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

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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.

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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	*Historical, current and potential future uses and users*	*Potential environmental interactions*
Example layers:	Example layers:	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)

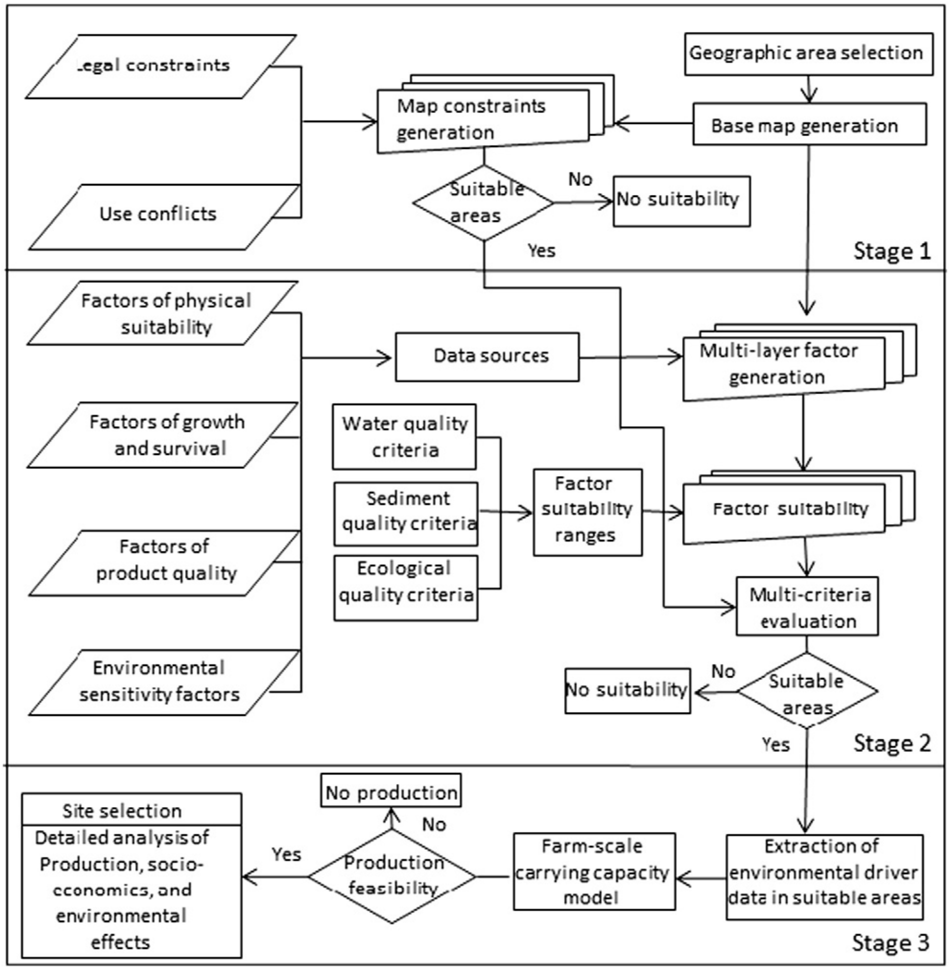

Fig. 1. Flow process and considerations for selection of shellfish aquaculture sites adapted from the framework of Silva et al. (2011) for this study. Here stages 1 and 2 represent steps taken in the CT *Aquaculture Mapping Atlas* for determination of suitability, stage 3 represents application of FARM model results to areas deemed suitable in stages 1 and 2. Here we look only at production using the time to reach harvest size as the key indicator.

sequentially. For example, a stepwise sequence to identify and exclude unsuitable areas:

1) Navigation layers: to identify proximity to federal navigation channels and associated no-construction buffers
2) Shellfish harvest areas: location of existing commercial and recreational harvest areas
3) Shellfish area classification: to identify where shellfish cannot be safely and legally harvested for human consumption
4) Environmental sensitivity index: to identify areas with protected habitats and species
5) Maritime use layers: to identify other recreational and commercial uses that may take precedent or may present use conflicts

The areas that remained were considered suitable for siting of aquaculture activities.

