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Long-term seafloor monitoring at an open ocean aquaculture site in the western Gulf of Maine, USA: Development of an adaptive protocol

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ABSTRACT

The seafloor at an open ocean finfish aquaculture facility in the western Gulf of Maine, USA was monitored from 1999 to 2008 by sampling sites inside a predicted impact area modeled by oceanographic conditions and fecal and food settling characteristics, and nearby reference sites. Univariate and multivariate analyses of benthic community measures from box core samples indicated minimal or no significant differences between impact and reference areas. These findings resulted in development of an adaptive monitoring protocol involving initial low-cost methods that required more intensive and costly efforts only when negative impacts were initially indicated. The continued growth of marine aquaculture is dependent on further development of farming methods that minimize negative environmental impacts, as well as effective monitoring protocols. Adaptive monitoring protocols, such as the one described herein, coupled with mathematical modeling approaches, have the potential to provide effective protection of the environment while minimize monitoring effort and costs.

1. Introduction

Marine aquaculture is a rapidly growing industry worldwide, with projections for continued growth and expansion (WHOI, 2007; Lucas and Southgate, 2012). Long-term success of marine aquaculture is in part dependent on further development of culture methods that minimize negative environmental impacts. Open ocean finfish cage culture is a relatively new endeavor that is being pursued in part because the potential for negative impacts are generally lessened in deeper offshore waters compared to shallower nearshore sites (Pearson and Black, 2001; Price and Morris, 2013). However, there have been relatively few published studies of open ocean aquaculture facilities, especially those reporting environmental monitoring data, which has hindered further development (Holmer, 2010).

The major effects on the seafloor from fish cage culture result from deposition of organic materials, including biodeposits from the culture organisms and excess food material. In general, studies to date on organic wastes indicate if deposition rates do not exceed the ability of benthic organisms to assimilate the organic matter, benthic communities are not detrimentally affected (Pearson and Black, 2001). The Pearson and Rosenberg (1978) conceptual model for the response of benthic infauna to organic inputs remains generally valid for mud-bottom habitats (Rhoads and Germano, 1982; Grizzle and Penniman, 1991; Nilsson and Rosenberg, 2000; Wildish et al., 2004). And models have been developed that are capable of predicting impacts to the benthos for various combinations of environmental conditions and fish biomass (Rensel et al., 2006; Kiefer et al., 2011). However, there still is a pressing need move beyond the heavy reliance on traditional and costly environmental monitoring programs commonly required by regulatory agencies to adaptive approaches that include predictive modeling.

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The University of New Hampshire (USA) initiated an experimental open ocean aquaculture (OOA) site in the western Gulf of Maine in 1993 and completed grow-out of a variety of species until the project ceased in 2010. Permitting and environmental monitoring requirements evolved over the term of the project but consistently included seafloor monitoring. Here, we describe the results of monitoring sediments and benthic macrofauna from 1999 to 2008 (the time period when similar methods were used), and how the persistent finding of 'no negative impacts' resulted in an adaptive approach to environmental monitoring that was implemented in 2008.

2. Materials and methods

2.1. Study site

The farm site was located 10 km offshore of Portsmouth, New Hampshire, USA in the southwestern Gulf of Maine in ~50 m of water (Fig. 1). The seafloor in the general vicinity is relatively heterogeneous, including bedrock outcrops, gravel, and muddy sands. However, the area most likely impacted by the aquaculture operation consisted primarily of poorly sorted, muddy sands.

Two major fish cage and mooring system deployments were conducted at the OOA site over the duration of the project. The first occurred in the summer of 1999 with the installation of two 600 m^3 SeaStation™ fish cages, each with a submerged, grid-type mooring system (design and deployment details can be found in Tsukrov et al., 2000; Fredriksson et al., 2000; Baldwin et al., 2000). With this mooring system, the cages could either be kept at the surface for better access and greater dispersal of wastes or submerged to reduce loads from winds, waves and currents. While the deployment of the two small SeaStation™ fish cages and moorings proved to be an engineering success (see Fredriksson et al., 2003), it was clear that this configuration had limited biomass capacity. Thus, in the summer of 2003, all gear was replaced with a new submerged grid mooring system capable of holding four SeaStation™ fish cages (in a 2 × 2 configuration) each with an internal volume of 3000 m^3. Though many of the design attributes were similar to the earlier cage moorings (Fredriksson et al., 2004), a much greater biomass capacity was achieved.

