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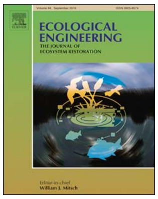

Restoration of tropical seagrass beds using wild bird fertilization and sediment regrading

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ABSTRACT

Shallow water seagrass meadows are frequently damaged by recreational and commercial vessels. Severe injury occurs where propeller scarring, hull groundings and mooring anchors uproot entire plants, excavate sediments, and modify the biophysical properties of the substrate. In climax tropical seagrass communities dominated by *Thalassia testudinum* (turtlegrass), natural recovery in these disturbances can take several years to decades, and in some environmental conditions may not occur at all. During the recovery period, important ecological services provided by seagrasses are absent or substantially diminished and injured meadows can degrade further in response to natural disturbances, e.g. strong currents and severe storms. To determine if we could accelerate rehabilitation and prevent further degradation of injured turtlegrass meadows, we evaluated a restoration method called "modified compressed succession" using the fast-growing, opportunistic species *Halodule wrightii* to temporarily substitute ecological services for the slower-growing, climax species *T. testudinum.* In three experiments we showed statistically significant increases in density and coverage rates of *H. wrightii* transplants fertilized by wild bird feces as compared to unfertilized treatments. In one experiment, we further demonstrated that regrading excavated injuries with sediment-filled biodegradable tubes in combination with wild bird fertilization and *H. wrightii* transplants also accelerated seagrass recovery. Specific recommendations are presented for the best practical application of this restoration method in the calcium carbonate-based sediments of south Florida and the wider Caribbean region.

1. Introduction

Worldwide, seagrass ecosystems flourish in shallow coastal environments with unconsolidated substrates (Hemmimga and Duarte, 2000; Green and Short, 2003; Larkum et al., 2006). A large fraction of seagrass biomass, growth and asexual reproduction occur belowground (Kenworthy and Thayer, 1984; Duarte and Chiscano, 1999; Di Carlo and Kenworthy, 2008) where roots and rhizomes anchor the plants, stabilize sediments, absorb nutrients, and enrich the substrate with organic matter (Kenworthy et al., 2014;). Because unconsolidated sediments are essential for most seagrasses, gap-forming disturbances that physically disrupt the substrate can cause acute and chronic modification of seagrass landscapes (Patriquin, 1975; Fonseca and Bell, 1998), sometimes with negative consequences for ecosystem structure and function (Kenworthy et al., 2002; Whitfield et al., 2002, 2004; Uhrin et al., 2011; Bourque et al. 2015).

Motor vessel propeller scars, hull groundings and anchor moorings create gap-forming injuries in seagrass meadows by excavating plants and sediments (Zieman, 1976; Walker et al., 1989; Durako et al., 1992; Hastings et al., 1995; Sargent et al., 1995; Dawes et al., 1997; Dunton and Schonberg, 2002; Whitfield et al., 2002, 2004; Uhrin et al., 2011; Bourque and Fourqurean, 2014). Surveys in Florida reported 70,000 ha of seagrasses damaged by motor vessels (Sargent et al., 1995) and this problem persists in the Florida Keys where ≥300 vessels run aground in seagrass beds annually (Kirsch et al., 2005; Farrer, 2010; Uhrin et al., 2011; Hallac et al., 2012). Whereas natural sediment disturbances from winds and tides cause gaps in seagrass beds that persist in a state of hydrodynamic equilibrium (Patriquin, 1975; Marba et al., 1994; Fonseca and Bell, 1998), vessel excavations often have steep, unstable margins that inhibit seagrass regrowth, making them vulnerable to erosion and expansion (Kenworthy et al., 2002; Whitfield et al., 2002, 2004; Uhrin et al., 2011). Vessel excavations penetrating beneath the

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seagrass rhizome layer destroy clonal integrity, damage meristems and disrupt ecosystem structure and function (Tomlinson, 1974; Dawes et al., 1997; Kenworthy et al., 2002; Di Carlo and Kenworthy, 2008; Bourque and Fourqurean, 2014; Bourque et al., 2015), while sediment berms formed adjacent to the injuries bury seagrass and interfere with regrowth (Fonseca et al., 2004). Organic matter accumulated and sequestered in the sediments (Fourqurean et al., 2012) is reduced or exported from the meadow, leaving substrates coarser-textured and nutrient depleted, and interrupts carbon sequestration (Dawes et al., 1997; Bourque and Fourqurean, 2014).

Decades of seagrass meadow succession and development can be reversed by a single vessel grounding (Whitfield et al., 2002, 2004). In climax *T. testudinum* meadows natural recovery is usually slow (> 3–10 y), and in some vessel excavations may not occur at all (Fonseca et al., 1987; Dawes et al., 1997; Kenworthy et al., 2002; Whitfield et al., 2002, 2004; Fonseca et al., 2004; Hammerstrom et al., 2007; Farrer, 2010; Uhrin et al., 2011; Bourque et al., 2015). In situations where the substrate has been severely disturbed, restoration may be necessary to rehabilitate the injuries and prevent further disturbance and degradation (Kirsch et al., 2005; Farrer, 2010; Bourque and Fourqurean, 2014).