2.2. Modeling: estimating shellfish growth in the suitable areas

The Farm Aquaculture Resource Management (FARM) model was used to estimate potential production in areas deemed 'suitable' for commercial shellfish activities without the cost and time required for implementation. For this pilot study, all stations were included in the modeling, regardless of suitability determination. The model was applied to data from each station within the three nearshore study areas (Westport, Milford, Mystic) and to the two sites in Connecticut waters of Long Island Sound (Stations 09, H2; Fig. 2). The model output used to evaluate site suitability was the estimated time for *C. virginica* seed (one in, 2.54 cm) to reach harvestable size (three in, 7.62 cm). Previous works have used similar modeling approaches to: evaluate the potential for reduction of eutrophic symptoms (i.e. nutrient bioextraction; e.g. Bricker et al., 2014, 2015; Rose et al., 2015), determine ecological carrying capacity and aquaculture optimization (e.g. Byron et al., 2011; Ferreira et al., 2007a, 2007b, 2009, 2011, 2012; Filgueira et al., 2014a, 2014b; Nobre et al., 2009; North et al., 2010; Silva et al., 2011), and assess the practicability of integrated multi-trophic aquaculture (e.g. Nunes et al., 2011; Saurel et al., 2014). This study uses a simpler modeling approach that is intended to be more accessible to users, with less stringent data requirements than the more complicated modeling approaches that use combinations of GIS capabilities with local and ecosystem scale and 3D high resolution circulation models. The model results here are used to create an additional GIS layer in Connecticut's *Aquaculture Mapping Atlas*, improving the power of the decision making process by showing which suitable areas would support the fastest growth of Eastern oysters to harvestable size.

The FARM model is a local scale model that combines physical and biogeochemical models, shellfish growth models, and screening models at the farm scale for the determination of shellfish production and for the assessment of water-quality changes on account of shellfish cultivation. The model has been used previously for decision support for aquaculture siting (e.g. Ferreira et al., 2012; Silva et al., 2011). It can be used for marginal analyses of farm production potential and profit maximization, while assessing potential credits for carbon and nitrogen trading (Ferreira et al., 2007a, 2007b, 2009, 2011; www.farmscale.org). The FARM model includes components of an eutrophication assessment

