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Research Article

Simulating the Range Expansion of *Spartina alterniflora* in Ecological Engineering through Constrained Cellular Automata Model and GIS

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Environmental factors play an important role in the range expansion of *Spartina alterniflora* in estuarine salt marshes. CA models focusing on neighbor effect often failed to account for the influence of environmental factors. This paper proposed a CCA model that enhanced CA model by integrating constrain factors of tidal elevation, vegetation density, vegetation classification, and tidal channels in Chongming Dongtan wetland, China. Meanwhile, a positive feedback loop between vegetation and sedimentation was also considered in CCA model through altering the tidal accretion rate in different vegetation communities. After being validated and calibrated, the CCA model is more accurate than the CA model only taking account of neighbor effect. By overlaying remote sensing classification and the simulation results, the average accuracy increases to 80.75% comparing with the previous CA model. Through the scenarios simulation, the future of *Spartina alterniflora* expansion was analyzed. CCA model provides a new technical idea and method for salt marsh species expansion and control strategies research.

1. Introduction

Spartina alterniflora (*S. alterniflora*) which is native to the Atlantic Coast and Gulf Coast of North America is a perennial and deep-rooted salt marsh grass that is found in intertidal wetlands, especially estuarine salt marshes. With its great capacity for reducing tidal wave energy, mitigating erosion, and trapping sediment, *S. alterniflora* has been widely planted on intertidal zones as a species for ecological engineering by many countries at the beginning of the 20th century. *S. alterniflora* was firstly introduced to China in 1979 purposely for beach protection and siltation promotion and has expanded rapidly outside of its original area along the coast of China [1, 2]. In recent years, however, some evidence has been reported that this species may outcompete native plants, alter the mudflat habitat, change and even diminish biodiversity, damage the coastal aquiculture, and cause declines in native species richness in the tidal land [1, 3]. As a result, since 2003, *S. alterniflora* was listed as 1 of the 16 invasive species by the Environmental Protection Bureau of China. *S. alterniflora* is a competent pioneer and serves a series of functions in coastal ecosystem. On the contrary, its rapid spread on tidal lands has made it a dreaded invader.

Chongming Dongtan wetland is an important young tidal wetland in the Yangtze River Estuary that plays an important role in balancing the carbon discharge of the estuary. The wetland was listed in the Chinese Protected Wetlands (1992) and was designated as internationally important under the Ramsar Wetlands Convention (2001) and a national nature reserve (2005). The salt marsh with elevation less than 2 m is characterized by mud flats without any vascular plants. The salt marsh between 2.0 and 2.9 m elevation is dominated by *Scirpus mariqueter* (*S. mariqueter*) community, with some rarer *Scirpus triqueter* community. Above 2.9 m, plant communities are dominated by *Phragmites australis* (*P. australis*) [4]. *S. alterniflora* was introduced to Chongming Dongtan in

