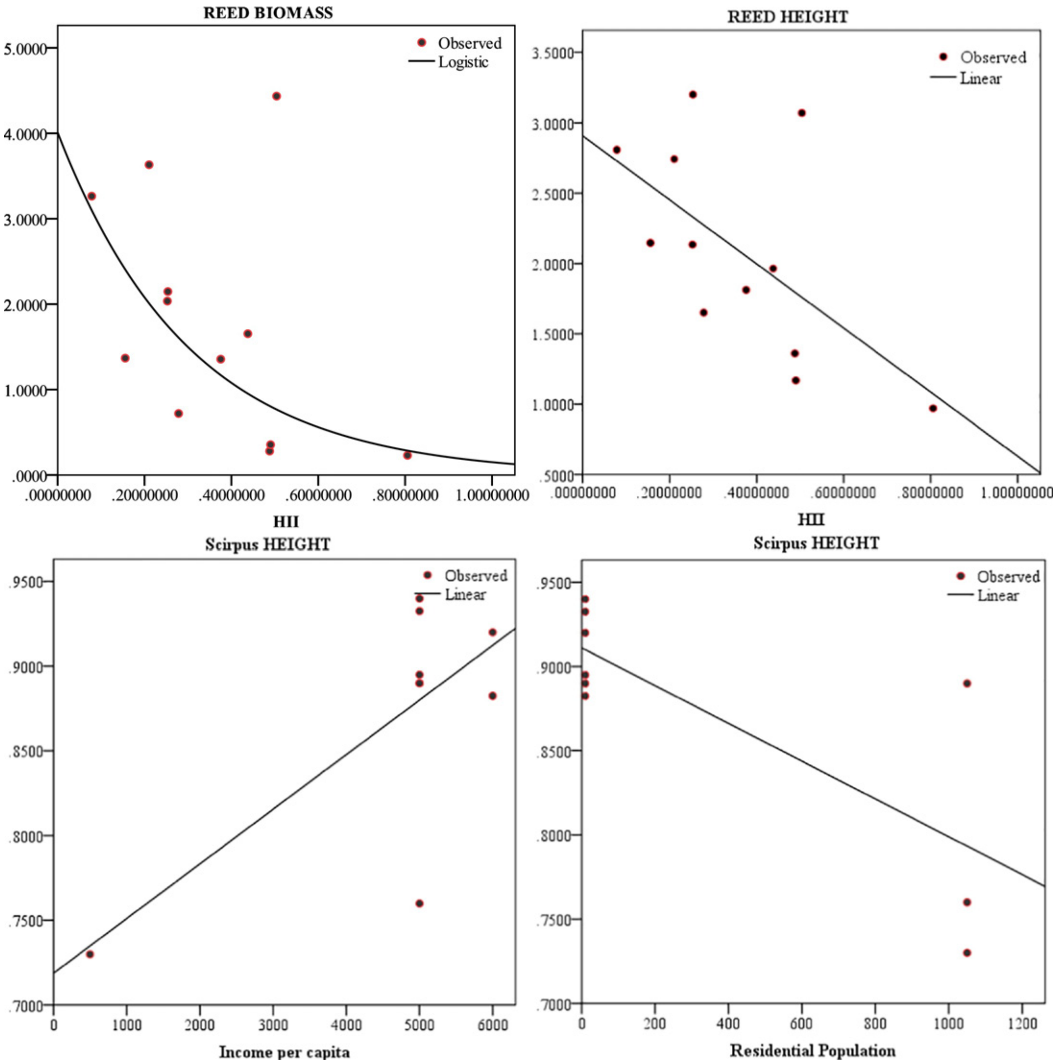

Fig. 3. By ordinary least square regression analysis, Reed above-ground biomass and height decreased with HII, while Scirpus height decreased with residential population but increased with income per capita. It might be in area with higher income per capita, the high human disturbance on land use could create more suitable landscape patches for Scirpus. Our analysis showed that income per capita was highly correlated to human impact index (Table 1), which meant higher income per capita was always linked with higher land use disturbances. But in areas with larger number of residential population, the landscape had been altered such that it was not suitable for Scirpus at all.

