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Integration of ecosystem-based models into an existing interactive web-based tool for improved aquaculture decision-making

Suzanne B. Bricker [a,*], Tessa L. Getchis [b], Cary B. Chadwick [c], Cori M. Rose [d], Julie M. Rose [e]

[a] NOAA, National Center for Coastal Science, 1305 East West Highway, Floor 9, Silver Spring, MD, USA
[b] Connecticut Sea Grant, UConn Extension, University of Connecticut, Groton, CT, USA
[c] Center for Land use Education and Research, University of Connecticut, Haddam, CT, USA
[d] U.S. Army Corps of Engineers, Concord, MA, USA
[e] NOAA Fisheries Northeast Fisheries Science Center Milford Laboratory, Milford, CT, USA

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ABSTRACT

Proper site selection is critical to the development and expansion of marine aquaculture. Major considerations for site selection include: potential for competing uses, environmental interactions, and animal productivity. Two types of existing site selection tools, mapping and modeling, have proven useful independently, and in some recent studies have proven useful when used together. GIS-based mapping tools have become important in the decision-making process. These tools provide access to marine and coastal datasets allowing farmers and extension agents to gather information on availability of cultivation sites. They are also used by resource managers to assess potential use conflicts (e.g. existence of commercial fishing, mooring areas, fixed fishing gear) and possible environmental interactions (e.g. presence of seagrasses, contaminants, threatened or endangered species). Models have been used separately to predict animal growth, farm productivity, and farm-related effects on the surrounding water and sediment quality.

The integration of the Farm Aquaculture Resource Management (FARM) model (http://www.farmscale.org) into the U.S. state of Connecticut's *Aquaculture Mapping Atlas* (http://seagrant.uconn.edu/whatwedo/aquaculture/shellmap.php) was tested in three geographically distinct waterbodies within Connecticut (CT) waters of Long Island Sound. Nearshore waters within the towns of Mystic, Milford, and Westport were selected as pilot locations to determine usability and capability of the combined tools. Data from two long-term offshore sampling stations adjacent to existing shellfish leases were used to test spatial and temporal sampling variability impacts on model results. Partnerships with local monitoring programs and growers were important for acquisition of water quality data, oyster measurement data, and information about local culture practices. All sites were deemed suitable for oyster aquaculture based on model results that predicted Moderate to High growth based on estimated time to reach harvest size from one in (2.54 cm) seed oysters (*Crassostrea virginica*). Time to harvest varied from 282 days (High growth) to 645 days (Moderate growth) among the 22 stations in the three nearshore sites, and 724–956 days (Moderate growth) at the two offshore sites. Results from the two long-term offshore stations indicate that data from the same year must be used when comparing production-based suitability of sites. Addition of potential production estimates improved the ability to select between suitable mapping-based sites. This mapping and modeling combination should be encouraged to provide a strong basis for successful siting and expansion of aquaculture while minimizing user conflict and adverse environmental interactions. This approach may be particularly useful in waterbodies where shellfish aquaculture is possible but is not well established.

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1. Introduction

Aquaculture is a large and growing segment of the global seafood economy, but the majority of aquaculture production occurs in just a few countries (FAO, 2010, 2014). As capture fisheries production continues to level off, or even declines, aquaculture is being increasingly viewed as the means to meet an ever-growing global seafood demand. One of the major challenges to the expansion of marine aquaculture in most nations is initial industry siting and subsequent expansion of aquaculture operations, including lack of information about suitability

Abbreviations: μg, micrograms; L, liter; g, gram; kg, kilogram; cm, centimeter; m, meter; h, hours; d, day; y, year; in, inch; SAV, submerged aquatic vegetation; ASSETS, Assessment of Estuarine Trophic Status; FARM, Farm Aquaculture Resource Management; CUSH, Clean Up Sound and Harbors; CT DEEP, Connecticut Department of Energy and Environmental Protection; EPA, Environmental Protection Agency; POM, particulate organic matter; TPM, total particulate matter; TSS, total suspended solids; PC, particulate carbon; POC, particulate organic carbon.

* Corresponding author.
E-mail address: suzanne.bricker@noaa.gov (S.B. Bricker).

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of bottom type, conflicting uses in the marine environment, and social license to farm (Soto et al., 2008; Angel and Freeman, 2009; Byron et al., 2011; Wikfors, 2011). In the United States, both the NOAA Marine Aquaculture Policy and the NOAA National Shellfish Initiative have highlighted the need for improvements to the aquaculture site selection process, further demonstrating the need for decision support tools to locate suitable areas for aquaculture with fewer procedural hurdles.

Presently there are several state-level, GIS-based shellfish aquaculture site selection tools under development or in use in the United States, including Connecticut http://seagrant.uconn.edu/whatwedo/aquaculture/shellmap.php, Massachusetts http://maps.massgis.state.ma.us/map_ol/oliver.php, Maryland http://dnrweb.dnr.state.md.us/fisheries/aquatool/aquatool.asp, New York http://gis.co.suffolk.ny.us/shellfish/index.html, Maine http://www.maine.gov/dmr/aquaculture/leaseinventory/index.htm, and North Carolina http://uncw.edu/benthic/sitingtool/. GIS mapping tools are also under development or are already being used for informing aquaculture siting in other countries such as New Zealand (Longdill et al., 2008) and Japan (Radiarta et al., 2008). These GIS based mapping tools have been created to allow visualization of aquaculture within the context of other coastal zone uses to minimize use conflicts and to overlay various datasets to depict potential environmental interactions (e.g. species, habitats, contaminants, food availability). GIS-based tools are successful at minimizing use conflicts for siting operations but mapping alone does not address productivity at these suitable sites (Longdill et al., 2008).