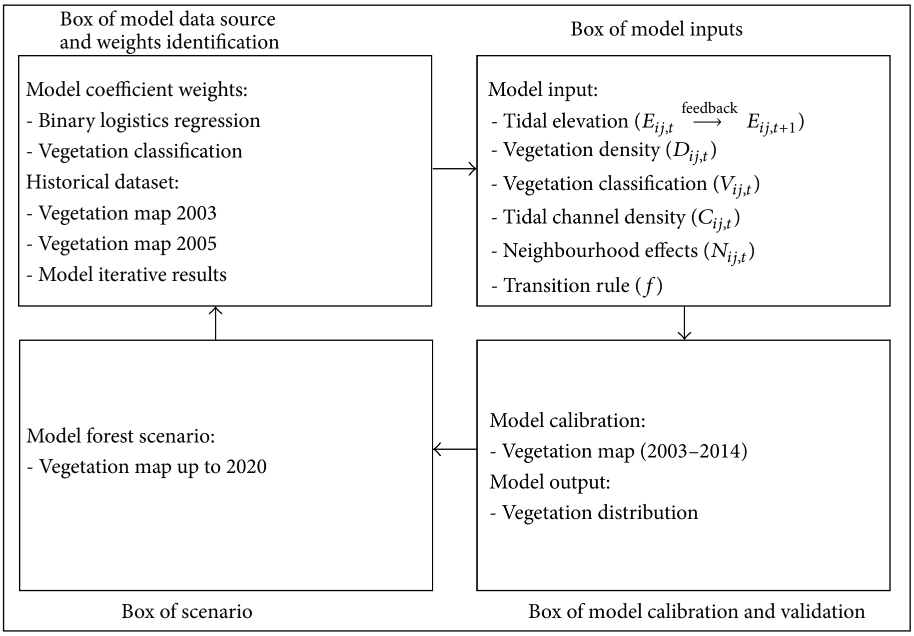

Figure 1: Diagram representing the conceptual model framework.

1995. There have been a rapid expansion of this species and hence a significant growth of wetland since then [5]. Over the last 20 years, *S. alterniflora* has gradually invaded large areas formerly covered by *P. australis* and has also started to invade the upper parts of the *S. mariqueter* community [3, 6–8]. In particular, the decrease of *S. mariqueter* on the high tidal flat due to *S. alterniflora* expansion will seriously threaten the habitat suitability for migratory birds at Chongming birds nature reserve [9, 10]. Some physical techniques were already promoted to control the invasion of the exotic species *S. alterniflora* [4, 11–13]. To understand the invasion dynamics and mechanisms of species, simulation model is a key tool to integrate information and test hypotheses and has been of great importance assisting management agencies with the design of effective monitoring and control strategies [14, 15].

Recently some cellular automaton models were constructed to simulate spatial variation as a consequence of competitive interactions [3, 16]. In fact, vegetation patterns are strongly linked to the topographic characteristics of the marsh, which stabilize marsh surface sediments, increase friction to hydrodynamic flow, and reduce water sediment transport, thereby increasing sedimentation from the water column [17, 18]. Such topographic modification could in turn strongly affect the vegetation communities' structure and distribution, providing more niches and thereby facilitating the range expansion [8, 18]. However, the few process-based ecological hypotheses and available parameters obtained from field measurement and experiment limited the accuracy and utility of the models [19]. Huang et al. (2008) only put the elevation parameter on the transition rules and controlled the expansion speed by the selective Moore radius in CA model [20]. In this paper, we employed a constrained CA (CCA) model to simulate the expansion of *S. alterniflora*, which already produced highly acceptable results in urban environment model. To improve the model accuracy, more environmental factors including elevation, tidal channel density, and vegetation density were incorporated in the CCA model. Meanwhile, a positive feedback loop between vegetation and sedimentation was also considered in CCA model through analyzing the erosion rate in different vegetation communities.

2. Establishment of CCA

A cellular automaton is defined by (S, N, f). A CA was defined with set language as follows:

$$S^t = f\left(S^{t-1}, N\right), \tag{1}$$

where S is a finite set and represents the cell state, t the transition step, f the transition rule or function, and N the cell neighbors. This CA only considers the effect of neighbors, which is called conventional CA. But this kind of CA can be inappropriate when modeling and predicting complex and dynamic vegetation processes realistically, because the vegetation class transitions are driven by the more environmental variables. For purposes of *S. alterniflora* dynamics, a more complex CA model (constrained CA model) is needed, which considers more relative factors. Constrained cellular automata (CCA) are produced with embedding some constraints in the transition rules of cellular automata, which are able to provide much better alternatives to actual development patterns [21].

2.1. Model Description. The CCA model was developed using Matlab software and ArcGIS software, in order to simulate the range expansion of *S. alterniflora* on the coastal mudflats. Figure 1 showed the simulation process with a four-step cycle, including model inputs, factor weights identification, model calibration and validation, and forecast scenario. E_{ij}, D_{ij}, V_{ij}, C_{ij}, N_{ij}, and the transition potential rule in model inputs box made up the model outputs for the calibration procedure. In model calibration and validation box, CCA was rectified through model results with corresponding vegetation map from remote sensing classification. The final step introduced one vegetation map scenario in scenarios box, which provided spatial information about the vegetation dynamics until 2020. Based on these outputs, the model was validated by comparing the simulated *S. alterniflora* distribution with the observed vegetation map to optimize the model coefficient weights in data source and weights identification box.