3.2. Variables affecting soil and vegetation characteristics by OLS analysis

Income per capita and residential populations were both associated with Scirpus height (Table 2). The Ad-R^2 of income per capita and residential populations were 0.432 and 0.555, respectively. Residential population was better in explaining the Scirpus height. Scirpus height was negatively correlated with residential population, but positively correlated with income per capita. It might be that in areas with higher income per capita, the higher human impacts could create more suitable landscape mosaic patches for Scirpus, but in areas with higher residential population, human changed the entire habitat of Scirpus (Fig. 3, Table 1).

Reed height and above-ground biomass were both affected by HII significantly ($p < 0.05$). The above ground biomass and height were both negatively correlated with HII, and the higher the HII, the lower the values (Fig. 3). In the study area, the human activities were always linked with the habitat loss for Reed, so the disturbed conditions were always a negative impact for Reed growth.

By stepwise linear regression, soil concentrations of Cr, Cu, and Cd could be quantified by different models with different variables (Table 2), but the R^2 values were all small, indicating the models did not have a good fitness.

By OLS analysis, other soil characteristics and vegetation were not found to have significant quantitative relationships with the variables of HII, income per capita, residential population, and reclamation time.

3.3. Variables affecting soil and vegetation characteristics by GWR analysis

The isotropic semivariogram analysis showed that soil HM, soil nitrogen and total phosphorous, and vegetation index were highly spatially correlated (Table 3). Except Scirpus height, other characteristics were strongly or moderately spatially correlated.

Compared with OLS analysis, GWR analysis revealed that all soil characteristics and vegetation indices were spatially regressed with the reclamation related variables (Tables 4, 5, and Supplementary Figs. S1–S3).

Income per capita, residential population, and reclamation time all caused Scirpus height spatial heterogeneity. The highest value of Ad_R^2 was 0.916 which was for the residential population, indicating residential population fitted the Scirpus height with a high accuracy. Compared with the OLS analysis, the R^2 of residential population was tremendously improved by GWR analysis. Income per capita, residential population, reclamation time, and HII all could be used to explain Reed height (Table 2, Supplementary Fig. S1)·The best fitness among them was residential population, followed by HII. Both of them had a better goodness-of-fit than the OLS analysis (Table 1). For Reed density and Reed above-ground biomass, the best fitted variable was residential population, followed by HII and reclamation time. The reclamation time was the best variable affecting *Suaeda glauca Bge* height, but the R^2 was not as good as other vegetation. For *Suaeda glauca Bge* density, the best-fitted variable was HII, then residential population and reclamation time.

For soil total phosphorous, the variable with best fit was reclamation time, then HII and residential population, with the Ad_R^2 of 0.599, 0.581, and 0.496, respectively. For soil nitrate nitrogen, the variable with best fitness was HII and reclamation time, and then residential population, and the Ad_R^2 values were 0.632, 0.631, and 0.270, respectively. For soil ammonium, the order of the variable goodness-of-fit was HII, reclamation time, and residential population, with an Ad_R^2 value of 0.562, 0.523, and 0.388, respectively.

For soil HM contents, HII was the variable with best goodness-of-fit for Cr, Cu, Zn, Cd, and Pb, with the Ad_R^2 value of 0.636, 0.712, 0.524, 0.588, and 0.572 respectively (Table 5). Except for HII, variables including reclamation time, income per capita, and residential population all could be used to explain soil HM spatial variance with different goodness of fitness (Table 5).

Table 3
Theoretical models and parameters for isotropic semivariogram analysis of the soil and vegetation characteristics.

	Simulation model	C_0	$C_0 + C$	$C/C_0 + C$ (%)	Spatial autocorrelation
Cr	Exponential	43.10	206.60	79.1	Strong
Cu	Spherical	0.02	0.99	98.3	Strong
Ni	Exponential	0.02	0.09	71.9	Moderate
Cd	Spherical	0.05	0.61	92.6	Strong
Pb	Linear	0.77	1.04	25.7	Moderate
NH_4^+	Spherical	0.01	0.32	97.5	Strong
NO_3^-	Exponential	0.002	0.009	77.8	Strong
TP	Exponential	0.103	0.207	50.2	Moderate
Scirpus H	Linear	0.004	0.005	20	Weak
Reed H	Spherical	0.129	0.763	83.1	Strong
Reed D	Linear	596	814.26	26.8	Moderate
Reed B	Linear	1.041	1.422	26.8	Moderate
Suaeda glauca Bge H	Linear	0.002	0003	33.3	Moderate
Suaeda glauca Bge D	Gaussian	4360	24,690	82.3	Strong

Notes: D, density; TP, soil total phosphorous; C_0, the nugget; $C_0 + C$, the still value.