Modeling has provided better insight into the potential success of candidate farm locations in terms of biological production and ecological carrying capacity (e.g. Filgueira et al., 2013a, 2013b, 2014a, 2014b; Tissot et al., 2012). Here we refer to ecological carrying capacity as the maximum stocking or farm density that is possible without unacceptable ecological impacts (Inglis et al., 2000). Potential production, socio-economic outputs, and environmental effects can be estimated through application of models, including scenarios, without the cost or time required for actual implementation. Site specific environmental data along with typical cultivation practices can be used to predict seed stocking density to determine the optimum long-term production that the area will support. In turn, this allows estimation and maximization of sustainable harvest of shellfish, as well as assessment of long-term socio-economic profits and negative and positive environmental externalities (e.g. Bricker et al., 2015; Ferreira et al., 2011; Grant and Filguiera, 2011; Silva et al., 2011).

Here we combine mapping and modeling to provide an improved GIS-based decision support tool to identify suitable areas for siting aquaculture that will minimize use conflict and assess the potential for successful growth. The combined tool is intended to help streamline and facilitate permitting, giving regulators, who have responsibility to prevent adverse impacts to habitat and to avoid use conflicts, the necessary information to evaluate grower requests. Thus it should facilitate the integration of social, environmental and economic factors in the decision-making process. The combined tool will assist informed and smart growth of aquaculture with expansion into areas best suited for shellfish production. Unlike some recent studies that have combined hydrodynamic, ecosystem, and shellfish production models with geospatial capabilities (e.g. Bricker et al., 2015; Filgueira et al., 2014a, 2014b; Nobre et al., 2009, Tissot et al., 2012) we use a simpler approach consistent with that of Silva et al. (2011; Figure 1). The simpler approach has less stringent data requirements that make it more accessible to users. Here we test the capabilities of combining potential production estimates from application of a local scale model with the existing GIS aquaculture mapper.

We combined the Connecticut, United States, *Aquaculture Mapping Atlas* (http://www.seagrant.uconn.edu/whatwedo/aquaculture/shellmap.php) with the local scale Farm Aquaculture Resource Management model (FARM; Ferreira et al., 2007a, 2007b, 2009, 2012; www.farmscale.org). This location was chosen because shellfish aquaculture is well established in Connecticut (CT), *The Aquaculture Mapping Atlas* has been in use for several years, and there is interest in shellfish industry expansion within the state. The intent was to improve shellfish siting decision support tools available to growers, resource managers, and regulators in CT and to create a relatively simple framework that will be transferable to other waterbodies. We used the Eastern oyster, *Crassostrea virginica*, as the target species because it has historically been fished and cultivated in this waterbody (Churchill, 1920; Kurlansky, 2006; state shellfish commission reports dating back to 1880s).

The approach and use of the combined tools were designed to answer two questions: 1) where can shellfish operations be sited, and 2) how well will shellfish grow at sites deemed suitable? The results were added as a GIS layer to the existing *Aquaculture Mapping Atlas*. We additionally evaluated: variability in growth rates among stations within an embayment, whether ecosystem model results could be used to fill in missing winter data at some sites, and the inter-annual variability of growth at two sites with long-term data. The improved tool is expected to increase the success of new and expanded oyster aquaculture in CT waters while minimizing use conflicts and detrimental environmental impacts.

2. Methods

2.1. Mapping: determination of suitable shellfish area

The approach used in this demonstration project followed the concept of Silva et al. (2011) and others (e.g. Radiarta et al., 2008; Tissot et al., 2012) whereby Connecticut's interactive *Aquaculture Mapping Atlas* (http://clear3.uconn.edu/aquaculture) was used to determine the areas likely to be unsuitable for aquaculture due to interactions with sensitive environmental resources, use conflicts, or contaminated bottom sediment or water quality (Table 1; Fig. 1). In general terms, this online mapping tool combines various layers of geospatial information to depict the location of restricted or potentially problematic areas, which provides a method to identify those areas that have limited regulatory constraints and suitable water quality to allow oyster aquaculture.

The three nearshore study areas, Mystic, Milford, and Westport, are small (5–30 km^2 area), shallow (~3 m average depth) and support a variety of marine based activities (e.g. recreational and commercial boating, fishing, aquaculture, and shipping; Fig. 2). The Long Island Sound stations are located in water depths of about 10 m and are adjacent to or overlapping with shellfish lease areas (Fig. 2). The base map, used to locate and identify these areas of interest, could be a street map, aerial imagery, topographic map or navigational chart. Once determined, geospatial data layers were used to depict unsuitable areas

Table 1
The Shellfisheries Mapping Atlas allows users to access, overlay, and view various types of site information.

Economy	Society	Environment
General site characteristics important for production, gear type, configuration Example layers:	*Historical, current and potential future uses and users* Example layers:	*Potential environmental interactions* Example layers:
• Bathymetry/soundings • Water quality • Sediment type • Shellfish classification type (e.g. approved, prohibited, conditional)	• Existing/potential aquaculture lease areas • Marina and mooring positions • Commercial fishery vessel density • Recreational shellfish beds	• Distribution/abundance of living marine resources • Native populations • Endangered species • Protected habitats (e.g. SAV)