2.2. Model Inputs. A number of ecologists have evaluated the environmental factors affecting the plant distribution patterns in salt marsh environments, for example, soil elevation [22, 23], salinity [24, 25], nutrient availability [26, 27], inter- and intraspecific competition [28, 29], and grazing and human management [12, 29]. These researches have provided more information on the controlling factors on vegetation expansion, which can be used to improve simulation models of the overall. In all these factors, tidal elevation is regarded as convenient metric that integrates a number of hydrologic and edaphic factors [24]. In our study area, Ge et al. also reported that the combination of dense *S. alterniflora* meadows with high elevation and weak flow intensity resulted in a higher density of seedling establishment [19]. So tidal elevation (E_{ij}) and vegetation density (D_{ij}) were selected as two important constrain factors in CCA model. Some studies have also shown that location and size of tidal channels are fundamental factors in determining plant distribution patterns, since the tidal channel networks largely control the distribution of tidal flooding within salt marshes [30, 31]. To quantify the effect of tidal channel, the density (C_{ij}) was also regarded as one of the model inputs. Another control factor was vegetation classification (V_{ij}) which indicated the competition between *P. australis*, *S. alterniflora,* and *S. mariqueter*. For example, *P. australis* and *S. alterniflora* were obstacles to each other and can only occupy the cells of *S. mariqueter* [20]. Finally, CCA is an array of cells that interact with one another locally according to some neighborhood rules. Each cell evolves which depends not only on the state of the cell but also on the neighboring cells (N_{ij}).

2.3. Transition Rules. A model transition rule changes each cell state to the state that has the highest potential. Based on this rule, transition potential is calculated for each cell during each time step of the simulation. This potential indicates the vegetation pattern for which the cell is best adapted. The potential for each cell is calculated as follows:

$$S_{ij}^{t+1} = f\left(S_{ij}^{t}, E_{ij}^{t}, D_{ij}^{t}, V_{ij}^{t}, C_{ij}^{t}, N_{ij}^{t}, \nu\right), \tag{2}$$

where S_{ij}^{t+1}, S_{ij}^{t} represent the cell (i, j) state at time $(t + 1)$ and time (t), E_{ij}^{t} is tidal elevation of the cell (i, j), D_{ij}^{t} is the vegetation density of cell (i, j), V_{ij}^{t} is the vegetation type of cell (i, j), C_{ij}^{t} is tidal channel density of the cell (i, j), N_{ij}^{t} is the neighbourhood space effect on the cell (i, j), and ν is the random perturbation term at time (t), which is defined as $\nu = 1 + [-\ln(\text{rand})]^{\alpha}$, where $(0 < \text{rand} < 1)$ is a uniform random variable and α is a stochasticity parameter that adjusts the perturbation size.

The five factors are further divided into suitability, resistant, and neighbor factors. The suitability of vegetation is based on three major factors, namely, elevation, vegetation density, and vegetation type, in which value 0 corresponds to the least suitability and value 1 corresponds to the highest suitability. The vegetation suitability is calculated by the following equation:

$$s_{k,ij}^{t}{}' = w_1 * E_{k,ij}^{t} + w_2 * D_{k,ij}^{t} + w_3 * V_{k,ij}^{t}. \tag{3}$$

$s_{k,ij}^{t}{}'$ is the suitability of cell (i, j) for marsh vegetation (k) at time (t). w_1, w_2, and w_3 denote the weights associated with elevation, vegetation density, and type. To consider the feedback loop between tidal elevation and vegetation, $E_{k,ij}^{t}$ is provided as follows:

$$E_{ij}^{t} = \begin{cases} E_{ij}^{0} + n\dfrac{a}{\sum \text{step}}, & S.\ alterniflora \text{ and } P.\ australis; \\ E_{ij}^{0} + n\dfrac{b}{\sum \text{step}}, & S.\ mariqueter; \\ 0, & \text{bare flat}. \end{cases} \tag{4}$$

