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Model assessment of nutrient removal via planting *Sesuvium portulacastrum* in floating beds in eutrophic marine waters: the case of aquaculture areas of Dongshan Bay

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Abstract

Many coastal seas are severely eutrophic and required to reduce nutrient concentrations to meet a certain water quality standard. We proposed a method for nutrient removal by planting *Sesuvium portulacastrum* at the water surface using the floating beds in the aquaculture area of the Dongshan Bay as an example, which is an important net-cage culture base in China and where dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphate (DIP) reach 0.75 mg/L and 0.097 mg/L, respectively far exceeding China's Grade IV water quality standards. Numerical simulations were taken using the ecological model, field observations and field plantation experimental results to assess the environmental restoration effects of planting *S. portulacastrum* at some certain spatial scales. Our field experiments suggested that the herbs can absorb 377 g/m^2 nitrogen and 22.9 g/m^2 phosphorus in eight months with an inserting density of ~60 shoot/m^2. The numerical experiments show that the greater the plantation area is, the more nutrient removal. Plantation in ~12% of the study area could lower nutrients to the required Grade II standards, i.e., 0.2 mg/L<DIN⩽0.3 mg/L and 0.015 mg/L<DIP⩽0.03 mg/L. Here the phytoremediation method and results provide helpful references for environmental restoration in other eutrophic seas.

Key words: phytoremediaton, *Sesuvium portulacastrum*, ecological model, nutrient removal

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1 Introduction

Irrational exploitation such as sea reclamation, pollution discharge, and excessive aquaculture has significantly deteriorated the ecological environment of many seas (Duarte et al., 2015) and resulted in the fact that some of environment conditions are no longer meeting the requirements of their functions in water quality (Islam and Tanaka, 2004; Li et al., 2015b). For seriously polluted marine areas involving some aquaculture bays, pollutant removal to restore and improve water conditions is an important issue that needs to be urgently resolved for sustainable utilization of marine resources (Wenzel, 2016).

The combination of fish or shellfish net-cage culturing and macroalgae raft farming is often an effective way to restore the aquaculture water (Neori et al., 2004; Li et al., 2015a). The cultured animals can devour excessive phytoplankton and other organic matters while the macroalgae such as *Gracilaria lamaneiformis*, *Laminaria japonica*, *Porphyra tenera* and the like can absorb excessive nutrients (Dumbauld et al., 2009; Forrest et al., 2009; Troost, 2010; Mineur et al., 2015). This kind of mixed cultivation has been well applied in multiple bays in China such as the Sanggou Bay and Xiangshan Bay (Wang et al., 2014; Wu et al., 2015).

In the intensive aquaculture area of the Dongshan Bay (Fig. 1) as the study area in this paper, which is an important aquaculture base in China, the dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphate (DIP, i.e., PO_4-P) have seriously exceeded the water quality standards (MEP, 2004) in recent years due to excessive aquaculture activities and poor water exchange conditions, leading to frequent mass deaths of cultured organisms and enormous fishery losses (Tang et al., 2005). This area is

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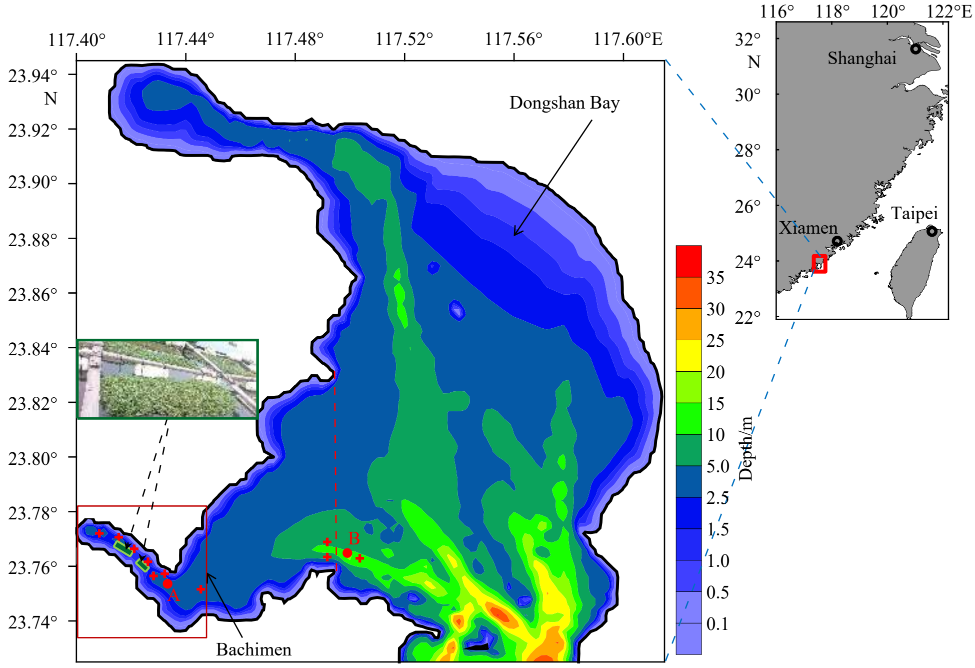

Fig. 1. Map of the study area. Red crosses represent investigation sites for biochemical elements. Red dots "●" (A, B) indicate hydrodynamic investigation sites. The whole Dongshan Bay is the hydrodynamic model area; the western part of the long dash line is the ecological model area; and the area in the red rectangular line (i.e., Bachimen) is the environmental restoration area.

named as Bachimen and once was the China's largest net-cage culture base with ~140 000 fish cages (Tang et al., 2005). According to China's standard of seawater quality (Table 1), aquaculture-function waters require to meet Grade II standards (MEP, 2004). For DIN and DIP, the required concentration ranges are 0.2 mg/L<DIN⩽0.3 mg/L and 0.015 mg/L<DIP⩽0.03 mg/L. However, our observations in this area show that the concentrations of DIN and DIP are far over Grade IV standards. Therefore, it is urgent to find an effective method for regulation and control so as to decrease the severe eutrophication and restore the ecological environment. Nevertheless, low water transparency (<1 m, our observation) in this intensive aquaculture area makes it unsuitable for planting macroalgae in water.

