Journal of Environmental Management 135 (2014) 27–35

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Effects of continual burial by sediment on seedling emergence and morphology of *Suaeda salsa* in the coastal marsh of the Yellow River estuary, China

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ARTICLE INFO

Article history:
Received 23 July 2013
Received in revised form
10 January 2014
Accepted 13 January 2014
Available online 5 February 2014

Keywords:
Continual burial
Morphological trait
Seedling emergence
Suaeda salsa
Yellow River estuary

ABSTRACT

A greenhouse study was conducted to determine the impacts of continual burial on seedling emergence and morphology of *Suaeda salsa*, a pioneer species in the coastal marsh of the Yellow River estuary. From May to June 2012, seeds of *S. salsa* were artificially buried to depths of 0 cm (no burial), 2 cm (burial of 1 mm d^{-1}), 4 cm (burial of 2 mm d^{-1}), 6 cm (burial of 3 mm d^{-1}), 8 cm (burial of 4 mm d^{-1}) and 10 cm (burial of 5 mm d^{-1}) in plastic pots filled with unsterilized sediment. Results showed that the percent emergence of seedlings had a significantly negative correlation with continual burial depth ($p < 0.001$). A large percentage of seedlings emerged from 2, 4 and 6 cm burial depths, with the highest emergence (56.00 ± 6.60%) occurring from 2 cm depth. The shortest emergence time occurred at 4 cm burial depth and seeds buried at 10 cm depth took longer to emerge than those at other depths. At shallow or moderate burials, a stimulatory effect on seedling height, stem diameter, number and length of branch, taproot length and dry mass were observed. With increasing burial depth, root-mass and leaf-mass ratios generally increased while stem-mass ratio decreased. Sediment burial also stimulated part of the hypocotyl below the sediment to form adventitious roots, implying that *S. salsa* seedlings had a special adaptive strategy in response to the rapid and dynamic burial environment in the coastal marsh of the Yellow River estuary. The use of thin-layer continual burial (1–2 mm d^{-1}) to promote the emergence of *S. salsa* seedlings in degraded marsh was feasible, and our study provided another way for the restoration of *S. salsa* marsh during the initial stage of seedling establishment and laid a good foundation for the scientific decision-making and management of restoration project at a large scale.

1. Introduction

Plants growing on coastal marshes are exposed to a number of extreme conditions, such as high wind velocities, drastic temperature fluctuations, high potential evapotranspiration, salt spray, low levels of sediment nutrients, inundation by seawater and burial in sediment (Baldwin and Maun, 1983; Maun, 1998; Deng et al., 2008). Among them, sediment burial has been recognized as a major selective force in the evolution of seed germination, seedling emergence, seedling establishment and survivorship of seedlings and adult plants (Maun, 1994). Depending on the magnitude of different disturbing agents (storms, tidally induced sediment movement and bioturbation) in coastal marshes, the sediment can be disrupted to various depths (Chandrasekaral and Frid, 1998), and the different sediment disturbances may result in the seeds, seedlings and adult plants being directly damaged and killed or buried within the sediment to different extent. Simultaneously, plants evolve a variety of adaptations (such as higher seedling height, longer hypocotyl and root system, and increased dry mass accumulation) that allow survival, growth and reproduction under relatively stressful and variable conditions (Maun and Riach, 1981; Maun and Lapierre, 1986; Redmann and Qi, 1992; Maun, 1994; Thampanya et al., 2002; Deng et al., 2008; Li et al., 2011; Wen et al., 2012).

The germination of seeds is related to the depth at which seeds are buried (Harper and Benton, 1966; Zhang and Maun, 1994). Burial at shallow depths generally stimulates more germination and emergence (Maun, 1994) and has significant stimulation to the

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0301-4797/$ – see front matter
http://dx.doi.org/10.1016/j.jenvman.2014.01.017

morphological traits of plants (such as height, leaf area and thickness, seed production, dry mass, length of leaf, stem, taproot, hypocotyl and internode, number of leaves, internodes, branches and tillers) (Disraeli, 1984; Maun and Lapierre, 1986; Zhang and Maun, 1990; Redmann and Qi, 1992; Chen and Maun, 1999; Thampanya et al., 2002; Deng et al., 2008), which is presumably due to the major changes in sediment nutrient status, temperature, microorganism composition, mycorrhizal fungi and sediment aeration (Maun, 1998). However, excessive burial may prevent seedlings from emerging above the sediment surface and thus affect survival, because pre-emergence mortality results from a cessation of seedling growth before it reaches the sediment surface or the seeds are unable to germinate due to lack of oxygen, light and temperature fluctuation (Maun and Riach, 1981; Zhang and Maun, 1990). Thus, there is a threshold of sediment burial depth for each plant to maximize seedling emergence and subsequent growth. Below the threshold level of burial, the emergence and growth of seedlings are stimulated by sediment burial. As the level of burial increases over the threshold, seedling emergence and growth are seriously constrained (Zhang and Maun, 1994; Maun et al., 1996).