E_{ij}^{0} is the tidal elevation at the start $(t = 0)$. n is the step number of the model. $\sum$ step is the total simulation steps in one year. a and b are the annual accretion rate of tidal flat. The suitability $s_{k,ij}^{t}$ for a nonvegetation cell to be converted into a vegetation cell can then be expressed as

$$s_{k,ij}^{t} = s_{k,ij}^{t}{}' \times \prod_{r=1}^{m} C_{r,k,ij} \times \nu. \tag{5}$$

$\prod_{r=1}^{m} C_{r,k,ij}$ is the product of a few binary variables used to represent the ecological constraints on the *S. alterniflora* expansion, such as being prevented by tidal channel. $C_{r,k,ij}$ will have a value of 0 if cell (i, j) is preserved due to constraint r where *S. alterniflora* cannot invade into the cell (i, j) occupied by tidal channel.

Salt marsh vegetation parameters in each cell take states of $S_{p\cdot a}$, $S_{s\cdot a}$, $S_{s\cdot m}$, and $S_{b\cdot m}$, representing *P. australis*, *S. alterniflora*, *S. mariqueter* community, and bare mudflat at the beginning of the simulation S_{ij}^{t-1}.The cell states in the next time step S_{ij}^{t} are then defined by salt marsh states and species interactions, which can be summarized by the following rule:

$$S_{ij}^{t} = \begin{cases} S_{p\cdot a}, & S^{t-1} = S_{p\cdot a}; \\ S_{s\cdot a}, & S_{ij}^{t-1} = S_{p\cdot a},\ s_{p\cdot a,ij}^{t-1} > \alpha,\ N_{ij}^{t-1} > \beta; \\ S_{s,a}, & S_{ij}^{t-1} = S_{s\cdot m},\ s_{s\cdot m,ij}^{t-1} > \alpha,\ N_{ij}^{t-1} > \beta; \\ S_{s\cdot a}, & S^{t-1} = S_{s\cdot a}; \\ S_{b\cdot m}, & S^{t-1} = S_{b\cdot m}, \end{cases} \tag{6}$$

where S_{ij}^{t} and S_{ij}^{t-1} represent the cell states at times t and $t - 1$, respectively. $s_{p\cdot a,ij}^{t-1}$ and $s_{s\cdot m,ij}^{t-1}$ denote the *S. alterniflora*

Table 1: Variables retained in the logistic regression model and their coefficients.

	B^1	S.E.^{2}	Wald^3	Df^4	Sig^5	Exp(B)^6	95% C.I. for Exp(B)^7	
							Lower	Upper
W_1	2.817	0.57	2484.209	1	0.000	16.723	14.969	18.682
W_2	−2.449	0.48	2611.628	1	0.000	0.086	0.079	0.095
W_3	1.061	0.28	1396.555	1	0.000	2.889	2.732	3.054

[1] B = logistic coefficient; [2] S.E. = standard error of estimate; [3] Wald = Wald chi-square values; [4] Df = degree of freedom; [5] Sig = significance; [6] Exp(B) = exponentiated coefficient; [7] 95.0% C.I. for Exp(B): 95% confidence interval for Exp(B).

suitability of cell (i, j) at *P. australis* and *S. mariqueter* communities at time $(t-1)$. The thresholds α and β are determined according to the actual cell conversion which is obtained from observation data [32].

2.4. Data Source. The spatial pattern of salt marsh vegetation classification (Figure 1) was based on the multitemporal satellite images of 2000–2005 with the resolution of 30 m on the ground. A supervised classification, using the Maximum Likelihood Classifier in ERDAS Imagine software, was then carried out and the classified imagery was then integrated into a GIS platform [20]. Wetland plants density and tidal channels were mapped from QuickBird image with the resolution of 0.6 m, which was acquired on September 29, 2005. For information not available from high-resolution Lidar elevation data, waterline method combining Landsat TM, tidal gauge, and field elevation transects has been used to generate digital elevation model (DEM) [10, 33–36]. All the data were converted into standard raster data and resampled with a 30 m × 30 m resolution for a total of 551 × 582 cells.