On the basis of multiple plant selections and plantation experiments for phytoremediation, we chose to plant *Sesuvium portulacastrum* at the water surface using the floating beds to restore the environment. *Sesuvium portulacastrum* is a perennial, herbaceous facultative halophyte naturally growing in the tropical and subtropical coastal areas (Lonard and Judd, 1997; Fan et al., 2010; Slam et al., 2015). Researchers (Dou et al., 2011; Wu et al., 2011; Huang et al., 2013; Boxman et al., 2017) through their experimental studies have shown that the herb could efficiently absorb nitrogen and phosphate. For an example, Wu et al. (2011) reported that its nutrient absorption rate is 4.28–11.11 μmol/(g·d) for nitrogen and 0.14–0.74 μmol/(g·d) for phosphorus under a certain conditions. In addition, rich in calcium, iron and potassium, this herb is a wild vegetable with potential health care function and a good animal feed and has a great medicinal value (Kanth et al., 2009; Fan et al., 2010; Lokhande et al., 2013).

Table 1. Concentration ranges of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphate (DIP) according to China's standard of seawater quality (MEP, 2004)

	Grade I	Grade II	Grade III	Grade IV
DIN/mg·L^{-1}	⩽0.2	⩽0.3	⩽0.4	⩽0.5
DIP/mg·L^{-1}	⩽0.015	⩽0.030	⩽0.030	⩽0.045

When choosing *S. portulacastrum* used for phytoremediation in eutrophic water, the essential concern is to explore a rational plantation scale so as to make nutrient reduced to a reasonable level. In the past, laboratory and field experiments have proved that this herb can absorb DIN and DIP and improve the environment (Huang et al., 2013; Boxman et al., 2017). However, no information in the literature is available about its practical application in large-scale plantation and its environmental restoration capacity. Without identification of the reasonable plantation scale in theory, it is not only expensive but also difficult to attain the goal if planting in an unjustified scale.

Numerical models can simulate 3D biochemical cycling across scales providing a quantitative hypothesis of process dynamics and rates among planktons, nutrients, discharged chemical matters and cultured organisms (Fulford et al., 2010; Wild-Allen et al., 2013; Jiang et al., 2015; Xia and Jiang, 2016). Using models, Fulford et al. (2010) evaluated the ecosystem response to oyster restoration and nutrient load reduction, and Ibarra et al. (2014) studied environmental impacts and carrying capacity of bivalve culture. So far, no study was reported about model assessment in phytoremediation of *S. portulacastrum* in eutrophic waters.

In this study, we used a 3D ecological model to quantitatively evaluate the ability of *S. portulacastrum* in reducing eutrophication and explore the rational plantation scale for phytoremediation, taking the intensive aquaculture area of the Dongshan Bay for example. To this end, based on interdisciplinary field observations and field plantation experimental results we built the ecological model for the aquaculture area, simulated the variations in key biochemical elements by planting *S. portulacastrum* in the restoration area at some certain scales, assessed the phytoremediation effect, and finally determined the reasonable plantation scale.

2 Data and methods

2.1 *Observation data*

2.1.1 *Environmental elements*

The background concentrations of the biological and chemical elements used in this study were the average results of twice observations performed on May 17 and 26, 2013. Figure 1 shows the ten investigation sites, seven of which are distributed in the environmental restoration area (i.e., Bachimen), and three in the vicinity of the open boundary of the ecological model. The main environmental elements include temperature, salinity, DIN, DIP, chlorophyll *a* (Chl *a*) and particulate organic carbon (POC). The values of detritus were obtained by deducing Chl *a* from POC.

The hydrodynamic model validation was based on the data (water depths, velocities and directions of water currents) observed from 9:00 am on 6 September to 10:00 am on 7 September 2013 at Site A in Bachimen and Site B in the vicinity of the ecological model boundary (Fig. 1). Current velocities were measured using HXH03-1S ultrasonic Doppler flow meters. The water depths and currents were measured every hour.

2.1.2 *Detritus release from aquaculture*

According to our investigations in 2003 conducted by Fujian Fisheries Research Institute, there were a total of ~10 000 fish cages in the Dongshan Bay, among which ~6 000 were located in Bachimen area. In the bay, the culture produced 3 166.8 t residual baits (containing 46.9 t organic nitrogen and 41.8 t phosphate) and 933.5 t fish manure (containing 8.5 t organic nitrogen and 5.6 t phosphate) per year. Based on the proportion of the cage quantity in Bachimen to the total quantity in the bay, 60% of these organic detritus were allocated to Bachimen water.

2.2 *Field experiments of planting S. portulacastrum*

The plantation experiments were carried out in the environmental restoration area by Fujian Fisheries Research Institute in 2014–2015. About 3 000 terrestrial *S. portulacastrumi* plants were transplanted from the seashore saline-alkaline land to the floating beds. Figure 2 shows the photos of *S. portulacastrumi* planted in the area. The plants with ~15 cm length stems were inserted into the floating beds in an initial density of ~60 shoot/m^2 (Fig. 2a) and reached the fast-growth period six months later (Fig. 2b).

Fig. 2. Pictures for 1 month (a) and 6 months (b) after planting *S. portulacastrum*.

According to our experiments, after eight months of growth from August 2014 to April 2015, the density of *S. portulacastrumi* was up to 1 488 plant/m^2, the average length of stem and root was 128 cm and 52 cm, respectively, the average weight of stem and leaf was 63.3 g/plant, the average root weight was 39.2 g/plant, and the average fresh biomass was up to 152.5 kg/m^2. In the period, the estimated nitrogen and phosphorus from water in the biomass were 377.0 g/m^2 and 22.9 g/m^2, respectively. Based on the experiments under laboratory conditions, Wu et al. (2011) reported that the nutrient absorption rate is 4.28–11.11 μmol/(g·d) for nitrogen and 0.14–0.74 μmol/(g·d) for phosphorus. According to their results, we estimated the total absorption in eight months is 225.0–580.9 g/m^2 for nitrogen and 16.3–85.9 g/m^2 for phosphorus. Our values from field plantation experiments are within their limits.

