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Effects of continual burial by sediment on morphological traits and dry mass allocation of *Suaeda salsa* seedlings in the Yellow River estuary: An experimental study

Zhigao Sun[a,b,*], Hongli Song[a,c], Wenguang Sun[a,c], Jingkuan Sun[b]

[a] Key Laboratory of Coastal Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai, Shandong 264003, PR China
[b] Shandong Provincial Key Laboratory of Eco-Environmental Science for Yellow River Delta, Binzhou University, Binzhou, Shandong 256603, PR China
[c] University of Chinese Academy of Sciences, Beijing 100049, PR China

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ABSTRACT

Information on the effects of continual burial by sediment on seedling survival and morphological growth in coastal marsh remains scarce. A greenhouse experiment was conducted to determine the effects of continual burial on seedling mortality, growth and dry mass allocation of *Suaeda salsa* in the coastal marsh of the Yellow River estuary. The seeds were planted at 0.5 cm depth in plastic pots filled with unsterilized sediment on May 5, 2012. A depth of 8 cm was chosen as the maximum of continual burial according to the sedimentary rate (6–7 cm) in the coastal marsh at seedling stage. Two weeks after emergence, seedlings were artificially buried to depths of 0 (D0, no burial), 33% (D33, burial of 1 mm d^{-1}), 67% (D67, burial of 2 mm d^{-1}), 100% (D100, burial of 3 mm d^{-1}) and 133% (D133, burial of 4 mm d^{-1}) of their mean height, with 20 days in total. Results showed that seedling height, stem and taproot diameter, number of branch, hypocotyl and taproot length, and dry mass were significantly affected by burial depth ($p < 0.05$). No seedlings died in the four burial treatments. Seedling heights in the D33 and D67 treatments were higher than those of the other treatments, indicating that shallow and moderate burials exhibited greater stimulation to seedling growth. Although stem diameter, number and length of branch, and dry mass of seedlings were stimulated in the four burials, the greatest stimulatory effect on stem diameter was observed in the D100 treatment while that on number and length of branch and dry mass occurred in the D67 treatment. With increasing burial depth (D67, D100 and D133), seedling taproot diameter and length decreased while hypocotyl length increased, reflecting that hypocotyl elongation might occur at the expense of development of the root system. The responses of morphological traits and dry mass allocation of *S. salsa* seedlings to the burial treatments indicated that they might have a special strategy to tolerate the continual burial in the coastal marsh of the Yellow River estuary. The use of thin-layer burial (2 mm d^{-1}) to promote seedling vigor in degraded *S. salsa* marsh was feasible, and our study provided valuable information for the restoration of *S. salsa* marsh during seedling growth.

1. Introduction

Coastal marshes are complex and dynamic, continually changing due to the action of tides and waves. Plants growing on coastal marshes are exposed to a number of extreme conditions, such as high wind velocities, drastic temperature fluctuations, high potential evapotranspiration, frequent ebb and flow of tide, 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 seedling and adult plants (Maun, 1994). 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 (Chandrasekara and Frid, 1998). Marsh plants also evolve a variety of adaptations that allow survival, growth and reproduction under relatively stressful and variable burial conditions (Redmann and Qi, 1992; Maun, 1994; Thampanya et al., 2002; Deng et al., 2008; Li et al., 2011; Wen et al., 2012).

* Corresponding author. Tel.: +86 0535 2109121; fax: +86 0535 2109000.
E-mail address: zgsunyic@126.com (Z. Sun).

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Sediment burial may increase the vulnerability of the plants (Maun and Riach, 1981), and their survivorship and growth are directly related to the depth at which seedling buried. Burial at shallow depths generally has significant stimulation to the morphological traits of plants (such as leaf area and thickness, biomass, length of leaf, taproot, stem and internode, number of leaf, internodes and tillers, seed production) (Disraeli, 1984; Zhang and Maun, 1990; Maun et al., 1996; Chen and Maun, 1999; Thampanya et al., 2002; Zhao et al., 2007; 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). Some species may actually require moderate burial in sediment to maintain high vigor (van der Putten et al., 1993). However, high levels of burial tended to inhibit plant growth (Maun, 1998), which is dependent on whether plants can overcome the suspension of photosynthetic activity and emerge from the burial deposit and then reinstate physiological activity (Perumal and Maun, 2006). Thus, there is a threshold of burial for each plant to maximize vigor. Below the threshold level, the growth of plants was stimulated by burial. As the level increased over the threshold, the response of plants might become deteriorated in growth and vigor (Zhao et al., 2007).