2.5. Weights Identification. Methods determining weights are often divided into two categories: subjective and objective weighting. Objective weighting is suitable to tackle the situations where suggestions of experts are not easily attained [37]. Moreover, objective methods are also able to avoid biases from experts or decision makers due to their predilections through some mathematical methods. In order to determine the weights values in the state transition rules, w_1, w_2, and w_3 were extracted through binary logistic regression method according to three main categories of *S. alterniflora* expansion factors. Binary logistic regression establishes a functional relationship between the binary coded *S. alterniflora* distribution (presence or absence), DEM, classified vegetation, and plants density factors that are recognized as playing a role in *S. alterniflora* expansion. Regression coefficients $w_0 \sim w_3$ show the contribution of each explanatory variable on suitability $s_{k,ij}^{t\ \prime}$. The statistical technique is a multivariate estimation method that examines the relative significance of the factors. By using the statistical analysis software SPSS (19.0), the model coefficients were estimated as shown in Table 1, which were then used to calculate the suitability of *S. alterniflora* expansion potential for all of the pixels in the study region. A positive value means that the variable helps to increase the probability of change, and a negative value implies the opposite effect. Tidal elevation showed more significant effect on *S. alterniflora* expansion than the other vegetation from Table 1. The variables with estimated coefficients having a significance value (Sig) of less than 0.05 were found to be significantly different from zero. These variables can be accepted as influential predictor variables.

The suitability $s_{k,ij}^{t\ \prime}$ was a standardized suitability score [0, 1] based on the consideration of factors. The classification threshold α was selected as 0.5 at $t = 0$ in this paper. By overlying multitemporal satellite data, the numbers of neighbor β were obtained through all the new converted *S. alterniflora* cells around old *S. alterniflora* cells in the area, where all other factors including tidal elevation, vegetation density, and vegetation type were similar (Figure 2). The average of converted numbers around old *S. alterniflora* was 5.68 from the statistics of converted pixels and $\beta = 5.68/8 = 0.71$ was selected at $t = 0$ in this research. A series of α and β was tested for *S. alterniflora* and the tentatively simulated results were compared iteratively with the corresponding salt marsh classification maps until they reached an acceptable range in the calibration procedure.

2.6. Model Calibration and Accuracy Evaluation. Calibration and validation are critical for the performance of CCA models because they largely depend on the appropriateness of the transition rules, which typically involve important parameters [38, 39]. The vegetation maps from 2002 to 2005 were used to calibrate the CCA model by treating the 2002 map as the starting time. The simulated outcome of 2003 and 2005 based on each set of weights was compared with vegetation map of the corresponding year and was used to rectify the model by changing the threshold values α and β. At last the optimized values were used for simulation from 2003 to 2020.

The CCA model accuracy was checked by overlaying the image classification and the simulation output for the whole study area in the ArcGIS platform (Figure 3). By overlaying the predicted *S. alterniflora* distribution with vegetation map, the percentage match of pixels indicated that 80.75% of *S. alterniflora* expansion was correctly predicted in the 8 years from 2005 to 2013 (Table 2). The CCA model accuracy ranged from 76% to 85%, which was higher than the CA accuracy ranging from 37% to 75% as discussed by Huang et al. [20].

3. Simulations and Results

3.1. The Past Expansion of S. alterniflora. Patches of *S. alterniflora* were firstly found on the northeast part of the Dongtan wetland in 1995. The seeds possibly came from the coast of

Table 2: Comparison between the measured and modeled range expansion of *S. alterniflora*.

Pixels	2003	2005	2007	2009	2013	2020
Measured pixels (number)	—	19550	20718	25978	32097	—
Corresponding area (ha.)	—	1760	1865	2338	2889	—
Modeled pixels (number)	11880	15221	17690	21947	24505	28746
Corresponding area (ha.)	1069	1370	1592	1975	2205	2587
Accuracy (%)	—	78%	85%	84%	76%	—
Average accuracy (%)						80.75%