2.3 *Model setup and numerical experiments*

2.3.1 *The ecological model*

The ecological model was established based on the hydrodynamic model coupled with the biochemical process with consideration of the effects of aquaculture and phytoremediation. The principle for selecting model variables is that important biochemical processes should be reflected but not too complicated. Here the conversions among nutrients and organic matters are required to be simulated. In the case of a lack of zooplankton (Z) observation, we used the *NPD* type model with variables of nutrients (*N*), phytoplankton (*P*) and detritus (*D*), with consideration of the detritus release from aquaculture and the nutrient absorption by *S. portulacastrum* (*Sp*). In the model, nutrients include DIN and DIP with units of mg/L, phytoplankton is represented using the Chl *a* concentration with a unit of mg/m^3, and detritus is expressed in mg/L (calculated by carbon). All mass conversions for each variable were computed as a source or sink in the hydrodynamic model to achieve simulations of biochemical processes. Figure 3 shows the conceptual sketch of the ecological model, and the process equations of the model are defined as

$$
\begin{aligned}
&\frac{\mathrm{d}}{\mathrm{d}t}P = Grow\_P - Rsp\_P - Exc\_P - Mort\_P\ ,\\
&\frac{\mathrm{d}}{\mathrm{d}t}N = -Grow\_P + Rsp\_P + Rm\_D - Grow\_Sp\ ,\\
&\frac{\mathrm{d}}{\mathrm{d}t}D = Mort\_P - Rm\_D + Exc\_P + Exc\_Aq - Sk\_D\ .
\end{aligned}
\qquad (1)
$$

where $\frac{\mathrm{d}}{\mathrm{d}t} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} - \frac{\partial}{\partial x}\left(A_\mathrm{h}\frac{\partial}{\partial x}\right) - \frac{\partial}{\partial y}\left(A_\mathrm{h}\frac{\partial}{\partial y}\right) - \frac{\partial}{\partial z}\left(A_\mathrm{v}\frac{\partial}{\partial z}\right)$. u, v and w are water current velocities. A_h and A_v are the horizontal and vertical turbulent diffusivities. Through literature references (Hu et al., 2004, 2016; Liu et al., 2010, 2015) and model calibration by numerical experiments, the functions of biogeochemical processes are expressed as follows:

The algal growth $Grow\_P = g_\mathrm{P}\mathrm{e}^{\mu_\mathrm{P}T}\min\left[\min\left(\frac{DIN}{DIN+K_\mathrm{N}}, \frac{DIP}{DIP+K_\mathrm{P}}\right), \frac{I}{I_\mathrm{opt}}\mathrm{e}^{\left(1-\frac{I}{I_\mathrm{opt}}\right)}\right]P$, where the maximum algal growth rate at 0°C is

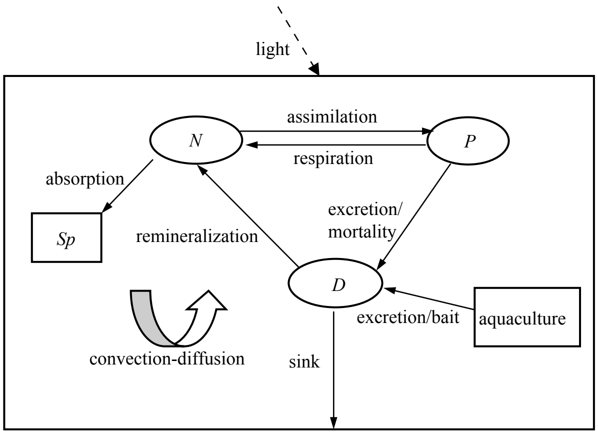

Fig. 3. Conceptual sketch of biochemical processes in the ecological model used in this study.

g_P=0.062 h^{-1}, and the exponent coefficient related to water temperature T is μ_P=0.05°C^{-1} (Liu et al., 2015). Half-saturation constants of nutrients are K_N=2.0 μmol/L and K_P=0.125 μmol/L. I=I_0 e^{-kz} is light intensity, I_{opt}=66 W/m^2 is the optimum radiation, I_0 is the solar radiation with effective photosynthesis at sea-surface, and the reduction coefficient of light is given by k=k_0+ k_1P+$k_2P^{2/3}$ (Radach and Moll, 1993) with k_0=0.65 m^{-1}, k_1= 0.008 8 m^2/mg and k_2=0.054 m/$mg^{2/3}$.

The metabolism of phytoplankton is expressed as $Rsp\_P = m_P e^{\gamma_P T}P$, where m_P=0.001 h^{-1} is the maximum respiration rate at 0°C and γ_P=0.063 3°C^{-1} is the exponent coefficient related to temperature (Liu et al., 2010).

The algal death is $Mort\_P = d_P e^{\gamma_d T}P$(Hu et al., 2016), where the natural mortality rate at 0°C is given by d_P=0.009 5 h^{-1} and γ_d=0.065°C^{-1} is the exponent coefficient.

The algal excretion Exc_P=$E_P Grow\_P$, where E_P=0.25 is the excretive coefficient.

The detritus remineralization $Rm\_D = em \cdot e^{\gamma_D T}D$ (Hu et al., 2016), where em=0.002 1 is the remineralization rate at 0°C and γ_D=0.06°C^{-1} is the exponent coefficient.

The sinking of detritus $Sk\_D = W_S \dfrac{\partial D}{\partial z}$, where W_S=5×10^{-6} m/s is the sinking velocity (Hu et al., 2004).