There was a clear spatial pattern for the local R^2 values for all the variables (Supplementary Figs. S1–S3). The R^2 value was higher in northern part, around the Sheyang Salt Field, for residential population and reclamation time and Scirpus height. For Reed height, the R^2 values around the Nature Reserve Area, the northern part, were higher (Supplementary Fig. S1). The local R^2 value was also higher around Dafeng Milu Nature Reserve Area and Liangduo River Gate in the Southern area for Reed and Scirpus height (Supplementary Fig. S1). For Reed density and above ground biomass, the local R^2 had a similar spatial pattern. *Suaeda glauca Bge* and Scirpus had a similar local R^2 spatial pattern to the Reed.

Table 4
Geographical weighted regressions between native vegetation, nitrogen, phosphorous, and reclamation variables.

Independent	Dependent	Sigma	AICc	Ad_R^2
Scirpus H	IP	0.05	−159.97	0.461
	RP	0.02	−258.24	0.916
	YR	0.05	−169.50	0.553
Reed H	IP	0.38	65.01	0.729
	RP	0.25	16.84	0.880
	YR	0.34	56.17	0.775
	HII	0.27	26.22	0.862
Reed D	RP	8.82	464.88	0.879
	YR	16.32	542.30	0.585
	HII	15.75	538.34	0.613
Reed B	IP	0.83	164.00	0.582
	RP	0.65	136.86	0.742
	YR	0.77	157.86	0.639
	HII	0.65	137.04	0.742
Suaeda glauca Bge H	YR	0.03	−603.09	0.295
Suaeda glauca Bge D	RP	97.44	1834.12	0.507
	YR	98.20	1835.33	0.499
	HII	96.61	1830.66	0.515
TP	RP	0.15	−100.63	0.496
	YR	0.13	−120.42	0.599
	HII	0.14	−115.28	0.581
NO_3-N	RP	0.09	−229.22	0.270
	YR	0.06	−302.90	0.631
	HII	0.06	−303.26	0.632
NH_4-N	RP	0.49	177.20	0.388
	YR	0.43	154.85	0.523
	HII	0.41	144.76	0.562

Note: Sigma, square root of the normalized residual sum of squares; AICc, corrected Akaike Information Criterion.

Table 5
Geographical weighted regressions between HM and reclamation variables.

Independent	Dependent	Sigma	AICc	Ad_R^2
Cr	YR	5.79	3160.46	0.470
	HII	4.81	2987.86	0.636
Cu	IP	5.16	3034.57	0.505
	RP	5.14	3041.10	0.509
	YR	4.45	2899.04	0.632
	HII	3.94	2791.19	0.712
Zn	RP	13.51	3995.76	0.268
	YR	13.27	3978.61	0.294
	HII	10.90	3796.68	0.524
Cd	IP	2.47	2306.70	0.334
	RP	2.33	2257.49	0.411
	YR	2.34	2265.17	0.402
	HII	1.94	2093.21	0.588
Pb	RP	3.00	2508.99	0.389
	YR	3.00	2510.53	0.388
	HII	2.51	2345.94	0.572

The spatial variance of local R^2 of the explaining variables was different for soil TP and nitrogen than for the native vegetation. In general, the local R^2 was higher in the southern part, around the Dafeng Habour and Liangduo River Gate (Supplementary Fig. S2).

For soil HM, the explaining variables' local R^2 was also spatially heterogeneous. In areas around the Sheyang Habour, the Dafeng Habour, and the Liangduo River Gate the values of local R^2 were general higher than those in other areas (Supplementary Fig. S3). In areas around the Sheyang Salt Field the values of local R^2 were lower (Supplementary Fig. S3).