There has been intense and increasing interest in understanding the response of seedlings to burial because burial is an important factor controlling the distribution and composition of plants in different communities (van der Valk, 1974; Maun and Lapierre, 1986; Leishman and Westoby, 1994; Chen and Maun, 1999; Thampanya et al., 2002; Li et al., 2006; Deng et al., 2008; Mou and Sun, 2011). Studies on the responses of seedling emergence and growth to burial have been widely reported, which mainly focused on arid/semi-arid dune (Maun and Lapierre, 1986; Leishman and Westoby, 1994; Huang et al., 2004; Li et al., 2006), coastal/lacustrine dune (Zhang and Maun, 1994; Cheplick and Grandstaff, 1997; Chen and Maun, 1999), coastal marsh (Deng et al., 2008; Mou and Sun, 2011) and mangrove swamp (Lee et al., 1996; Terrados et al., 1997; Thampanya et al., 2002). Overall, previous studies mostly focus on single one-time burial, while information on the tolerance or stimulation responses to continual burial episodes is lacking. Actually, plants in natural habitats are most often exposed to dynamic and stochastic disturbance events, and the chances of seedling emergence may be much higher since dynamic burial generally maintains a low-stress environment around seeds compared to single one-time burial (Maun et al., 1996).

The Yellow River is well known as a sediment-laden river. Every year, approximately 1.05×10^7 tons of sediment is carried to the estuary and deposited in the slow flowing landform, resulting in vast floodplain and special marsh landscape (Xu et al., 2002). Sediment deposition is an important process in the formation and development of coastal marsh in the Yellow River Delta. The deposition rate of sediment in the Yellow River not only affects the formation rate of coastal marsh, but also influences the water or salinity gradients and the succession of plants from the land to the sea. *Suaeda salsa* is the most prevalent plant in the coastal marsh of the Yellow River estuary. It generally germinates in late April, blooms in July, matures in late September and completely dies in late November (Gu, 1998). As a pioneer plant, it is often affected by the sediment of tide physical disturbance, which is generally dependent on prevailing wind velocities. Although *S. salsa* can tolerate high salinity habitat, there is an optimum ecological threshold of sediment salinity (12.71 g kg^{-1}) for the plants (Cui et al., 2008). If the salinity level exceeds the threshold, the plants will not grow better and generally exhibit varying degrees of degradation. As the coastal mash is frequently supplied by freshwater, the sediment salinity can be maintained around the optimum ecological threshold, which is favorable for the growth of *S. salsa*. It was reported that the annual runoff of the Yellow River showed great inter-annual changes since the 1980s. The runoff reached the maximum value of 49.1 billion m^3 in 1983 and then decreased and fluctuated at 20.0 billion m^3 in the following several years. From 1997 to 2002, the annual runoff was mainly below 10.0 billion m^3 (Cui et al., 2009). The low flows of the Yellow River led to a significant decrease in freshwater supply to the estuary and the *S. salsa* marshes near the estuary exhibited seriously degraded status. In order to restore degraded marshes, the 'water and sand regulation project' (WSRP) was initiated by the nation in 2002. The purpose of the WSRP was to increase the supply of freshwater and sediment for the Yellow River estuary by discharging the water in Xiaolangdi Reservoir and scouring the sediment in the reservoir and riverbed (Cui et al., 2009). During the WSRP (from June to July in each year), the river water frequently flooded the *S. salsa* marshes near the estuary and resulted in considerable sediment deposition (approximately 5–6 cm thick), which continually and significantly influenced seedling emergence and growth (Mou, 2010). However, little is known about the impacts of continual burial on seedling emergence and morphology in the coastal marsh of the Yellow River estuary.

In this paper, the effects of continual burial on seedling emergence and principal morphological traits of *S. salsa* were investigated experimentally. The primary objectives of this study were *i*) to examine whether sediment burial caused by continual burial episodes would have great impacts on seedling emergence, *ii*) to determine the different influences of continual burial on morphological traits, and *iii*) to investigate the feasible of continual burial in restoration and management of degraded marsh.

2. Materials and methods

2.1. Study site

This study was conducted in a greenhouse in the Shandong Key Laboratory for Eco-Environmental Science of the Yellow River Delta in Binzhou University. The sediment used in this experiment was sampled from the coastal marsh of the Yellow River estuary [sample depth: 15 cm; sediment salinity (water extracted salinity): $1.49 \pm 0.27\%$ ($n = 5$)], which is located in the Nature Reserve of Yellow River Delta (37°35′N ∼ 38°12′N, 118°33′E ∼ 119°20′E) in Dongying City, Shandong Province, China. The nature reserve is of typical continental monsoon climate with distinctive seasons. The average annual temperature is 12.1 °C and the frost-free period is 196 d. Annual evaporation is 1962 mm and annual precipitation is 551.6 mm, with about 70 percent of precipitation occurring between June and August. The soils in the study area are dominated by intrazonal tide soil and salt soil, and the main vegetations include *Phragmites australis*, *S. salsa*, *Triarrhena sacchariflora*, *Myriophyllum spicatum* and *Tamarix chinensis* (Sun et al., 2012). Coastal marsh is the main marsh type, with an area of 964.8 km^2, accounting for 63.06% of the total area of the Yellow River Delta (Cui et al., 2009). The tide in the intertidal zone of the Yellow River estuary is irregular semidiurnal tide and the mean tidal range is 0.73–1.77 m (Li et al., 1991). As the pioneer plant in coastal marsh, *S. salsa* is often affected by the sediment deposition of tidal disturbance, bioturbation and Yellow River flooding during the WSRP. The sedimentary rate in the *S. salsa* marsh is about 9–10 cm yr^{-1}, and approximately 6–7 cm occurs at the seedling stage due to the significant influences of both tidally induced sediment and WSRP (Mou, 2010).

2.2. Experimental method

Seeds of *S. salsa* were collected in the fall of 2011 from four typical regions of the Yellow River estuary. Seeds were collected