Acta Ecologica Sinica 37 (2017) 307–314

Contents lists available at ScienceDirect

Acta Ecologica Sinica

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

Spatial pattern changes of *Spartina alterniflora* with different invasion ages in the Yancheng coastal wetland

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ARTICLE INFO

Article history:
Received 21 June 2016
Received in revised form 30 November 2016
Accepted 22 February 2017

Keywords:
RS
GIS
Yancheng coastal wetland
Spartina alterniflora
Invasion age
Spatial pattern

ABSTRACT

Spatial pattern changes of *Spartina alterniflora* with different invasion ages affects the soil properties and ecological environment of the invaded area and changes the ecological process. Studies on the spatial pattern changes of *S. alterniflora* with different invasion ages will help to enhance our understanding of the effect of *its* invasion and reveal the relationship between spatial pattern changes and ecological processes in coastal wetlands. Therefore, based on remote sensing (RS) images and survey data collected during the period 1996–2015, spatial distribution pattern of *S. alterniflora* with different invasion ages was studied using space-for-time substitution, overlay analysis, and landscape pattern index analysis, together with RS and geographical information systems (GIS) technologies. Moreover, spatial pattern changes of *S. alterniflora* with different invasion ages and its influence on the ecological environment of the invaded area were determined by analyzing the characteristics of seaward and landward expansion, centroid shifts, and landscape index transformations. The results indicated that: (1) the spatial pattern changes of *S. alterniflora* with different invasion ages have stage characteristics: the patch area of *S. alterniflora* with invasion age of 15–20 years was very large with an average area of 425.40 hm^2, formed in zones; the patch area of *S. alterniflora* with invasion age of 8–14 years became smaller with an average area of 153.64 hm^2, and was formed in blocks with patchiness; the patch area of *S. alterniflora* with invasion age of 1–7 years was the smallest with an average area of 87.47 hm^2; (2) in the early stage of invasion, the patch centroid of *S. alterniflora* shifted to the northeast, and later moved to the southwest. The seaward distance of *S. alterniflora* increased by 917.78 m at a rate of 48.30 m/year, whereas the landward distance of *S. alterniflora* increased by 697.70 m at a rate of 36.72 m/year. Therefore, seaward expansion was the predominant *S. alterniflora* invasion pattern; and (3) the landscape shape index of the *S. alterniflora* with middle invasion ages was higher than those of lower and higher invasion ages; therefore, with decreasing invasion age, the interspersion juxtaposition index and mean patch fractal dimension indexes showed an increasing trend, which was contrary to the trend indicated by the aggregation index. In conclusion, the patches of *S. alterniflora* distributed from the center to surrounding areas increased with invasion age. Higher *S. alterniflora* invasion ages showed more regular patch shapes and greater degrees of fragmentation.

1. Introduction

S. alterniflora was intentionally introduced to the coastal wetlands of Jiangsu province, China in 1979 from the United States [1]. The strong adaptability and reproductive ability of the species have led to its extensive dispersal along the eastern coast of China, where it has had a negative impact on the ecological system. Subsequently, its invasion and control have become a major challenge and received intense interest from biologists and ecologists in China and abroad [2–8]. A large number of studies have revealed the effect of *S. alterniflora* invasions on coastal wetland ecosystem [3–16]. And a mounting number of studies have begun to explore the impact of *S. alterniflora* with different invasion ages on soil environment in recent years [14–17]. For example, Zhang et al. [14] pointed out that *S. alterniflora* with different invasion years had a significant effect on the composition of soil active organic carbon; moreover, some studies have shown that *S. alterniflora* with short invasion years led to an increase of SOC [15]; and others showed that there were significant differences in the number, diversity, and population structure of macrofauna in the soil of *S. alterniflora* with different invasion ages [16]. Therefore, studies on *S. alterniflora* with different invasion ages will help to enhance our understanding of the effect of *S. alterniflora* invasion.

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https://doi.org/10.1016/j.chnaes.2017.09.002
1872-2032/

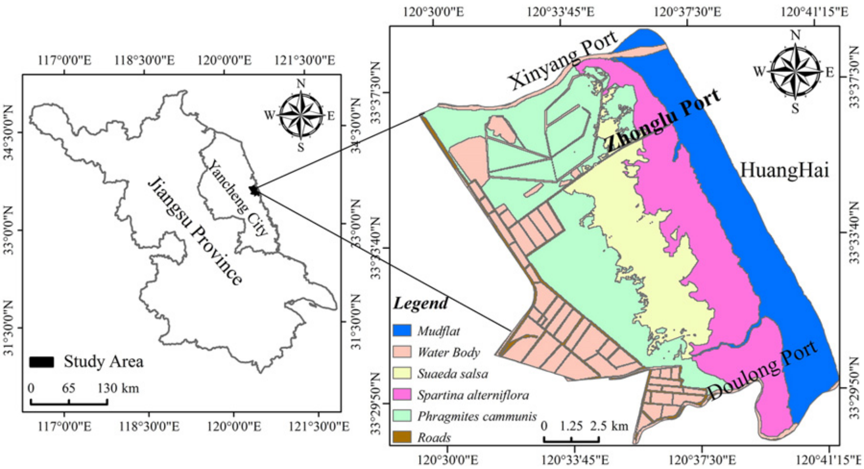

Fig. 1. Landscape type distribution of study area.