The solar radiation I_0=$I_S P_a(1-R_a)F$, where the reflective coefficient at sea surface R_a=0.04 (Liu et al., 2010), the penetration ratio through cloud P_a=0.75, and the light energy rate for photosynthesis F=0.47. The radiation above cloud is given by $I_S = I'$ (sin$d(\psi)$sin$d(n)$+cos$d(\psi)$cos$d(n)$cos$d(\lambda)$), when h_1<h<h_2 (else I_S=0), where I'=I_{10}(1.006+0.334 3 cos$d(\varphi)$+0.001 sin$d(\varphi)$), ψ=arcsin (sin$d$(23.5)sin(2π(ID–80)/365)), φ=2π(ID–2.84)/365, λ=–15h–E+292.5, $h_1 = (292.5 - E - \lambda')/15$, $h_2 = (292.5 - E + \lambda')/15$, I_{10}=1 367 W/m^2, λ'=arccosd(-tand(n)tand(φ)), ID is the day's sequence number in a year, and n, E and h are latitude, longitude and Beijing standard hour, respectively (Hu et al., 2016).

The specific ratio of Chl *a* to nitrogen is 1.68 g/mol, the ratio of carbon to nitrogen is 75.6 g/mol in detritus, and the mole ratio of nitrogen to phosphorus is 16 for phytoplankton and detritus (Liu et al., 2010, 2015).

Exc_Aq is the detritus release from aquaculture, and *Grow_Sp* is the absorption of nutrients by *S. portulacastrum*. Their values are given from our field experimental results shown in Section 2.2 and Section 2.3.3.

2.3.2 *Model configuration*

The biochemical processes were simulated using a physical-biogeochemical coupled plankton ecosystem model (PECOM) (Wan et al., 2001) which has been well used in some seas in China and abroad (e.g., Hu et al., 2004, 2016; Liu et al., 2010, 2015). Compared to other ecological models with more complex biochemical processes (e.g., Anderson et al., 2010; Jiang et al., 2015; Xia et al., 2016), our model is a type of *NPZD* mainly focusing on the conversation process among these biochemical variables and satisfies the demand of this study. Besides, Princeton Ocean Model (POM) (Mellor, 2004) was used to reproduce the physical process.

In the study bay, tidal currents are the prominent physical process (Zheng et al., 2013), so wind-circulation and baroclinicity related to salinity were not considered in the hydrodynamic model. In the model, a water-level forcing is adopted at the open boundary,

$$H = h_0 + \sum A_i \cos(w_i t - \theta_i + \phi_i), \tag{2}$$

where h_0, A_i, θ_i and ϕ_i represent the average depth, amplitude, phase lag and initial phase of tide constituents, respectively. Four component tides are M_2, S_2, O_1 and K_1. The modeled region covers the whole of the Dongshan Bay (Fig. 1), and the open boundary is at the bay mouth. The harmonic constants of these tides in Eq. (2) were obtained from interpolating harmonic tidal results of an operational high-resolution wave-tide-circulation coupled ocean model for the China seas (Wang et al., 2016; Zhao et al., 2018). The grid distances in horizontal directions of east-west and south-north are both ~200 m. In vertical, five layers were equally split. The calculation step is 2 s for the outer mode and 10 s for the internal mode.

The investigated results of biochemical variables, salinity and temperature were used for initial values at each grid point by performing spatial inverse-distance interpolation. An upstream advection scheme (Mellor, 2004) was adopted at the open boundary where the values were given by averaging observations at three outmost stations. With same grids as the physical model, the ecological model area covers the west of the long dash line (shown in Fig. 2). The circumstances in May of 2013 were simulated with a calculation step of 0.5 h. In order to make the biochemical variables do not change following the spring and neap tides, the model simulated the moderate tide situation. Because the model was verified using the background concentration in May of 2013 for evaluating phytoremediation, the simulation was conducted under the light intensity condition of this month.

2.3.3 *Numerical experiments for the assessment*

After verification of the background ecological model, the phytoremediation effects of planting *S. portulacastrum* was then numerically assessed by involving its absorption of nutrients into the environmental restoration area as shown in Fig. 1. The absorption rates were obtained by equally dividing the values of 377.0 g/m^2 (N) and 22.9 g/m^2 (P) by the growing period of 240 d into each hour time in the model.

Some area proportions (from 5% to 20% with an interval of 1%) of the whole restoration area used for planting *S. portulacastrum* were taken in numerical experiments for the assessment. To compare the phytoremediation effects, the numerical experiments were taken within a same time period as that of the background model.