4. Discussion

The two scientific questions raised could be answered here: (1) Residential population, income per capita, HII, and years of reclamation all could quantitatively affect soil characters and native vegetation. Based on OLS and GWR analysis, HII and residential population explained the soil characteristics and native vegetation spatial variance with better fit, followed by income per capita and reclamation time; and (2) GWR analysis was a more reliable method than OLS given the higher value of R^2 generated by GWR. Spatially-informed methods should be further developed to quantify the relationships between reclamation variables and soils and native vegetation.

In this study we revealed that coastal reclamation time exerted soil and vegetation characteristics in a quantitative way. From GWR analysis, reclamation time exerted Scirpus height, Reed height, density and above ground biomass, *Suaeda glauca Bge* height and density, soil TP, soil nitrate nitrogen and ammonium with considerably high R^2 values (Table 4). We found soil HM contents were also affected by reclamation time (Table 5). The difference between this research and other reclamation time studies was that we further provided the goodness-of-fit of reclamation time in a quantitative way (Kwak et al., 2008; Li et al., 2013; Sun et al., 2011; Yin et al., 2016). Sun and colleagues found species richness, species diversity and above-ground biomass increased with reclamation years (Sun et al., 2012). However, in this study, Reed above-ground biomass and height decreased with HII, while Scirpus height decreased with residential population, but increased with income per capita (Table 4). A comparison of the spatial patterns of reclamation variables (Fig. 2) with vegetation characteristics (Fig. 4) showed that the vegetation characteristics decreased with reclamation time in general. It should be noted that we only tested hydrophyte taxa vegetation, but Sun et al. included xerophyte vegetation in their work (Sun et al., 2012).

As reported by Li et al. (2013) and Sun et al. (2011), land use appeared to affect soil and vegetation characteristics (Table 2, Table 4). The difference between this work and their work was that in this work a quantitative index, i.e. HII, was analyzed (Fang et al., 2010). We further used the GWR and OLS methods to quantify the relationships between HII and soil nitrogen and phosphorous, native hydrophyte vegetation, and HM. HII was a more comprehensive index of human disturbances that explained the soil and vegetation characters with better goodness-of-fit than other variables (Tables 1, 2, 4). In this study, by using GWR analysis we revealed that certain heavy metals,