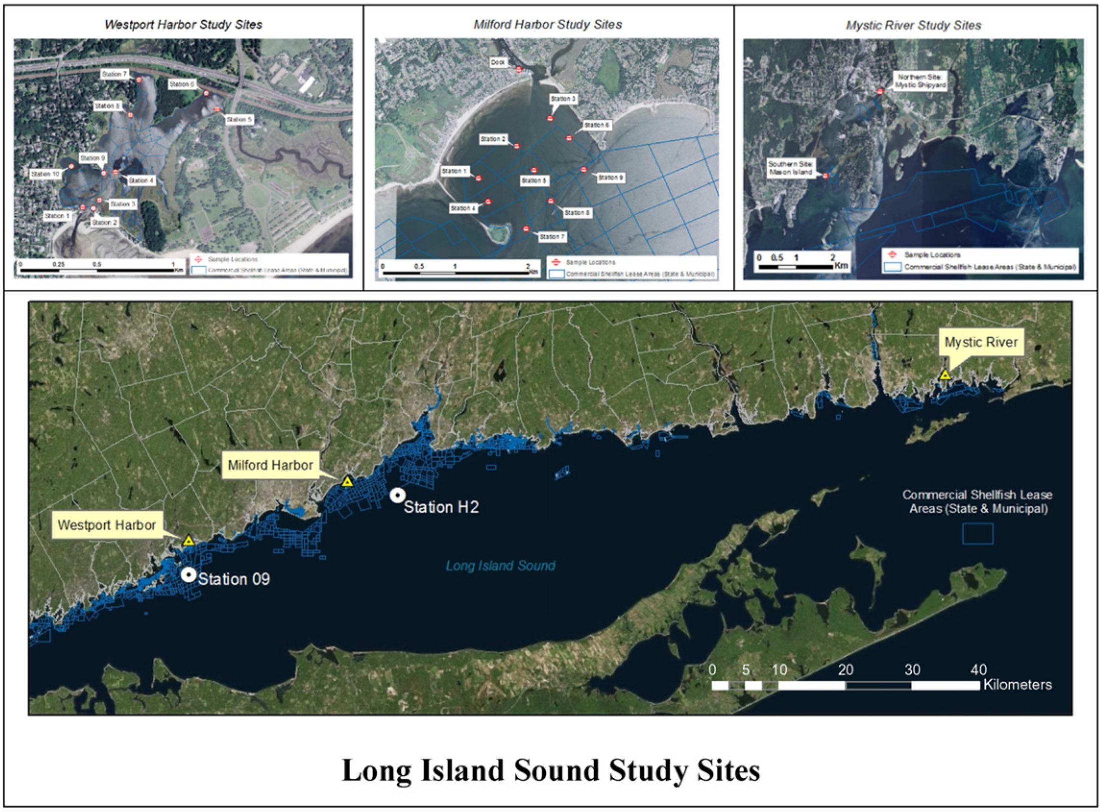

Fig. 2. Map of individual study sites (upper panel) and their locations (lower panel) in Long Island Sound with detail of relative location of the Long Island Sound Study long-term monitoring stations 09 and H2.

model ('Assessment of Estuarine Trophic Status' [ASSETS], Bricker et al., 2003) that allows evaluation of changes in the eutrophication indicators, chlorophyll *a* and dissolved oxygen (DO) that result from the filtration of the oysters during the culture period.

The FARM model can be applied to simulate various cultivation practices; suspended culture from rafts or longlines, as well as bottom culture. Here we simulate bottom culture. Inputs for shellfish modeling (Table 2) include data on culture practice (e.g. farm layout, species, and stocking densities) and environmental parameters, including shellfish food particles in the water column (i.e., phytoplankton and detritus). Monthly data points for at least one year are required for the food and environmental parameter inputs, while current speeds are input as peak flow at neap and spring tides (Table 3). The model output of interest evaluated in this study was the time for an Eastern oyster to reach harvestable size (i.e. three in, 7.62 cm) from a seed of one in length (2.54 cm).

2.2.1. Oyster aquaculture in Long Island Sound: culture practice model inputs

There are about 300 people from 45 companies cultivating oysters in Connecticut. The 2015 harvest of oysters and clams was estimated to be worth $30 million (David Carey, Connecticut Bureau of Aquaculture, Personal communication). Typical culture practice in Connecticut includes collection of seed oysters of one and two inches (2.54 and 5.08 cm) height from restricted areas, and grow out to three inch (7.62 cm) harvest size in conditional and approved lease areas. Typically grow out takes from one year, using the larger size, to two years using the smaller seed size. We used the AquaShell™ generic model

Table 2
FARM model required inputs and model outputs. The output of interest to our study was the time it takes for the one in *Crassostrea virginica* seed to reach market size (three in; 7.62 cm).

Farm model inputs		Farm model outputs
Farm layout:	*Environment*:	Weight (g)
Farm width	Water temperature	Length (cm)
Farm length	Salinity	Harvest (tonnes)
Farm depth	Current speed	Concentration (upstream, within and downstream of farm):
Number of sections	Wind speed	Chl
Section volume	Concentration:	POM
Total animals	Chlorophyll *a* (Chl)	TPM
Shellfish cultivation:	Particulate Organic Matter (POM)	DO
Species	Total Particulate Matter (TPM)	DIN
Cultivation period	Dissolved Oxygen (DO)	Total Physical Product (TPP)
Stocking density	Dissolved Inorganic Nitrogen (DIN)	Average Physical Product (APP)
Population	*Water Quality data inputs ideally at least once per month*	Total revenue (TR)
		Total carbon (TC)
		Profit
		Time to market size

Table 3
Summary of a) environmental data, b) culture practices, c) current speeds used for inputs for the FARM simulation.