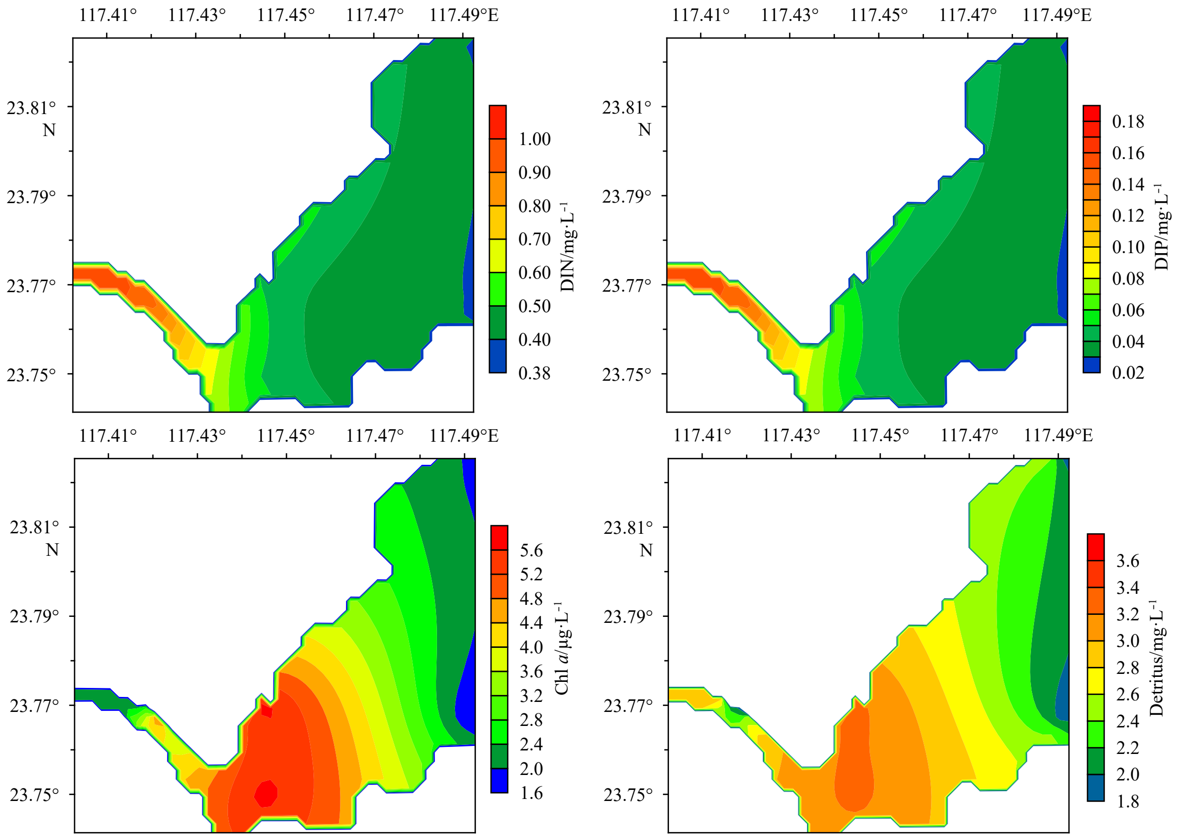

Fig. 4. Observed depth-averaged background concentrations of DIN, DIP, Chl *a* and detritus in the study area.

3 Results and discussion

3.1 *The observed background concentrations*

Figure 4 shows the observed depth-averaged background concentrations of DIN, DIP, Chl *a* and detritus. It can be seen that the nutrient concentration is relatively high in Bachimen, where the average DIN and DIP is 0.75 mg/L and 0.097 mg/L, respectively, much higher than Grade IV standards, i.e., 0.4 mg/L< DIN⩽0.5 mg/L and 0.03 mg/L<DIP⩽0.045 mg/L (MEP, 2004), and also the mean concentrations in the Dongshan Bay where DIN was 0.30–0.40 mg/L and DIP was 0.04–0.06 mg/L (Chen et al., 2014). The water in Bachimen is of severe pollution and eutrophication. The concentrations of Chl *a* and organic detritus at the Bachimen mouth are higher than those in the water enclosed by Bachimen and the outer area. Their average concentrations in Bachimen are 4.56 mg/m^3 and 3.14 mg/L, respectively. Higher Chl *a* and detritus concentrations, especially Chl *a*, are conducive to food intake of aquatic organisms. As the main function of Bachimen is aquaculture, the water should meet Grade II quality standards. The concentrations of nutrients have exceeded environmental carrying capacities and need to be reduced to the required ones.

3.2 *Model validation*

3.2.1 *Water levels and currents*

Figure 5 shows the simulated and observed water levels, surface current velocities and surface current directions at the two observation sites. It can be seen that the simulated water levels and velocities are consistent with observations, and the simulated curves are basically coincided with the observed. Overall, the model objectively reproduces the tidal process in the study area. The maximum tidal range of the two observation sites is ~3.5 m and the maximum current velocity is ~0.46 m/s in the inner of Bachimen, and 0.7 m/s (relatively high) in the outer. Moreover, the model and observations indicate that the tidal process is the dominant hydrodynamic process in the Dongshan Bay, which tallies with the study by Zheng et al. (2013).

The observed and modeled results indicate that the tide in the study area is semidiurnal and shows a characteristic of strong reciprocating flows. The observations by Zheng et al. (2009) also show these features. The main flow directions at the two measurement sites are from northeast to southwest. The northeastward is the flood direction and the southwestward is the ebb direction. Besides, the maximum velocity at the flooding period is smaller than that at the ebbing. The overall tidal current flows along the coastline with velocities which are higher at the bay mouth than those in the inner bay and higher in the middle deep area than those of the near-shore shallow water. These regimes also have been observed by Zheng et al. (2009, 2013).

3.2.2 *Nutrients and organic matters*

Figure 6 shows the modeled distributions of the depth-averaged background DIN, DIP, Chl *a* and detritus, and Fig. 7 compares the modeled concentrations of them and the observed at seven investigation sites which are marked from west to east in the rectangle in Fig. 1.

Figure 6 indicates that the simulated DIN and DIP are the highest in the inner of Bachimen, where the average DIN is ~0.82 mg/L (nearly equal to the observed value of 0.75 mg/L) and the average DIP reaches 0.10 mg/L (nearly equal to the observed value of 0.097 mg/L), which are far higher than Grade IV stand-