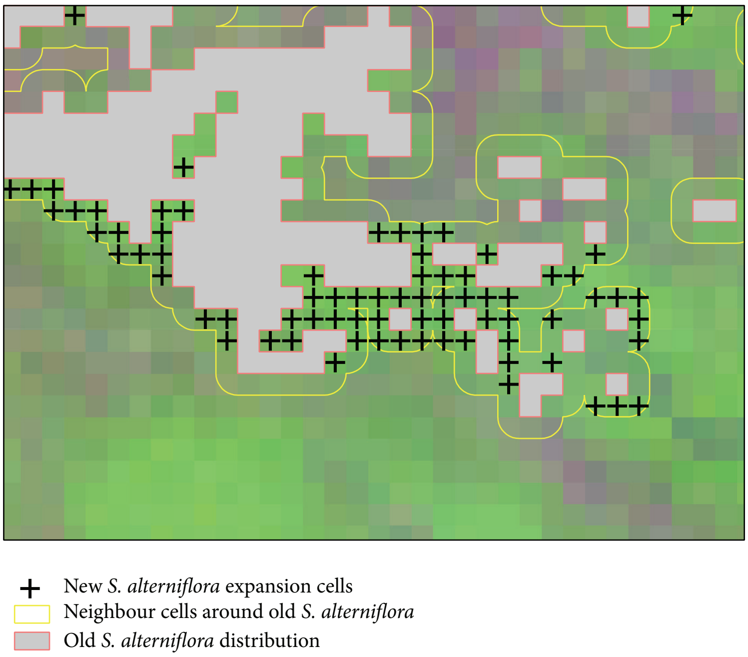

Figure 2: Neighbor effects on expansion pattern.

Jiangsu Province despite natural dispersal by tidal currents [40]. Since then, *S. alterniflora* experiencedslow expansion and formed many stable communities in colonization. For rapid sediment accretion in salt marsh in the estuary, 337 ha and 370 ha of *S. alterniflora* were planted in a belt on the north and northeast in May 2001 and May 2003, respectively [41]. Since 2003, *S. alterniflora* kept a rapid population growth and range expansion (Figure 3). In the spatial pattern, *S. alterniflora* began to expand towards the east and north and emerged among the original *S. mariqueter* community along with the accretion of elevation. As in the simulation process, *S. alterniflora* increased in the ten years from 1069 ha in 2003 to 2205 ha in 2013, which matched closely the area (2889 ha) based on remote sensing vegetation map in the corresponding year (Table 2). The speed of range expansion of *S. alterniflora* subsequently slowed down after 2013, which distributed dominantly in the northern and eastern marshes in Chongming Dongtan.

3.2. The Future Expansion of S. alterniflora. *S. mariqueter* is the pioneer vegetation in the tidal flat, whose emergence and growth create conditions for the colonization of *S. alterniflora* and *P. australis*. *S. alterniflora* has the more rapid expansion due to its wider ecological niche and stronger competitive capacity than native *P. australis* [2]. *S. alterniflora* will continuously expand northwards and eastwards in the future (Figure 4) and the areas will amount to 2587 ha in 2020 according to the simulation (Table 2). With the accretion of intertidal flats, it could be also anticipated that the rapid range expansion of *S. alterniflora* would last for a considerable time on the Chongming Dongtan. So, more attention should also be paid to the dynamics of *S. alterniflora* in the future. In particular, the decrease of *S. mariqueter* due to *S. alterniflora* expansion will seriously threaten the habitat suitability for migratory birds. Some physical techniques were already promoted to control the invasion of the exotic species *S. alterniflora*. The first stage of control project of *S. alterniflora* on the Chongming Dongtan started in 2011. The third stage also launched in May 2013. The weirs of control project were shown in Figure 4. In the simulation of 2020, these projects were not considered in the CCA model.

4. Conclusions

Present CA models focusing on neighbor effect often failed to account for the influence of environmental factors and