Input data	Value	Source and notes
a) Environmental data		
Water temperature, Salinity, Chlorophyll *a*, Particulate organic matter, Total particulate matter, Dissolved oxygen, Wind speed		Water quality variables were measured in Milford Harbor monthly during 2012. In Westport and Mystic study sites, water quality samples were only taken from May to September. Surface samples were taken for all parameters except dissolved oxygen, which was measured at the seafloor. Wind speed on the sampling dates at the Sikorsky weather station, Bridgeport, Connecticut, was obtained from www.wunderground.com
b) Culture practice for bottom culture with no gear (this practice is used by approximately 90% of growers in CT; K. DeRosia-Banick, T. Getchis, R.Rheault – Personal communication)		
Farm width	400 m	This yields a ~ 50 acre (20 ha) farm which is within the range of farm sizes in CT
Farm length	500 m	
Farm depth	Site specific	
Number of sections	three (equal)	
Seeding density	225 oysters m^{-2}	Typical of CT growers, T.Getchis, *Personal communication*
Seed weight 1 in (2.54 cm) oyster	1.94 g	Used 1.00 in (2.54 cm) only for modeling for representing conservative time to harvest estimate, acknowledging that 2.00 in seed (5.08 cm) is also used by growers.
Harvest weight 3 in (7.62 cm) oyster	50.7 g	Legal harvest size = 3.00 in (7.62 cm) in CT/LIS
Species cultivated	*Crassostrea virginica*, Eastern oyster	Historically important species of oyster in Long Island Sound (Churchill, 1920; Kurlansky, 2006; state shellfish commission reports dating back to 1880s)
First seeding day	October 15	T.Getchis, Personal communication
Mortality	40%	This is a conservative estimate. It is extremely high for natural populations, and representative for hatchery seed. Interannual mortality is highly variable, and the reported range is 20–100%. Since the model accepts only a single input value we have used 40% as an estimate, not an average
Cultivation period	1500 d (~4 y)	1500 d cycle to represent the potential 4 y to grow to harvest size (4 y) since anything above 4 y is considered not feasible for two reasons: 1) the oysters will succumb to disease and 2) it is not profitable to wait that long to harvest.
*c) Current speeds**		
Sites	Peak Spring current ($m\ s^{-1}$)	Peak Neap current ($m\ s^{-1}$)
Milford Harbor (from NOAA Tides and Currents; Charles Island location)	*0.31*	*0.15*
Milford Dock	0.18	0.08
Mystic Ram Point (Station 14) (from NOAA Tides and Currents; The Race)	*0.41*	*0.31*
Mystic Shipyard (Station 9)	0.30	0.10
Westport Stations 1, 2, 3, 4, 9	0.16	0.12
Westport Stations 5, 6, 7, 8, 10	*0.08*	*0.06*
Station 09 (from NOAA Tides and Currents; Pine Creek location)	*0.46*	*0.26*
Station H2 (from NOAA Tides and Currents; Charles Island location)	*0.31*	*0.15*

* Current Speeds (measured in black text, estimated or calculated in italics). A flow meter was used to measure currents at shore-based locations. For offshore stations in Milford and Mystic, current speeds were obtained from NOAA Tides and Currents (http://tidesandcurrents.noaa.gov). For Westport Stations 5, 6, 7, 8, 10, we used an estimate of current speeds in the upper harbor as half the speed measured in the lower harbor, due to logistical problems accessing the shallow, flow-restricted northern stations.

framework (Silva et al., 2011), calibrated and validated for *C. virginica* in Long Island Sound, with environmental drivers from the study to determine the typical weight of seed and harvest size oysters, the units required as inputs for the FARM model. While typical aquaculture practices in Connecticut can include the use of two inch seed, the simulations were performed with the smaller seed size in order to provide an estimate of the maximum time required for grow out. For consistency and for comparative purposes, the same input weight for seed and harvest size oysters were used for simulations at all study locations. In addition, the same cultivation period, starting day and cultivation practices were used for all simulations, though environmental variables (salinity, temperature, water quality measures, current speeds) were site specific.