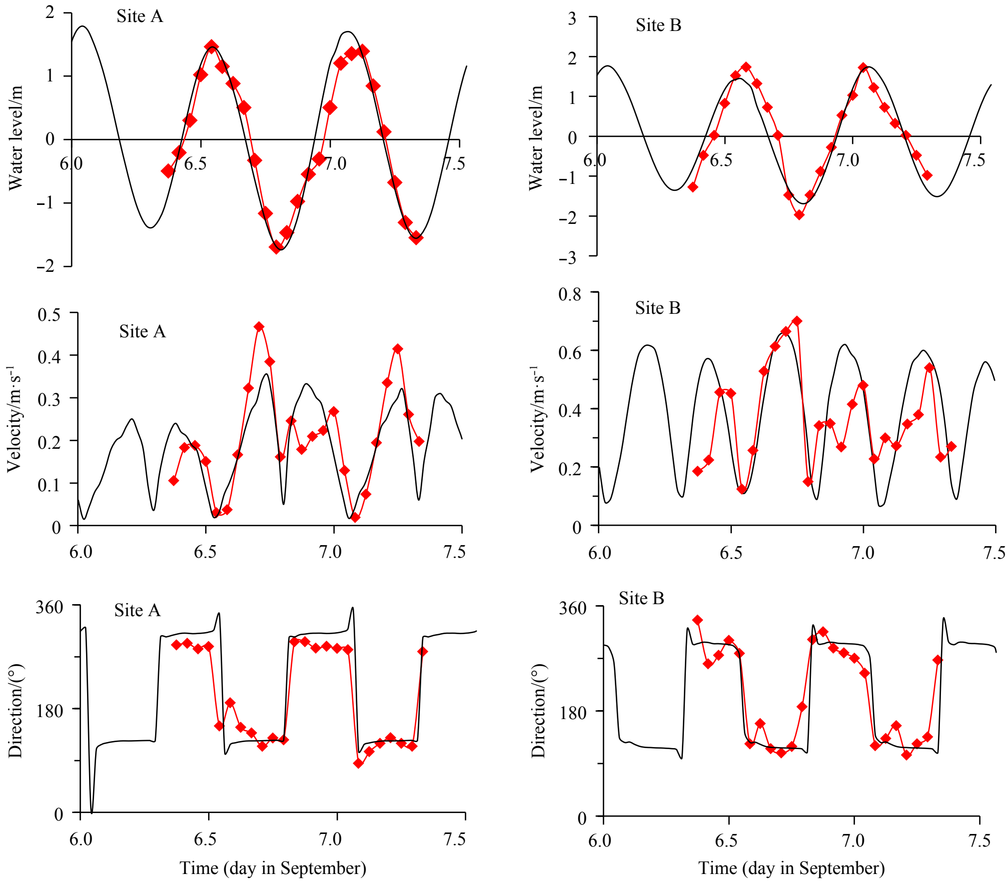

Fig. 5. Simulated (black lines) and observed (red dotted lines) water levels, surface current velocities and surface current directions at two observation sites.

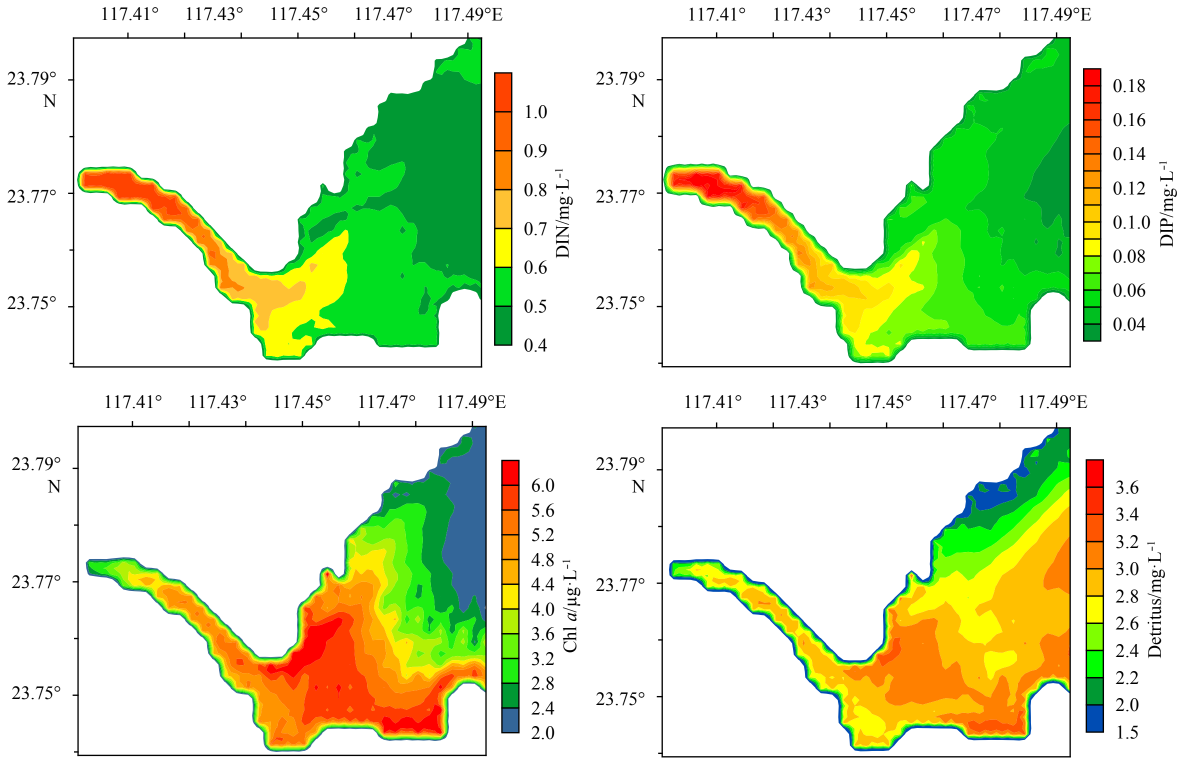

Fig. 6. Simulated depth-averaged background concentrations of nutrients, Chl *a* and detritus in the study area.

