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Establishment of intertidal seaweed beds of *Sargassum thunbergii* through habitat creation and germling seeding

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ABSTRACT

Many naturally occurring macroalgal beds on the coastal areas of China have been severely degraded by various anthropogenic perturbations. Few attempts have been made to develop restoration techniques for seaweed beds in intertidal ecosystems, owing to the complex and dynamic variations in physical conditions of the habitat. We developed a new *Sargassum thunbergii* restoration method involving creating intertidal habitat and seeding with artificially collected germlings. In June 2010, artificial rectangular pools constructed of a 4:5:1 rate of high-strength cement, sand and water on a rocky intertidal platform were seeded with *S. thunbergii* germlings released from fertile thalli during low tide. Artificial pools were covered with a double-layer shading net until the next tidal cycle to prevent germlings from being dislodged by water motion, resulting in a majority of young germlings successfully attaching to the pool bottom by rapid development of rhizoids. Two months after seeding, juvenile sporophytes attained a length of 15–20 mm. After one year following seeding, *S. thunbergii* in the restored bed reached a density of 118.5 ± 13.2 (mean ± SE) thalli m^{-2}, covered $32.7 \pm 0.1\%$ of the artificial substrate, and grew to an average length of 34.2 ± 1.6 cm with 7.3 ± 0.6 laterals per thallus. The proportion of fertile laterals of restored population was $73.6 \pm 3.0\%$, indicating that these fertile thalli may serve as a source of new recruits to enhance the recovery of the algal population. Furthermore, restored *S. thunbergii* beds facilitated the presence of seven other species of macroalgae with species richness (R), diversity (H') and evenness (J') reaching 0.65 ± 0.04, 1.06 ± 0.09 and 0.67 ± 0.05, respectively. Therefore, the construction of artificial pools coupled with seeding germlings in natural habitat may be an effective approach for the restoration of *S. thunbergii*, and potentially other seaweeds in rocky intertidal habitats.

1. Introduction

Macroalgal beds on rocky bottoms have been recognized to play an important role in ecological and biological function. They provide crucial habitats and spawning grounds for a wide variety of marine organisms and are an essential source of carbon for complex food webs in the rocky coastal ecosystem (Largo and Ohno, 1993; Terawaki et al., 2001; Oyamada et al., 2008). However, the rocky coastal ecosystems have been severely affected by various anthropogenically induced perturbations, such as land reclamation, nutrient pollution, over exploitation and climate change (Terawaki et al., 2003; Jones et al., 2010; Gallego-Fernández et al., 2011). Consequently, many naturally occurring macroalgal beds have been seriously degraded in a number of coastal areas of the world (Carney et al., 2005; Zhang and Sun, 2007; Yao et al., 2010). Given the essential function of macroalgal beds on rocky shores, much attention has been focused on effective methods to restore seaweed habitat on damaged rocky coastal ecosystems (Terawaki et al., 2003; Falace et al., 2006).

Numerous attempts of construction of artificial macroalgal beds have been conducted in the last decade and several techniques have been developed (Stekoll and Deysher, 1996; Hernández-Carmona et al., 2000; Terawaki et al., 2003; Correa et al., 2006; Yoshida et al., 2006; Yamamoto et al., 2010). Common methods for restoring macroalgal beds include supplying microscopic zoospores, transplanting juveniles and adults, deploying artificial reefs, and removing herbivorous fishes and animals (Largo and Ohno, 1993; Choi et al., 2002; Kang et al., 2008). These restoration studies demonstrated that seaweed populations could be reestablished successfully in the benthic or subtidal zones of many regions. However, restoration efforts on rocky intertidal shores have been largely unexplored (Carney et al., 2005; Susini et al., 2007; Whitaker

