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An examination of photoacclimatory responses of *Zostera marina* transplants along a depth gradient for transplant-site selection in a disturbed estuary

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ABSTRACT

Growth and photosynthetic responses of *Zostera marina* transplants along a depth gradient were examined to determine appropriate transplanting areas for seagrass restoration. Seagrass *Z. marina* was once widely distributed in the Taehwa River estuary in southeastern Korea, but has disappeared since the 1960s due to port construction and large scale pollutant inputs from upstream industrial areas. Recently, water quality has been considerably improved as a result of effective sewage treatment, and the local government is attempting to restore *Z. marina* to the estuary. For seagrass restoration in this estuary, a pilot transplantation trial of *Z. marina* at three water depths (shallow: 0.5 m; intermediate: 1.5 m; deep: 2.5 m relative to MLLW) was conducted in November 2008. The transplant shoot density increased gradually at the intermediate and deep sites, whereas the transplants at the shallow site disappeared after 3 months. To find the optimal transplantation locations in this estuary, the growth and photosynthetic responses of the transplants along a depth gradient were examined for approximately 4 months following transplantation in March 2009. In the 2009 experimental transplantation trial, shoot density of transplants at the shallow site was significantly higher than those at the intermediate and deep sites during the first 3 months following transplantation, but rapidly decreased approximately 4 months after transplantation. The chlorophyll content, photosynthetic efficiency (α), and maximum quantum yield (F_v/F_m) of the transplants were significantly higher at the deep site than at the shallow site. Shoot size, biomass and leaf productivity were also significantly higher at the deep site than at the shallow site. Although underwater irradiance was significantly lower at the deep site than at the shallow site, transplants at the deep site were morphologically and physiologically acclimated to the low light. Transplants at the shallow site exhibited high mortality during the early period of transplantation perhaps due to high physical disturbances at the site, but transplants at the intermediate and deep sites showed higher growth through more efficient photosynthesis and morphological adaptation. Thus, the intermediate and deep sites (1.5–2.5 m relative to MLLW) appeared to be more appropriate seagrass transplantation sites in this estuary.

1. Introduction

Seagrass is an important component of coastal and estuarine ecosystems, but significant declines in seagrass meadows, mainly due to anthropogenic causes, have been reported during recent decades (Boström et al., 2002; Hauxwell et al., 2003; Burkholder et al., 2007; Montefalcone et al., 2010). Although seagrass decline tends to be rapid, the natural recovery of disturbed seagrass meadows is comparatively slow (Kirkman, 1998; Meehan and West, 2000). Thus, numerous attempts at seagrass restoration through transplantation have been conducted worldwide (Thorhaug, 1987; Fonseca et al., 1994; Orth et al., 1999; Fishman et al., 2004; Bastyan and Cambridge, 2008; Li et al., 2010). Environmental conditions at planting sites can highly influence the survival of seagrass transplants, and thus the selection of appropriate areas is essential for the success of seagrass restoration through transplantation (Short et al., 2002). Heterogeneous environmental conditions in transplantation areas might result in large variability in the morphology, physiology and growth of seagrass transplants (Jensen and Bell, 2001; Cambridge and Kendrick, 2009).

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Seagrass photosynthesis, and thereby growth, survival, and distribution, are directly linked to underwater irradiance (Dennison et al., 1993; Cabello-Pasini et al., 2003; Lee et al., 2007). Large losses of seagrass coverage have been reported from many parts of the world as a consequence of underwater light reduction (Onuf, 1994; Short and Wyllie-Echeverria, 1996). As underwater light intensity is attenuated exponentially with water depth, seagrasses often grow in distinct bands from the intertidal zone to water depths at which seagrass shoots receive the minimum light necessary for survival (Duarte, 1991; Greve and Krause-Jensen, 2005). Seagrasses have exhibited a wide variety of photosynthetic and growth responses along depth gradients (Dennison and Alberte, 1986; Dennison, 1987), and the survival of seagrass transplants has also been found to be depth dependent (Zimmerman et al., 1995). Thus, water depth is a significant criterion for the selection of appropriate seagrass transplantation sites and is considered an important parameter in a site-selection model that has been developed to select optimal transplanting areas for *Zostera marina* ecosystem restoration (Short et al., 2002).

The Taehwa River estuary, SE Korea, previously had widely distributed *Z. marina* but the meadows in the estuary have disappeared since the 1960s due to port construction, reclamation, and large-scale pollutant input from upstream industrial areas (Kang et al., 1999; Khim et al., 2001). Only a few small patches of *Z. marina* now remain in the estuary, although water quality in the estuary has improved considerably. Since landscape and topography of the estuary have changed after the construction of the port, environmental conditions for seagrass growth should also have changed considerably in this estuary. Thus, a pilot transplantation experiment was conducted in the estuary to evaluate the possibility of restoring the degraded seagrass meadows in 2008. Water depths in the estuary ranged from 0.3 m on the southwestern side to approximately 3.5 m on the northeastern side (Fig. 1). To determine the optimal depth for seagrass transplantation in this estuary, we planted *Z. marina* shoots at three different water depths (shallow: 0.5 m; intermediate: 1.5 m; deep: 2.5 m relative to MLLW) in this estuary. Although transplant shoot density increased gradually at the intermediate and deep transplantation sites, the transplants at the shallow site disappeared approximately 3 months after transplantation probably due to the severe transplantation stress at the site. Thus, in the present study, the growth and photosynthetic responses of the transplants were examined at the three water depths to evaluate the transplantation stress and the establishment success of the transplants along the depth gradient using transplants planted in 2009.