2.2.2. Environmental data model inputs

2.2.2.1. Nearshore areas. Partner monitoring programs collected physical data (temperature, salinity, DO) and water samples for the authors, at two of the three locations (Westport and Mystic). The authors collected all physical data and water samples at the Milford locations. The authors processed the water samples for all locations for chlorophyll *a* and particulate matter. Milford Harbor water samples were collected by the authors approximately monthly for one year during 2012–2013 onboard the R.V. Loosanoff. Westport samples were acquired from the organization Harbor Watch who collected them as part of their water quality monitoring program (http://www.earthplace.org/page/projects-of-harbor-watch). Mystic samples were acquired from Clean Up Sound and Harbors (CUSH, http://cushinc.org/) who collected them as part of their water quality monitoring program. All samples were kept on ice and immediately transported to the NOAA Northeast Fisheries Science Center Milford Lab for analysis of chlorophyll *a* and particulate matter by the authors. Samples from Westport and Mystic were collected twice monthly from May to September 2012.

Temperature and salinity were measured using a handheld YSI Pro30, and DO was measured using a handheld optical YSI ProODO (YSI, Yellow Springs, Ohio). Water samples for chlorophyll *a* and particulates were collected at all locations just below the surface using a bucket. Chlorophyll *a* samples were filtered under low pressure onto 25 mm GF/F filters, extracted at −20 °C in 90% acetone for 24 h, then read on a Turner 10-AU digital fluorometer (Welschmeyer, 1994). Samples for particulates were filtered through washed, pre-weighed GF/C filters and rinsed with isotonic ammonium formate. Filters were dried at

60 °C for 48 h and weighed to obtain the total particulate matter, then ashed at 450 °C for four hours and weighed again to determine the total inorganic matter. Particulate organic matter was calculated as the difference between total particulate matter and total inorganic matter (Galimany et al., 2013).

2.2.2.2. Long Island Sound sites. Water quality monitoring data for Stations H2 and 09 are sampled year round by the Connecticut Department of Energy and Environmental Protection (CT DEEP) as part of the EPA Long Island Sound Study monthly water quality monitoring program. Surface and bottom samples for FARM model inputs (i.e. temperature, salinity, chlorophyll *a*, total suspended solids, particulate carbon (PC), DO, nitrate + nitrite and ammonia) from 1995 to 2012 were downloaded from CT Long Island Sound Integrated Coastal Observing System's data portal (LISICOS; http://lisicos.uconn.edu/dep_portal.php). Note that data for nitrogen species were added together to represent total dissolved nitrogen (nitrate + nitrite + ammonia). Also, particulate organic matter (POM) estimates are calculated from measured particulate carbon (PC), POM is not measured directly. The conversion is based on measures of Grant and Bacher (1998) who report one gram of POM for 0.38 g of particulate organic carbon (POC). Additionally, total particulate matter (TPM) was represented by measurement of total suspended solids (TSS).

2.2.3. Analysis of spatial variability

Data from three embayments and two long-term Long Island Sound stations allowed us to answer questions about the spatial variability within an embayment as well as whether surface samples of POM and chlorophyll *a* can be used to effectively model food availability for bottom cultured Eastern oysters.