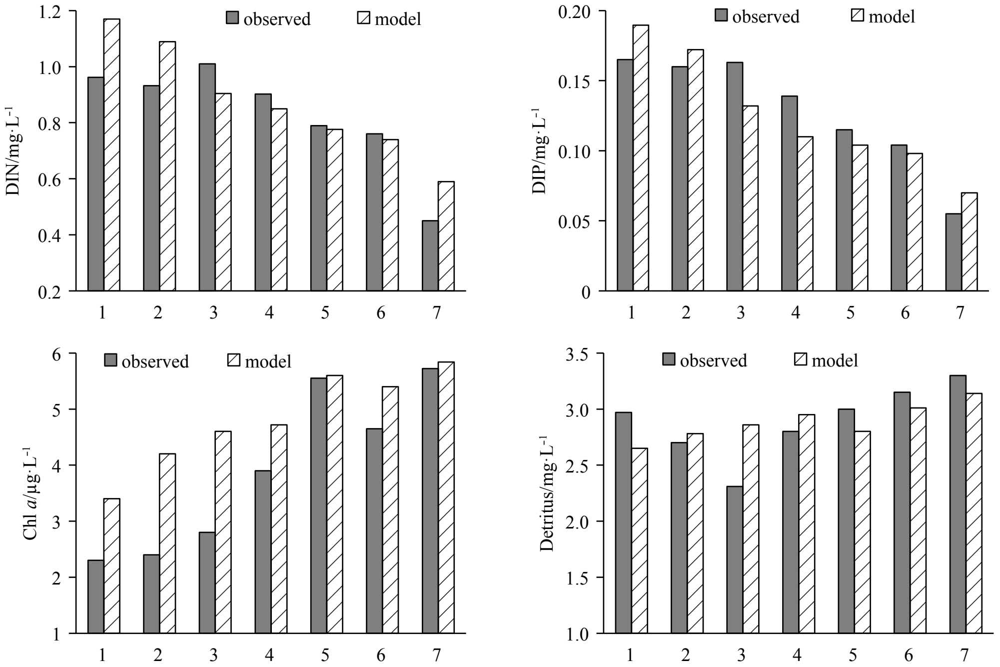

Fig. 7. Comparison between the simulated and observed depth-averaged concentrations of DIN, DIP, Chl *a* and detritus at seven investigation sites, which are sequently marked from west to east in the rectangle in Fig. 1.

ards. With the longer distance from Bachimen and the water increasing depth, the nutrient concentrations gradually decrease. Chl *a* and detritus are relatively high at the mouth of Bachimen. In Bachimen, the average concentrations of Chl *a* and detritus are 4.8 mg/m^3 and 3.0 mg/L, respectively, which are very close to the observed values of 4.56 mg/m^3 and 3.14 mg/L. Due to the poor water exchange, nutrient concentrations are high in Bachimen. Moreover, due to high transparency, appropriate depth and favorable nutrient composition to the algal growth, Chl *a* is the highest at the mouth of Bachimen.

It can be seen from Figs 4 and 6 that the simulated values and distributions of DIN, DIP, Chl *a* and detritus are in good agreement with observations. Their average concentrations are close to the observed, which can be also seen from Fig. 7 by comparing the simulations and the observations at the seven sites. The modeled values for the four variables are around the observations. The average deviation between the simulations and observations of these sites is 13% for DIN and 15% for DIP. In general, the model effectively describes the background concentration of key ecological elements in the study area and can be used to assess phytoremediation.

3.3 *Nutrient removal by S. portulacastrum*

The laboratory and field experiments have proved that *S. portulacastrum* can absorb N and P and improve marine environment (Huang et al., 2013; Boxman et al., 2017). However, no information in literature was available about its practical application in large-scale plantation and environmental restoration capacity in seawater. To evaluate the eutrophic decease in the restoration area beforehand, the numerical simulations were taken for some plantation scales (given in Section 2.3.3). It is proved that *S. portulacastrum* can absorb excessive nutrients to efficiently restore the environment. Figures 8a and b show the simulated changing processes of DIN and DIP concentrations under circumstances of plantation within 70 d from 1 May 2013, and Fig. 8c shows the nutrient concentrations after phytoremediation.

The numerical experiments show that if the plantation scale is 5%–7% of the restoration area, the concentration of DIN is still higher than the Grade IV standard and the water is still of severe pollution. If the plantation scale increases to 9%, DIN is reduced to 0.41 mg/L, in line with Grade IV, indicating that the water is moderately polluted. If the scale increases to 10%–12%, DIN is reduced to the Grade III standard (0.3 mg/L<DIN≤0.4 mg/L) and the water is mildly polluted. If the scale increases to 13%–16%, the concentration is reduced to the required for Grade II, and the water becomes relative clean. If the scale increases to 17%, the concentration is reduced to ≤0.2 mg/L, in line with Grade I and the water is clean.

For the DIP, if the plantation scale is 9%, the average concentration is simulated to be 0.046 mg/L and the water is severely polluted. If the plantation scale increases to 10% and 11%, the concentration is reduced to 0.041 mg/L and 0.035 mg/L, respectively, in line with the Grade IV standard. If the scale increases to 12%–17%, DIP is reduced to meet the Grade III standard and the required Grade II standard. If the scale increases to 18%, the concentration is reduced to 0.015 mg/L, in line with the Grade I standard (≤0.015 mg/L), and the water becomes clean.

Overall, if the plantation scale is less than 9%, the restoration area is still severely polluted. If the plantation scale is 11%, the overall water quality in the area is of Grade IV and the water is moderately polluted. If the scale is 12%, the nutrient level meets the Grade III standard. If the plantation scale reaches 13%, DIN and DIP concentrations are reduced to 0.28 mg/L and 0.027 mg/L, respectively, meeting the required standard of Grade II. If the scale reaches 18%, the water quality is Grade I.

Numerical assessments indicate that planting *S. portulacastrum* in 13% of the restoration area can reduce nutrient concentrations to the levels meeting Grade II standards suitable for aquaculture.

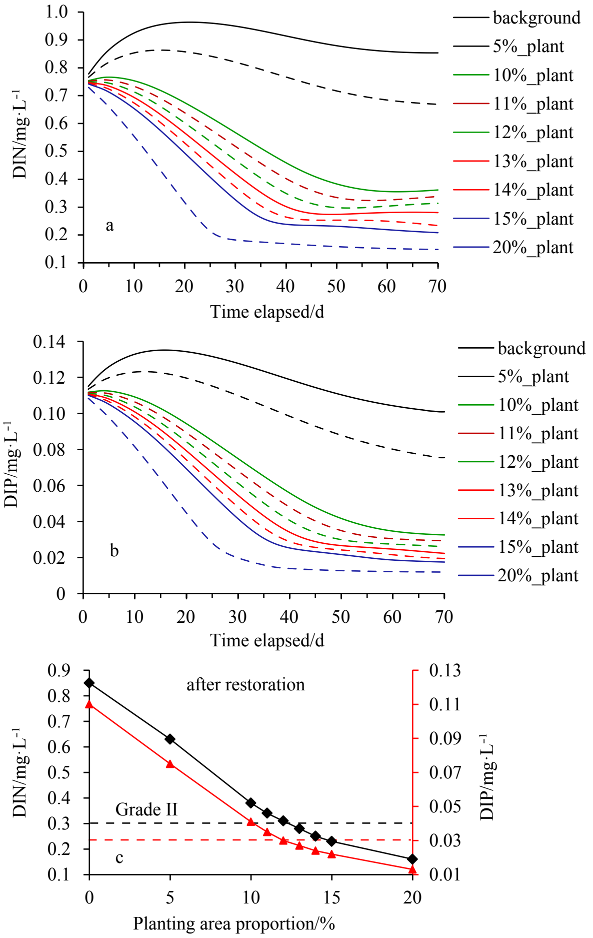

Fig. 8. Simulated changes of average concentrations of DIN (a) and DIP (b) with time under circumstances of planting *S. portulacastrum* at a certain scales in the restoration area; and the relationships of average nutrient concentrations after phytoremediation with the plantation scales (c). The percent value represents the proportion of the plantation area to the restoration area, and two horizontal dash lines represent critical levels of Grade II for DIN and DIP.