There has been intense and increasing interest in understanding the responses of seedlings to burial because burial is an important factor controlling the distribution and composition of plants in different communities (Maun and Lapierre, 1984; Maun, 1994, 1996; Maun et al., 1996; Brown, 1997; Terrados et al., 1997; Chandrasekara and Frid, 1998; Thampanya et al., 2002; Zhao et al., 2007; Sun et al., 2010). Studies on the responses of seedling survival and morphological growth to burial have been widely reported, which mainly focused on arid and semi-arid dune (Sykes and Wilson, 1990; Maun, 1996; Brown, 1997; Liu et al., 2006; Yang et al., 2007; Zhao et al., 2007; He et al., 2008), coastal/lacustrine dune (Maun, 1994, 1998; Maun et al., 1996; Franks and Peterson, 2003), coastal marsh (Deng et al., 2008; Sun et al., 2010) and mangrove swamp (Lee et al., 1996; Terrados et al., 1997; Thampanya et al., 2002). Current studies mostly focus on single one-time burial, while information on the tolerance or stimulation responses to continual burial events is lacking. Actually, plants in natural habitats are most often exposed to dynamic and stochastic disturbance episodes, and the chances of seedling survival may be much higher since continual burial maintains a low stressful environment around plants compared to single one-time burial events (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 marshes in the Yellow River Delta. The deposition rate of sediment in the Yellow River not only affects the formation rate of coastal marshes, but also influences 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 marshes of the Yellow River estuary. As a pioneer plant, it is often affected by the sediment of tide physical disturbance, which is generally dependent on the prevailing wind velocities. It was reported that the annual runoff of the Yellow River reached the maximum of 49.1 billion m^3 in 1983 and then decreased and fluctuated at 20.0 billion m^3 until 1996 (Cui et al., 2009). During 1997–2002, the annual runoff was mainly below 10.0 billion m^3. Low flows exhibited by the Yellow River led to significant decreases in freshwater and sediment inputs to the estuary, and the *S. salsa* marshes therein did not grow better and exhibited significant degraded status due to the sediment salinity level over the optimum ecological threshold for the plants (Cui et al., 2008). In order to restore the degraded marshes, the nation carried out "water and sand regulation project" (WSRP) in 2002 by increasing the supply of freshwater and sediment for the estuary. During WSRP, the river water frequently flooded the *S. salsa* marshes near the estuary and the sediment salinity could be maintained around the optimum threshold for *S. salsa*. Moreover, considerable sediments were continually deposited (approximately 5–6 cm thick) in the marsh during WSRP, which might significantly influenced seedling emergence and growth of *S. salsa* (Mou, 2010). However, little is known about the effects of sediment continual burial on seedling morphological traits of *S. salsa* in the coastal marshes of the Yellow River estuary.

Although freshwater subsidy was another important factor in maintaining *S. salsa* marshes, in this paper, we mainly focused on the effects of continual burial on seedling morphological growth and dry mass allocation because, during WSRP, the influences of sedimentation on seedlings were more drastic than those of freshwater subsidy. It was anticipated that there would have a threshold of burial to maximize plant growth vigor, and morphological traits and dry mass allocation would respond differently to continual burial. Objectives of this paper were (i) to determine the responses of morphological traits and dry mass allocation of *S. salsa* seedlings to continual burials, and (ii) to determine the threshold of continual burial required to maximize seedling growth vigor.

2. Materials and method

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 in 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 annual average 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% 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). As the pioneer plant in coastal marshes, *S. salsa* is often affected by the sediment deposition of tidal disturbance, bioturbation and Yellow River flooding during 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 effects 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 from multiple individuals (about 800 individuals) in each region and mixed together. Seeds were cleaned, dried at room temperature for 2–3 weeks, then stored at 8 °C under dry, dark conditions. The planting was carried out on May 5, 2012. The sediment was poured into each plastic pot (28 cm in diameter, 32 cm in height) up to the same depth (22 cm) and moistened, then the seeds ($n = 15$) were