Zostera marina transplants usually show high mortality during the first 2–3 months following transplantation due to initial short-term stresses resulting from injuries, desiccation and impaired function during the planting process (Struve et al., 2000; Park and Lee, 2007; Lee and Park, 2008). After this period of initial loss, surviving seagrass transplants become established at the new planting sites and shoot density increases through new lateral shoot formation from rhizome branching (Park and Lee, 2007; Lee and Park, 2008). Since high mortality of the transplants at potentially unsuitable site has occurred within 3–4 months after transplantation during the pilot transplantation trial, growth and photosynthetic characteristics of the transplants were examined for approximately 4 months following transplantation. Because the transplants at the shallow site disappeared in the early period of transplantation, we hypothesized that *Z. marina* transplants at the shallow site would show distinctly lower growth rates and photosynthetic efficiency than those at the intermediate and deep sites during the initial time period required for the establishment of the transplants.

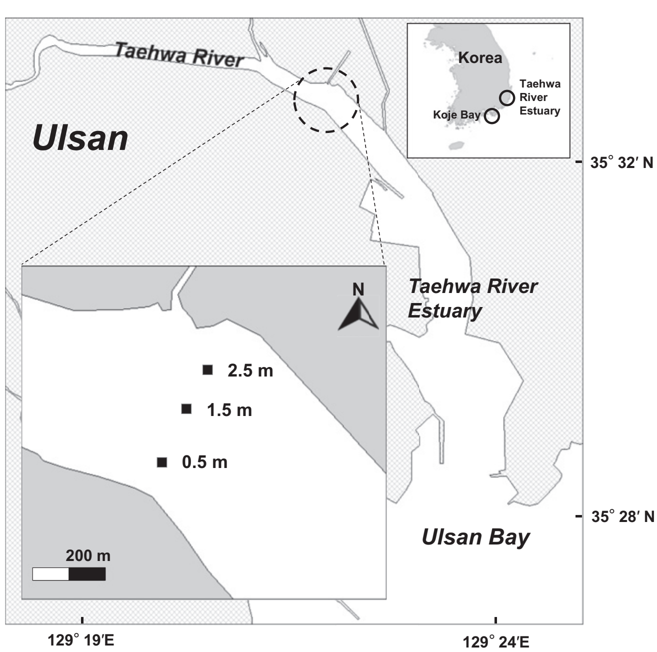

Fig. 1. Transplantation sites in the Taehwa River estuary on the southeastern coast of Korea.

2. Materials and methods

2.1. Study site

The Taehwa River Estuary (35°32.5′N, 129°22.1′E) is located on the southeastern coast of Korea (Fig. 1). The Taehwa River flows through the urban and industrial area of Ulsan, a port city in Korea, and empties into the East Sea at Ulsan Bay. The mean spring tidal range in the estuary is about 60 cm and the mean high water interval is approximately 7 h. Most of the bottom is covered with alluvial sandy loam sediments. Seagrass *Zostera marina* was once widely distributed throughout the entire estuary but physical disturbance and pollution caused its disappearance. Water quality has improved considerably in the estuary due to the construction of a sewage treatment plant and recent efforts to improve water quality. The transplantation sites were located in the upper estuary which previously supported *Z. marina* (Fig. 1). The *Z. marina* vegetative shoots used for transplantation were collected from a dense bed at approximately 1.0 m water depth relative to MLLW in Koje Bay (34°48.0′N, 128°35.0′E), where *Z. marina* is the dominant seagrass species (Fig. 1).

2.2. Pilot seagrass transplantation in 2008

To assess possibility of seagrass restoration in this estuary, a pilot transplantation of *Z. marina* at three water depths was conducted in November 2008. Shoots were collected individually by hand to minimize damage to the donor bed. Mature shoots with similar shoot size were selected. Each shoot had intact leaf blades and five to seven rhizome/root internodes. The collected shoots were placed in large coolers filled with seawater for transporting to the transplant sites, and were planted within 24 h. Three transplantation depths, at 0.5 m (shallow), 1.5 m (intermediate), and 2.5 m (deep) relative to mean lower low water (MLLW) were established along the depth gradient. At each transplantation depth, approximately 1,000 shoots were transplanted using the staple method anchored with bent metal wires and SCUBA diving.