A large number of studies on *S. alterniflora* with different invasion ages have focused in its impact on the ecological environment [14–17], however, spatial pattern changes of *S. alterniflora* with different invasion ages have not been reported; yet, spatial pattern changes of *S. alterniflora* with different invasion ages affect the soil environment of the invaded area and change the ecological invasion process [17], as well as indirectly leads to the changes of the whole coastal wetland ecosystem [18–19]. Therefore, studies on spatial pattern changes of *S. alterniflora* with different invasion ages are of great importance for enhancing our understanding of the effect of *S. alterniflora* invasion and revealing the relationship between spatial pattern changes and ecological processes in coastal wetlands. In addition, traditional methods for calculating the invasion ages of the *S. alterniflora* are difficult to quantitatively evaluate its impact on the ecological environment, which used overlay analysis with merely a few years of remote sensing data [1–2,14–24].

The aim of this study is to (1) provide a new idea and reference for mastering the dispersal mechanism of *S. alterniflora* and improve our understanding of the effect of *S. alterniflora* invasion; (2) derive the distribution maps of *S. alterniflora* with different invasion ages in Yancheng Nature Reserve during the period 1996–2015; (3) analyze spatial pattern changes of *S. alterniflora* with different invasion ages and discuss their driving mechanism and influence on the ecological environment of the invaded area.

2. Materials and methods

2.1. Study area

The study area was located in Yancheng Nature Reserve (33°25′0″–33°39′04″N, 120°26′40″–120°40′40″E, Fig. 1). The coastal wetland area totals approximately 19,100 ha, with substantial variability in the wetland landscape. The area is located in the transition zone from the subtropical zone to the warm temperate zone, belonging to typical subtropical climate, receiving rich rainfall and solar radiation energy, where the annual average temperature is between 13.7 and 14.8 °C, and the annual precipitation is 900–1100 mm [22]. Various wetland ecological types were developed in tidal flat wetland, which was mainly composed of clay and silt fine particulate matter, due to the suitable hydrological and climatic conditions [23]. The wetland is rich in vegetation, with a complete tidal flat vegetation succession; the vegetation types from land to sea can be mainly classified into the *Phragmites communis* belt, the *Suaeda salsa* belt, the *Spartina alterniflora* belt and the mudflats belt [25].

2.2. Data sources

The non-native species *S. alterniflora* cannot be recognized from remote sensing imagery until 1996, which was introduced in 1982 in Yancheng Nature Reserve. Therefore, we chose the image from 1996 to 2015 as the basic data. Landsat TM (1996–1998) and Landsat ETM (1999–2015) remote sensing images (30 m-resolution) were selected for the purpose of harmonizing the scale and avoiding the difference in resolution of different data sources (Table 1).

The tide data referenced to the tide tables of Xinyang gang, the tidal datum lies 200 cm below mean sea level.

2.3. Remote sensing image processing and analysis

Remote sensing image preprocessing includes atmospheric correction, geometric precision correction, strip noise removal, image clipping, and feature extraction. The ROI training areas of *water body*, *roads*, *mudflat*, *P. communis*, *S. alterniflora* and *S. salsa* was established, and the spectral reflectance values of different kinds of objects from 1996 to 2015 were analyzed according to the historical and field survey data. The image classification accuracy of each period reached more than

Table 1
Remote sensing image information and tide data.

Sensor	Track number	Time	Height of tide/cm		Sensor	Track number	Time	Height of tide/cm	
			2:00	3:00				2:00	3:00
TM	119/37	1996/05/01	205	175	ETM+	119/37	2006/05/21	216	221
TM	119/37	1997/06/05	120	153	ETM+	119/37	2007/05/08	120	175
TM	119/37	1998/07/10	134	125	ETM+	119/37	2008/04/24	177	144
TM	119/37	1999/11/02	126	151	ETM+	119/37	2009/06/14	222	192
ETM+	119/37	2000/06/05	195	163	ETM+	119/37	2010/09/21	185	146
ETM+	119/37	2001/06/08	185	146	ETM+	119/37	2011/09/24	237	193
ETM+	119/37	2002/05/26	138	118	ETM+	119/37	2012/05/05	150	176
ETM+	119/37	2003/10/20	136	161	ETM+	119/37	2013/07/11	189	146
ETM+	119/37	2004/08/03	114	127	ETM+	119/37	2014/10/18	112	125
ETM+	119/37	2005/06/03	201	219	ETM+	119/37	2015/05/14	209	223