Table 2. The simulated Chl *a* and detritus concentrations under the circumstances of phytoremediation at certain plantation scales

Plantation scale	10%	12%	13%	14%	15%
Chl *a*/mg·m^{-3}	3.4	2.8	2.4	1.8	1.4
Detritus/mg·L^{-1}	2.0	1.4	1.1	0.85	0.74

Note: The percent represents the proportion of plantation area to the restoration area.

Table 3. The simulated DIN and DIP concentrations after phytoremediation combined with controlling aquaculture

Plantation scale	10%	11%	12%	13%
DIN/mg·L^{-1}	0.35	0.33	0.30	0.26
DIP/mg·L^{-1}	0.032	0.028	0.025	0.021

Note: The percent represents the proportion of plantation area to the phytoremediation area, and the same proportion for the culture scale is reduced.

3.4 *The effects of planting S. portulacastrum on organic matters*

As the main function of the study area is fish culture and the fish need to intake organic matters in water, especially phytoplankton, a higher organic content can reduce the dependence on feed and the brought pollution. Planting *S. portulacastrum* could decrease nutrients and bring about their resultant restrictions to algal growth, thereby reducing the biomass of phytoplankton and the primary productivity. Therefore, when decreasing the levels of nutrients, it is better not to significantly reduce the concentrations of organic matters.

Our model shows the simulated Chl *a* and detritus concentrations after lowering the nutrient level via planting *S. portulacastrum* (Table 2). When the plantation scale is 10%, 12%, 13%, 14% and 15%, Chl *a* is reduced to 3.4, 2.8, 2.4, 1.8 and 1.4 mg/m^3, respectively, and the average detritus is 2.0, 1.4, 1.1, 0.85 and 0.74 mg/L, respectively. Obviously, a direct result of planting *S. portulacastrum* is that the algal growth is limited, resulting in a decrease of the concentrations of organic matters. The larger the plantation scale is, the lower the concentrations. The laboratory tank experiments (Lin et al., 2011) and field campaign (Huang et al., 2013) also proved that *S. portulacastrum* could remove organic matters in water. In order to facilitate fish-culturing, the optimal acreage for plantation should be defined to decease the nutrient concentration to the required level, while not significantly decrease organic matters. When the plantation scale is 13%, Chl *a* is decreased to about half of the initial concentration. Although the plantation at this scale has a significant impact on phytoplankton, its concentration is not reduced too much. Besides, fish culture is mainly dependent on feed rather than phytoplankton in water. Therefore, 13% acreage for planting *S. portulacastrum* is a reasonable scale.

3.5 *Combination of planting S. portulacastrum and controlling the aquaculture scale*

To facilitate the plantation, we proposed to reduce a certain scale of cage-culturing and plant *S. portulacastrum* on the top of these cages. The ecological model was used to simulate the restorative effects of reducing the aquaculture scale by 10%, 11%, 12% and 13%, respectively (meanwhile planting the herbs on these idle cages and the floating beds, the total plantation area is equivalent to this proportion of the restoration area). In the model, the reduction of aquaculture means decreasing the flux of organic detritus by the corresponding proportion. The simulation results show that under this method, when the plantation scale is 10%, 11%, 12% and 13%, the average concentrations of DIN is reduced to 0.35, 0.33, 0.3 and 0.26 mg/L, respectively, and DIP is reduced to 0.032, 0.028, 0.025 and 0.021 mg/L, respectively (Table 3). The water quality after phytoremediation at the latter two scales, rather than the former two, meets the Grade II standard.

Therefore, we proposed to cut the scale of fish cage culturing by 12% and use these culturing facilities and the floating beds to plant *S. portulacastrum* in 12% of the restoration area. By doing so, we can restore the nutrient-polluted water to meet the Grade II standard. In this circumstance, the concentrations of Chl *a* and detritus are 3.0 mg/m^3 and 1.3 mg/L, respectively, higher than those of planting *S. portulacastrum* at 13% of the area without reducing aquaculture.

4 Conclusions

In this study, the phytoremediation for the severe eutrophic water via planting *S. portulacastrum* in the floating beds was evaluated using the ecological model based on field surveys and field plantation experimental results. The field experiments show that *S. portulacastrum* can absorb 377 g/m^2 nitrogen and 22.9 g/m^2

phosphorus in eight months with an initial inserting density of ~60 shoot/m^2. The model assessment suggests that for the aquaculture area of the Dongshan Bay where the nutrient level with 0.75 mg/L nitrogen and 0.097 mg/L phosphorus far exceeded China's Grade IV water quality standards, if *S. portulacastrum* is planted at 13% of the area in the above inserting density, or alternatively at 12% combining with reduction of aquaculture by this percent, DIN and DIP concentrations will be reduced to the Grade II standards (0.2 mg/L<DIN⩽0.3 mg/L, 0.015 mg/L<DIP⩽0.03 mg/L, suitable for aquaculture). These assessment results provide the basis for the future plantation for environmental restoration.

Taking the case of the intensive aquaculture area of the Dongshan Bay, our study indicates that *S. portulacastrum* has a strong ability of nutrient removal. The study shows a new method to restore marine environment for eutrophic waters by planting this herb, and further provides a helpful reference for determining the reasonable plantation scale for other eutrophic waters.

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