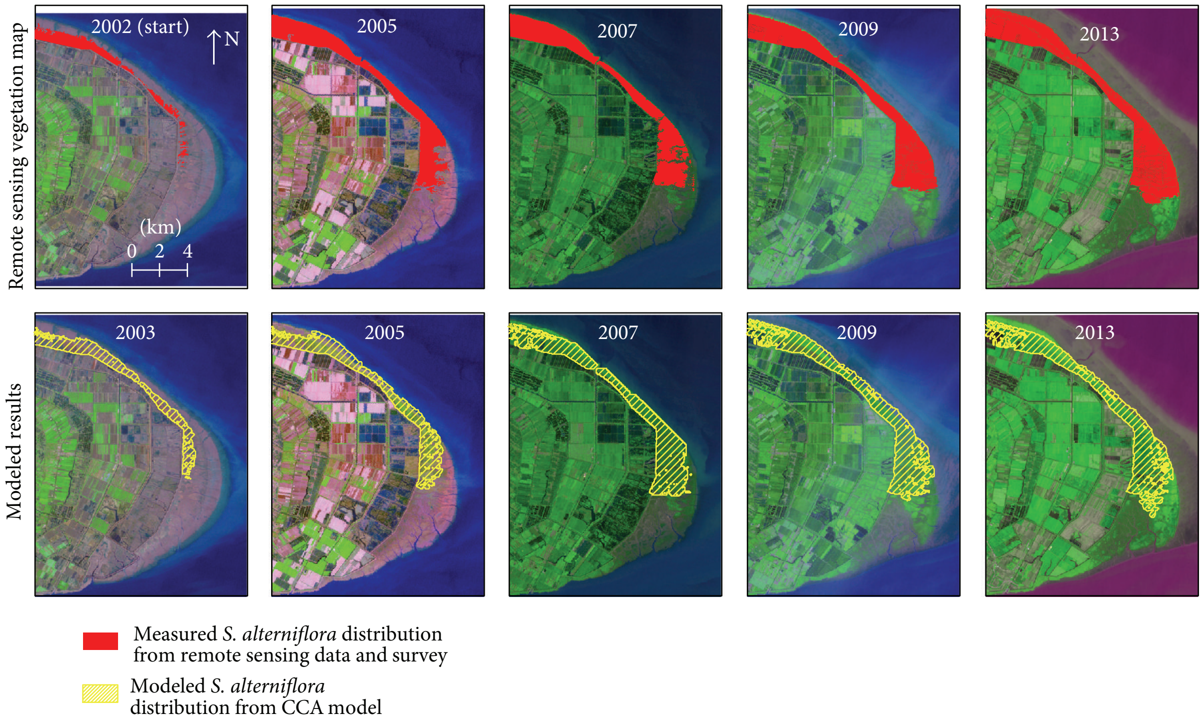

Figure 3: Comparison between modeled results and remote sensing classification.

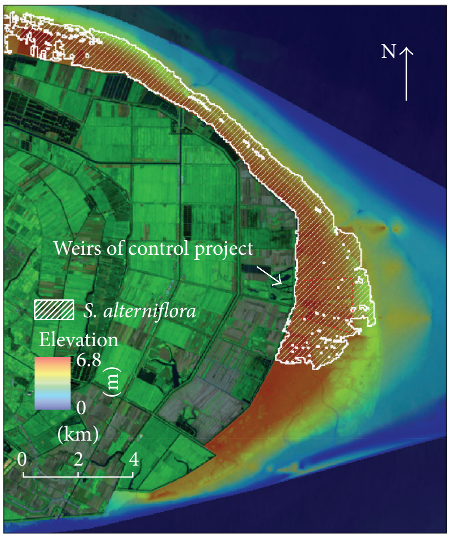

Figure 4: The future of *S. alterniflora* distribution in the future of 2020.

were therefore inadequate for accurately simulating salt marsh vegetation evolution. Environmental factors play an important role in *S. alterniflora* dynamics in salt marsh. This paper proposed a CCA model that enhanced CA model by integrating the influence of tidal elevation, vegetation density, vegetation classification, and tidal channels. The average accuracy for the simulated *S. alterniflora* expansion increased to 80.75% comparing with previous CA model accuracy ranging from 37% to 75%. The simulation results suggest a continuing *S. alterniflora* growth in the study area and show that the future expansion is most likely to take place in the northeast of Chongming Dongtan. Close attention should be paid to these areas to effectively detect, study, and solve the problems associated with such expansions in hope for wetland biodiversity conservation and resource management. Currently, the control project is in progress on the Chongming Dongtan, by integrating physical or mechanical control measures such as cutting, cutting plus waterlogging, and spraying chemicals. Based on the CCA model, the effective assessment of these control strategies should be the key point of the next research.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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