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Experimental determination of the effects of light limitation from suspended bag oyster (*Crassostrea virginica*) aquaculture on the structure and photosynthesis of eelgrass (*Zostera marina*)

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ABSTRACT

Recent studies have hypothesized reduced eelgrass distribution in areas exposed to suspended bag oyster aquaculture of *Crassostrea virginica* in Eastern Canada is related to shading from aquaculture stock and equipment. The results of a 359-day manipulative field experiment support this hypothesis. Reductions in underwater light, at levels comparable to those found at suspended oyster operations, caused reduced eelgrass structure, morphometrics, and photosynthesis. Increased organic matter deposition under suspended bags neither led to biologically relevant declines in eelgrass metrics, nor mitigated the effects of light limitation. Shoot density, above-ground biomass, below-ground biomass, canopy height, leaf area index, leaf width, and photosynthetic capacity were all significantly reduced. These variables declined along a gradient of increased shading, with significant responses detected in as few as 67 days after exposure to 26% subsurface irradiance. Subsequent sampling 253 days after the removal of experimental treatments documented the potential for recovery in the form of seedling recruitment to the plots of heaviest impact. However, eelgrass response variables remained significantly reduced relative to controls, indicating previous assumptions of a rapid recovery potential for eelgrass exposed to suspended bag oyster aquaculture were incorrect.

1. Introduction

Currently, more than 1 billion people live within 50 km of seagrass beds and major threats to the persistence of this habitat include coastal development, eutrophication, sedimentation, and climate change (Waycott et al., 2009).

According to a recent synthesis of 215 peer-reviewed studies on seagrass distribution, seagrass habitat declined worldwide at a rate of 110 km^2 per year between 1980 and 2006 with additional analysis estimating a 29% decline in known areal extent since 1879 (Waycott et al., 2009). Specific to *Zostera* populations, worldwide declines are associated with anthropogenic stresses, especially those linked to decreased underwater light levels or reduced water clarity associated with increased nutrient and sediment loading (Moore and Short, 2006; Moore et al., 1997).

Seagrass declines due to aquaculture-related nutrient level alteration, organic enrichment, sedimentation, physical destruction, and shading have been documented internationally for a variety of culture species and their associated rearing and harvesting practices. Extensive declines of *Posidonia oceanica* have been linked to increased sedimentation, nutrient concentrations of phosphorous and nitrogen, and organic loading at Mediterranean fish farms (Cancemi et al., 2003; Holmer et al., 2003; Katavic and Antolic, 1999; Ruiz et al., 2001). *Zostera marina* reductions of upwards of 75% at stake and rack culture plots of *Crassostrea gigas* in the Pacific northwestern United States have been linked to shading, erosion, sedimentation and physical disturbance (Carleton et al., 1991; Everett et al., 1995; Pregnall, 1993; Simenstad and Fresh, 1995; Wisehart et al., 2007). Surveys of *C. gigas* aquaculture sites in Willapa Bay, WA, USA (Tallis et al., 2009) have demonstrated 3-fold reductions in *Z. marina* density, 32% lower biomass, and 70% lower areal productivity at bottom (either dredged or handpicked) and longline culture sites as a result of physical impacts and space competition. Wagner et al. (2012) suggest that this space competition resulted in at least 50% loss of shoot density and occurred above a threshold of about 20% cover of bottom cultured oysters. De Casabianca et al. (1997) link shifts from *Zostera* spp. community

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dominance to opportunistic algae (*Ulva* and *Gracilaria* spp.) to altered nutrient dynamics at oyster and mussel culture sites in France.

Suspension-feeding bivalves, however, are also capable of positively interacting with seagrass communities in a variety of manners (reviewed by Dumbauld et al., 2009). By filtering large quantities of particulate nitrogen, which is then remineralized as ammonium available for plant growth, suspension-feeding bivalves are part of a positive feedback loop which can increase nitrogen cycling rates (Dame et al., 1989, 1984). Reductions in turbidity resulting from filtering by eastern oysters have been predicted to substantially increase water clarity which could permit seagrass to colonize greater water depths (Newell and Koch, 2004). Bivalve fecal matter also contributes considerable amounts of phosphorous to sediments (Dame et al., 1989), which then release phosphate under anaerobic conditions (Nixon et al., 1980), thus potentially encouraging plant growth. Such positive reactions have been recorded between natural bivalve populations and seagrass. Reusch et al. (1994) reported a doubling of sediment concentrations of ammonium and phosphorous as a result of feces and pseudofeces deposits by mussels (*Mytilus edulis*) and suggested this may fertilize the growth of *Z. marina.* Support for this hypothesis exists in the results of experiments addressing these mechanisms by Peterson and Heck (2001a). Plots of *Thalassia testudinum* were treated with densities of 0, 500, and 1500 *Modiolus americanus*·m^{-2}. In mussel plots, sediment concentrations of total nitrogen and phosphorous doubled and C:N, N:P, and C:P ratios in plant tissues significantly decreased, suggesting these bivalves increased sediment nutrient content and these nutrients were utilized by the seagrass. Leaf lengths and net primary production were also significantly greater in mussel treatments, demonstrating a positive influence of a suspension-feeding bivalve on seagrass (Peterson and Heck, 2001a). Further corroboration has been provided in follow-up studies utilizing alternate bivalve species such as *Mercenaria mercenaria* (Carroll et al., 2008) as well as *Crassostrea virginica*, *Mytilus edulis, and Argopecten irradians* (Wall et al., 2008, 2011).