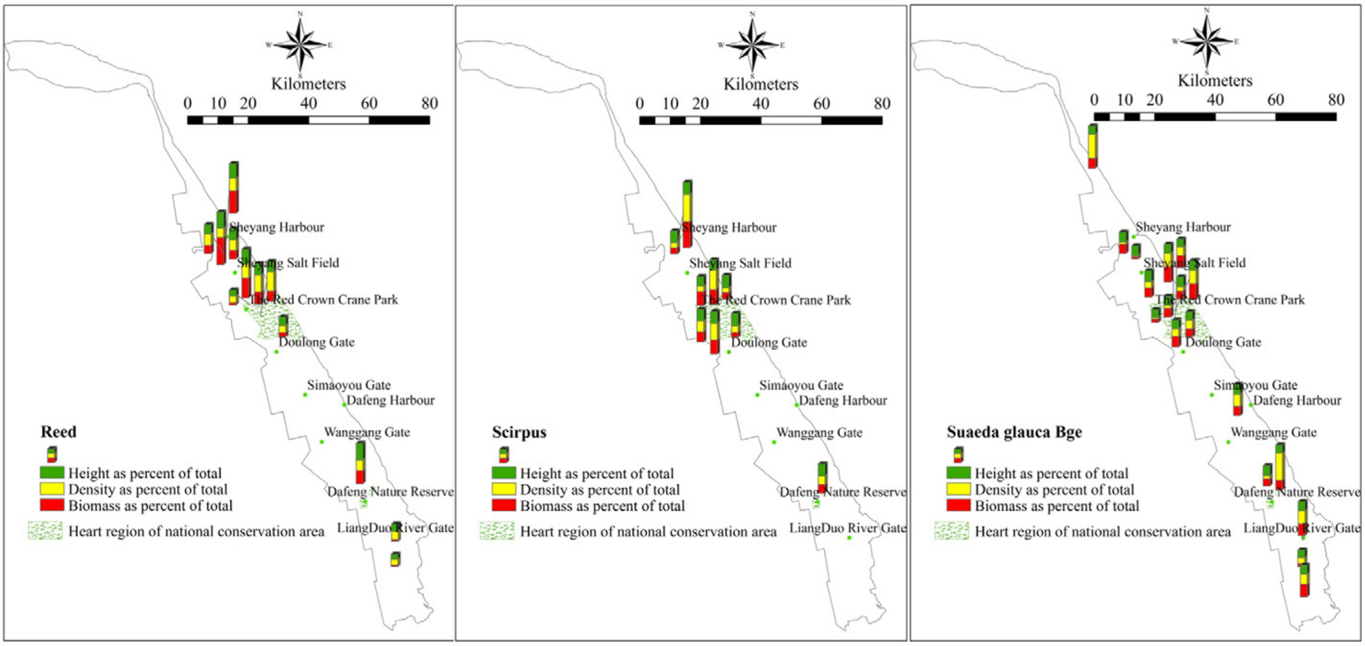

Fig. 4. The spatial heterogeneity of native hydrophytic vegetations characteristics. Compared with the reclamation variables (Fig. 2), the longer the reclamation time and the larger the residential populations, the lower the values of the hydrophytic vegetation indices distributed. Comparing the indices value of seaward with landward, the values of seaward were higher than that of landward. Areas around the Red Crown Crane Park were the hot spots with higher indices values. Because of the fast industry development and harbor building, in the central part around the Dafeng Harbor the hydrophytic vegetation almost disappeared.

i.e., Cr, Cu, Cd, Zn, and Pb, were mainly human-induced along the coastal areas, which might be more accurate compared with that reported by Gao et al. (2016).

The considerably high value of R^2 by GWR analysis demonstrated that human reclamation activity seriously changed the structure and function of the coastal ecosystem. Ihm et al. reported soil-water relations and soil texture were the main factors explaining coastal vegetation (Ihm et al., 2007). Min and Kim argued that soil salt leaching was the first stage of coastal plant succession for the interacting soil-plant system and then other soil characteristics and plant biomass changed (Min and Kim, 2000). Zhang et al. found bacterial relative abundance was affected by the reclamation activities (Zhang et al., 2016). In this study we revealed soil characteristics and native vegetation were significantly disturbed by reclamation activities with large spatial heterogeneity.

Our study implied that the priority work for coastal ecosystem conservation was twofold: human population size control and proper land use planning. In this study residential population size was correlated with reclamation time, while income was highly correlated with HII (Table 1). Coastal master planning was critical for reclamation project establishment and population size management in a long run. Furthermore, land use intensity should be taken into account for future potential development scenarios given that income per capita was highly correlated with HII.

To answer the question of where and how to perform reclamation work in coastal areas, accurate and process-based models should be developed to quantify how typical ecosystems' structure or function respond to coastal natural and/or human impacts such as reclamation (Cui et al., 2016). This study demonstrated that spatial explicit models should be the priority to develop in the future (Fang et al., 2015). Detecting the critical thresholds and characteristics' scales with which coastal ecosystems respond to human impacts, natural events such as climate change, or the joint impacts of human and natural impacts would be a promising research direction for coasts in the future (Fang et al., 2010).

5. Conclusion

Reclamation related variables, i.e., residential population, income per capita, reclamation time, and land use-based HII, had significantly changed coastal soil and vegetation characteristics. OLS and GWR methods were both effective in quantifying the coastal soil and vegetation characteristics with reclamation impacts. Compared with OLS method, GWR analysis more accurately reflected the impact of reclamation on coastal ecosystems' structure and function. By using OLS analysis, income per capita, residential population, and HII could be used to explain Scirpus height, Reed height, and above ground biomass with statistical significance. However, by using GWR analysis, the soil characteristics include soil nitrogen, phosphorous, and HM, and the vegetation characteristics including height, density, and above ground biomass could be explained by the reclamation related variables with higher levels of accuracy. This revealed that coastal reclamation affected coastal ecosystems with high spatial dependence.

Of all the variables used to explain the soil and vegetation characteristics, both GWR and OLS analysis revealed that HII and residential population were better indices. Although this study did not answer where and how to perform reclamation work in coastal areas, it emphasizes the development of spatial explicit and process-based models as a priority direction for future coastal reclamation research.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.02.133.

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