Thalassia testudinum restoration presents difficult challenges (Fonseca et al., 1987; Lewis, 1987; Fonseca et al., 1998; Treat and Lewis, 2006). The deeply buried apical meristems essential for growth, reproduction and meadow expansion are present in low density and difficult to harvest and re-plant. Acquiring sufficient planting stock and avoiding damage to donor beds is labor intensive and expensive (Fonseca et al., 1998; Lewis et al., 2006; Paling et al., 2009). Depending on the site logistics and monitoring plans, seagrass restoration costs are high compared to terrestrial plant restoration (Fonseca, 2006; Treat and Lewis, 2006; Engeman et al., 2008; Paling et al., 2009) and the likelihood of transplant success is demonstrably uncertain (Lewis et al., 2006; Paling et al., 2009; Fonseca 2011; Van Katwijk et al., 2016). Where the goal of seagrass restoration is to re-establish slow growing *T. testudinum* meadows, valuable ecological services will be lost in the interim (Fonseca et al., 2000) and the injuries may further degrade (Whitfield et al., 2002, 2004; Uhrin et al., 2011). The costs in lost services and rehabilitation clearly demonstrate the need for developing practical and reliable methods for restoration of *T. testudinum* meadows.

To determine if rehabilitation of tropical seagrass meadows could be accelerated, we tested a modification of a restoration approach referred to as "compressed succession" (Derrenbacker and Lewis, 1982; Durako and Moffler, 1984; Lewis, 1987). Compressed succession utilizes a fast-growing species, *Halodule wrightii,* to temporarily substitute ecological services during the relatively slower recovery period of the climax species *T. testudinum*. We modified the original approach by using *H. wrightii* transplants in combination with fertilization and sediment regrading to test whether we could accelerate natural succession. Previous studies of seagrasses growing in phosphorous-limited, calcium carbonate sediments demonstrated that faster *H. wrightii* growth can be attained by adding phosphorus-rich excrement defecated by wild seabirds (Powell et al., 1989; Fourqurean et al., 1995; Herbert and Fourqurean, 2008). Seabirds encouraged to roost on stakes inserted in the sea floor act as a passive fertilizer delivery system (primarily phosphorous), favoring and stimulating faster growing *H. wrightii*. Here, we report the results of three experiments evaluating whether seagrass recovery in climax *T. testudinum* meadows severely disturbed by propeller scarring and larger vessel excavations could be accelerated by application of modified compressed succession.

Initially we examined if fertilization by seabirds would increase survival and growth of *H. wrightii* transplants in unvegetated propeller scars. In two additional experiments we examined a combination of wild bird fertilization and topographical restoration. We hypothesized that re-grading injuries with fine-grained sediments and leveling the topography would physically stabilize excavated injuries and provide a more favorable environment for faster *H. wrightii* recovery and eventually lead to the re-establishment of *T. testudinum*.

2. Methods

2.1. Study site

All three experiments were conducted in the Lignumvitae Key Submerged Land Management Area (LKSLMA) in the middle Florida Keys (24.91 °N, 80.68 °W) (Fig. 1). LKSLMA is comprised of extensive, shallow, calcium carbonate-based seagrass banks dominated by *T. testudinum* typical of south Florida, the tropical western Atlantic and the Caribbean region (Zieman, 1982; Short et al., 1985). Water depths were generally ≤1.5 m (mean high water) and the tidal range was approximately 1m.

2.2. Study plan

In Experiment 1 we evaluated the use of bird roosting stakes to fertilize *H. wrightii* transplants, and tested whether this fertilization technique accelerated rehabilitation of propeller scars. Experiments 2 and 3 were designed to evaluate bird roosting stakes and *H. wrightii* transplants in combination with sediment regrading. We examined recovery of propeller scars (Experiment 2) and a larger vessel excavation (Experiment 3) using a combination of wild bird fertilization*, H. wrightii* transplanting, and a method for re-grading excavations with sediment-filled, biodegradable fabric tubes (hereafter referred to as Sediment Tubes[1]).

2.3. Restoration techniques

2.3.1. Bird roosting stakes

In Experiments 1, 2 and 3, PVC pipe stakes (1.25 cm dia.) capped with 10 cm x 10 cm x 5 cm pressure-treated wooden blocks were designed to encourage seabirds, particularly cormorants (*Phalacrocorax auritus*) and terns (*Sterna spp.)*, to perch and defecate phosphorus-rich feces into the water and sediment (Powell et al., 1989) (Fig. 2). Control stakes (no fertilizer added) in Experiment 1 were fashioned by eliminating the wooden block and cutting the PVC pipe diagonally at the top to discourage roosting birds. Stakes were inserted into the sediment until ≈ 0.25-0.5 m of each stake extended above the water surface at mean high tide.

2.3.2. Sediment tubes

In Experiments 2 and 3, sediment tubes were used to regrade excavated seagrass beds. The tubes (1.0–1.5 m long, 15–20 cm dia.), filled with fine-grained calcium carbonate screening sand (0.63–0.85 mm dia.), were manually deployed into injuries from a shallow draft vessel (Fig. 3).

2.3.3. Seagrass transplanting

We followed the recommended procedures for seagrass bare root transplanting (Fonseca et al., 1998). *Halodule wrightii* shoots with intact roots and rhizomes were collected from a meadow adjacent to Lignumvitae Key, rinsed free of sediment, assembled into planting units and planted the same day. Planting units (hereafter referred to as PU or PUs) were constructed by attaching horizontal rhizomes and shoots to a 25 cm U-shaped metal staple using paper-coated wire twist ties. Each PU had approximately 15–30 shoots and ≥5 rhizome apical meristems. For installation of the PUs into sediment tubes, 5–10 cm slits were cut lengthwise into the top of the sediment tube fabric with a dive knife to create a space for inserting the PUs, and to allow horizontal rhizome growth while the fabric decomposed.

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[1] Patented by James F. Anderson, founder of Seagrass Recovery, 5858 Central Ave., St Petersburg, FL 33707.

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