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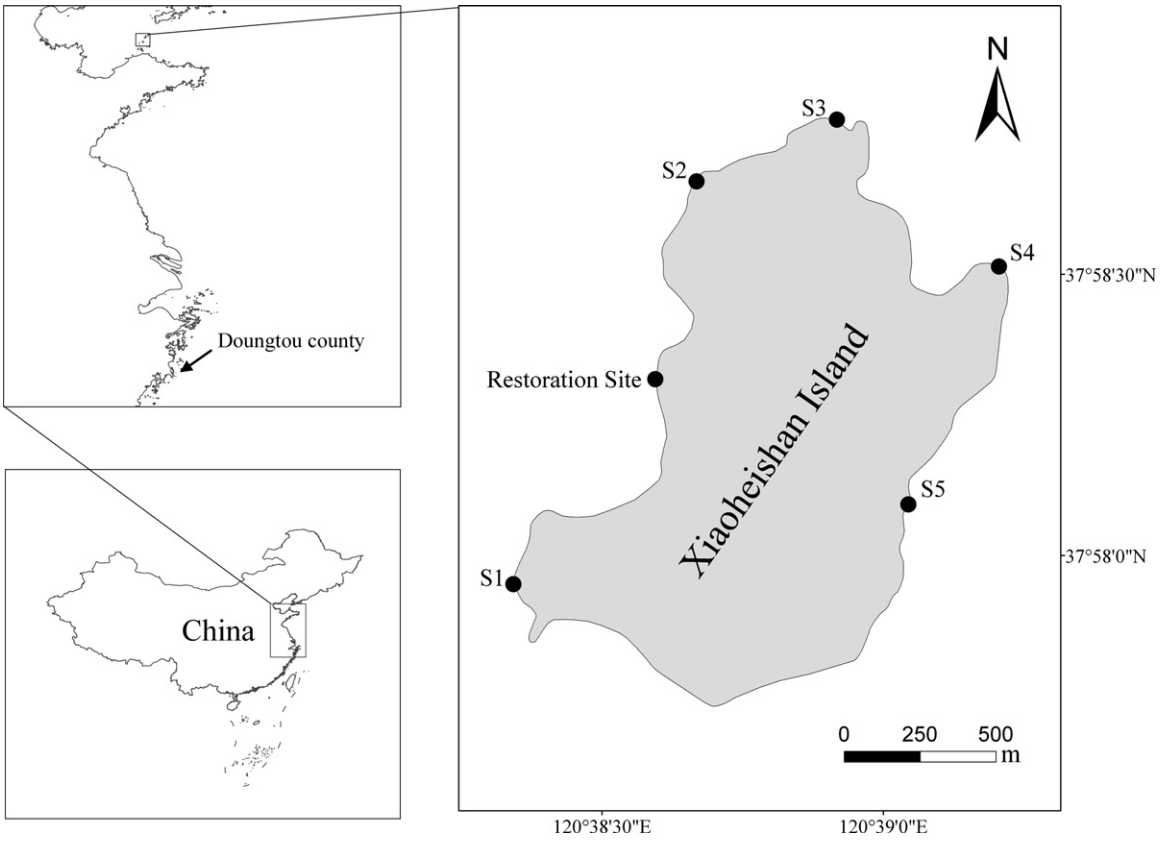

Fig. 1. Location of the restoration and five reference sites around the Xiaoheishan Island, China.

et al., 2010). The marine intertidal zone is considered among the most stressful of all environments, because daily exposure at low tide results in daily fluctuation in a variety of physical factors such as temperature, humidity, salinity, wave exposure and light (Bell, 1993; Davison and Pearson, 1996; Wright et al., 2004; Chapman and Reed, 2006). Consequently, in comparison to subtidal habitats, restoration of the intertidal macroalgal beds may be more challenging in the stressful environment.

Species of the genus *Sargassum* (Fucales) are a significant component of seaweed flora in the tropical and temperate coastal waters around the world (Phillips, 1995). They have a biogenic, habitat-forming role in shaping rocky intertidal community structure, making them especially good candidates for restoration. *Sargassum thunbergii* (Mert.) O. Kuntze, a brown canopy forming species of algae, distributes widely along the coasts of China, Japan and Korea (Umezaki, 1974; Koh et al., 1993; Zhang et al., 2009). This species occupies mainly rocky shores where it forms dense monospecific stands spanning low intertidal, including tide pools, to shallow subtidal regions (Zhao et al., 2008). In recent years, *S. thunbergii* is widely used in alginate production, extraction of bioactive products and biosorption of heavy metal ions (Padilha et al., 2005; Zhao et al., 2007; Chu et al., 2011). In addition, it is particularly used as a preferred food source for holothurian and abalone aquaculture. In recent years, natural populations have been largely harvested as desirable feed for the rapidly developing aquaculture of *Stichopus japonicus* in this region, which has resulted in the depletion of intertidal macroalgal beds (Zhao et al., 2007; Zhang et al., 2011). The decline of *S. thunbergii* from these extensive coastal areas highlights the urgent need to design effective strategies for restoration. To our knowledge, few attempts have been made to develop restoration techniques for intertidal *S. thunbergii* populations.

In this study, artificial cement pools were constructed on a rocky intertidal platform, and then inoculated with *S. thunbergii* germlings shortly released from fertile thalli at low tide. To evaluate the efficacy of this method, we measured abundance, density, and morphological characteristics of *S. thunbergii*, as well as macroalgal species diversity, in artificial seaweed beds after one year following seeding.

2. Materials and methods

2.1. Restoration area

Our restoration was conducted on the island of Xiaoheishan (Changdao Archipelago), approximately 20 km off the northern side of Shandong Peninsula, China (Fig. 1). This island is 1.9 km long in a north-south direction and 1.2 km wide in an east-west direction, with an area of approximately 1.36 km^2. It is characterized by a warm temperate continental monsoon climate with distinctive seasons and rainy summers. The mean annual air temperature is 12 °C and annual precipitation is 565 mm. The tides are regular semidiurnal, with spring tide amplitudes to 3 m. Annual ranges for sea surface temperature and salinity in this area were 1.8–23.3 °C and 29–31 psu, respectively. *S. thunbergii* was the dominant species historically on the intertidal coast of this island but overexploitation has depleted the area of intertidal macroalgal beds.

The target restoration site was established on the semi-exposed, west-facing coast of the island. An unvegetated intertidal rock platform with an area of ca. 120 m^2 was selected for *S. thunbergii* bed restoration. This platform was composed of sandstone, and was backed by a 15–20 m high cliff. At low tide, the entire rock platform was completely exposed to air for approximately 8.5 h twice a day. *S. thunbergii* was absent within 100 m from the restoration area, and