During multiple field surveys of suspended oyster aquaculture leases in bays and estuaries in the southern Gulf of St. Lawrence (sGSL) separated by as much as 125 km, consistent declines in above-ground eelgrass biomass were observed; on average 57% but as high as 79% relative to reference sites (Skinner et al., 2013). Reductions in biomass were negatively correlated with both oyster stocking density and the age of culture leases. The efficiency and capacity of eelgrass photochemistry at culture sites were also reduced, accompanied by primary production declines of 37.9% (Skinner et al., 2013). We hypothesized these eelgrass declines at Atlantic Canadian suspended oyster aquaculture leases were occurring as a result of light limitation caused by shading from aquaculture stock and equipment. We predicted the structure, morphometrics, and photosynthesis of eelgrass would negatively respond to increasing shading intensity. In addition, oyster stocking density was manipulated to examine the potential for cumulative or mitigating effects related to organic matter deposition to the benthos. The aims of this study were to examine the timing and magnitude of eelgrass responses to commercial-scale suspended oyster aquaculture under controlled conditions, and to provide preliminary estimates of its recovery potential.

2. Methods

2.1. Study area

Bay St. Simon south (BSS) is a narrow, shallow bay with an approximate area of 900 ha. extending north to south from Shippagan Bay in northeastern New Brunswick (Fig. 1). This bay has 97.7% eelgrass coverage with a mainly soft-firm silt bottom (Senpaq Consultants, 1990). Land-based activities include Shippagan Provincial Park, limited cottage development and a peat harvesting operation at the southernmost tip of the bay. While no commercial fishing is conducted in the bay, there are approximately 39 shellfish aquaculture leases (predominantly Eastern oyster) occupying a total of ~200 ha. Only a small fraction of this leased area is currently under active production. Eastern oyster culture in New Brunswick involves the suspension of oysters in plastic mesh bags from lines (Fig. 2) at, or just below, the water's surface in the shallow subtidal zone (~0.3–5.0 m depth, chart datum) from approximately April to mid-October. For the remainder of the year, these oysters are either moved to alternate locations with more favorable overwintering characteristics, or sunk to just above or directly on the substrate to protect stock from ice and severe weather (Bastien-Daigle et al., 2007).

2.2. Experimental design

Over 359 days between July 2009 and June 2010, a manipulative experiment was conducted in Bay St. Simon south to examine the potential influences of shading and stocking density of suspended oyster aquaculture on the distribution, growth, and photosynthetic capacity of eelgrass. Plots of eelgrass (~3 m^2 surface area) were exposed to varying levels of oyster stocking density, a potential source of organic enrichment, and shading from suspended bag culture structures for 106 days (October 2009), after which treatments were removed. A post-winter reassessment of plots was conducted in late-May/June 2010 (328 or 359 days, depending on the response variables). Plots were established in an area zoned for suspended oyster aquaculture that had never been used for commercial production (N 47.732049°, W −64.775638°; 0.6 m depth, chart datum). Experimental treatments were constructed using commercial supplies and were installed and removed with the assistance of aquaculture professionals to accurately replicate commercial oyster aquaculture practices. Treatments were randomly assigned to plots arranged in a grid with a minimal spacing of 8 m between experimental plots.

Experimental factors included Shading [three levels: S1 (60% subsurface irradiance), S2 (28.5% subsurface irradiance), and S3 (19.7% subsurface irradiance); fixed factor] and Oyster Stocking Density [three levels: O1 (0 kg oysters m^{-2} using empty, clean oyster shells), O2 (3.2 kg oysters m^{-2}; commercial oyster stocking density), and O3 (6.4 kg oysters m^{-2}; double commercial stocking density); fixed factor] in an orthogonal 3×3 factorial design for a total of nine treatment combinations ($n = 3$ replicates/treatment). This naming convention will be used throughout the remainder of the paper; i.e. S2O2 will represent the experimental treatment combining the middle level of shading (S2 = 28.5% subsurface irradiance) and the middle level of oyster stocking density (O2 = 3.2 kg oysters m^{-2}). Subsurface irradiance (SSI) was measured 1 cm below the water's surface using a handheld meter (LI-1400 Datalogger with LI-192SA Underwater Quantum Sensor, LI-COR Inc., Lincoln, Nebraska, USA). Time (seven levels: 1, 18, 38, 52, 67, 93, and 359 days post-exposure initiation; random factor), was incorporated in a two-way repeated measures analysis of variance (ANOVA) design as a "within subjects" factor with Shading and Oyster Stocking Density included as orthogonal "between subjects" factors (Quinn and Keough, 2002). Shading levels were manipulated by using commercial suspended oyster structures. Low shade (S1) treatments utilized floating pontoon racks supported by a rebar frame (1.2 m wide × 2.4 m long) with oysters (35–50 mm initial shell length) glued in triplicate clusters on parallel ropes running the length of the frame (Fig. 2A). Medium shade (S2) treatments consisted of four conventional floating plastic mesh bags arranged two bags wide by two bags long (~1.4 m wide × 2.0 m long) in a single layer (Fig. 2B). High shade (S3) treatments were arranged as per S2 Shade treatments with the addition of shade screens affixed to the tops of the bags (Fig. 2C). Shade screens were constructed from commercially available garden weed screening, double layered over a wooden frame. Oysters were sourced from a commercial oyster lease in Bay St. Simon south. An additional group of control plots ($n = 3$), of an equivalent surface area with no treatments applied and set-up in the same fashion as treated plots, were established to give a final total of 30 experimental plots.