2.2. Monitoring history and study design

Concurrent with these changes in cage configurations there were also variations in fish species, densities and biomasses deployed to the cages over the study period (Table 1). Although the field and laboratory methods (see below) remained consistent from year to year, the number of sampling sites, their locations, and sampling frequency varied substantially over time, mainly in response to feedback from the permitting agencies as the program evolved. Sampling frequency was on an approximately monthly basis for 1999–2001, quarterly from 2002 to 2004, and semi-annually from 2005 to 2007. Finally in 2008, a single set of samples was taken and an adaptive monitoring protocol was implemented (see detailed section below). In order to minimize variability and directly compare the data from all 10 years of the study, the overall dataset was averaged to a series of annual means, one for reference (or control) sites and another for impact sites.

Determination of the spatial extent of the impact and reference areas was accomplished initially using a collection of unpublished environmental data (e.g., currents) and the application of a simple settling model (Gowen et al., 1989). This process identified a 700 m × 450 m rectangular "impact area" (Fig. 2). Though the calculations supporting this decision are not shown herein, it was evident that a limited amount of detailed current velocity information existed. The process also verified the need to establish a long-term observational platform for which more accurate currents at the site could be measured and therefore waste movement better estimated. Therefore, as part of the overall environmental monitoring program, an oceanographic buoy was installed at the site from 2001 to 2008, with a typical deployment period between 2 weeks and 3 months. Instrumentation on the platform included wave measurement sensors, temperature,

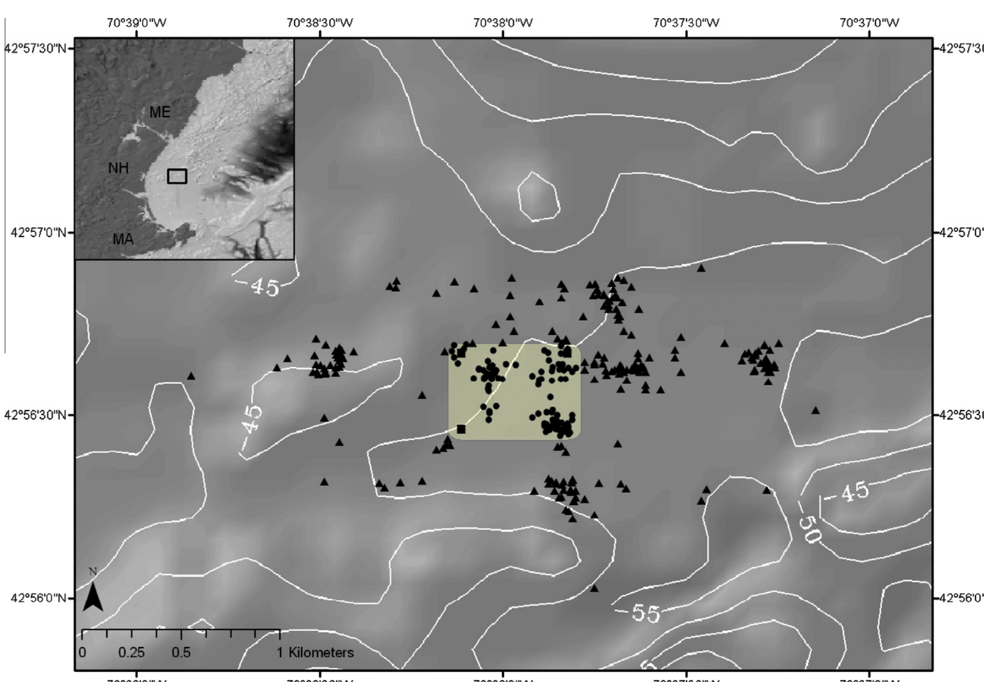

Fig. 1. Box corer sample locations in impact (light colored rectangle; sample locations shown as circular dots) and reference (sample locations shown as triangles) areas. Water depth contours in meters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)