2.2.3.1. Within an embayment. In order to determine spatial variability across a typical Connecticut embayment, separate FARM model simulations were performed for each of the nine stations sampled across the Milford Harbor embayment. Water quality data were also compared across Milford and Westport Harbor stations to assess spatial variability at a single location.

2.2.3.2. Surface vs bottom. Water samples for analysis of chlorophyll *a* and particulates in the three embayments were available from the surface only. For model inputs, only measurements of surface chlorophyll *a* were considered appropriate, since the amount of chlorophyll *a* per phytoplankton cell is highly light-dependent, and chlorophyll *a* concentrations in bottom samples may not adequately represent actual phytoplankton biomass. POM (and TPM) are not affected by light availability, and interpretation of data from bottom samples is much more straightforward. Therefore, a comparison of bottom and surface POM was completed using long-term Long Island Sound Study Water Quality Monitoring Program data from stations H2 and 09, for which both surface and bottom samples have been collected monthly for >15 years. The FARM model was applied to each year of available data (Station 09 for 1995–2012; Station H2 for 1995–2010) for surface and for bottom POM data separately, keeping all other input variables the same (Table 3).

2.2.4. Analysis of temporal variability

The FARM model requires a year of data for simulation, however, at the Westport and Mystic sites sample collection was dependent on partnerships with local water quality monitoring programs who only sampled in summer months (May–September). There was also uncertainty whether a single year of data would provide sufficient information necessary to choose among candidate sites.

2.2.4.1. What to do when there are no winter data. Since the FARM model ideally needs monthly data for one year, there was some question about the adequacy of data in Westport and Mystic study sites. An ecosystem model (http://www.ecowin2000.org/) was run as part of another project in Long Island Sound (Bricker et al., 2015) providing the opportunity to use simulated results to fill in the missing data. The EcoWin2000 ecological modeling package is an object-oriented framework designed to simulate key components of biogeochemical cycles at the system scale, including processes in the water column and sediments, and targeting issues of relevance to coastal zone management, including eutrophication and aquaculture (Ferreira, 1995). EcoWin2000 model outputs were used as FARM model inputs for October through April. Since the EcoWin results simulate conditions throughout the Sound, and they were available for model boxes that cover all of the waterbody, monthly modeled data were available for boxes that included each of the three sites (Bricker et al., 2015). EcoWin2000 data representative of the Milford site were used for calibration and validation purposes in combination with the measured data, since the Milford site was sampled for a full calendar year.

FARM model outputs for Milford Harbor based on measured data only were compared to FARM model outputs from a combination of measured summer data (May–September) + modeled winter EcoWin2000 data (October–April), and to a simulation using annual data only from EcoWin2000 output for the model box that included Milford Harbor. Since the measured data covered most of the expected growing season of oysters (based on recorded water temperatures), we were optimistic that the modeled data would not have a large impact on the FARM model outputs at the sites where data were missing.

2.2.4.2. Use of a single year of data for site comparison. The same long-term data from Long Island Sound stations H2 and 09 that were used for the surface vs. bottom comparison of particulates were used to determine the inter-annual variability in potential farm production, here represented as the time to reach a harvest size oyster from the one in (2.54 cm) seed oyster. The results of the FARM model simulations for each year at each site were used to evaluate how well a single year of data represented the entire 16- or 18-year data set.

2.2.4.3. Good vs bad year. Simulation of long-term monitoring data from the two Long Island Sound Study Water Quality Monitoring stations (see Fig. 2 for locations) also provided an opportunity to determine whether 'good' and 'bad' growth years could be distinguished and whether boundaries could be developed of expected farm production at an individual site. These data were also used to determine how to formulate a comparative framework, i.e. if a grower was looking at two different sites that both have long-term data, could a comparison be developed that would help make a siting decision?

2.2.5. Statistical analyses of data and results

All statistical analyses were performed using R version 3.0.1 (www.r-project.org). Comparison of monthly chlorophyll *a* and POM measurements in Milford and Westport was accomplished using a bootstrap-based repeated measures analysis based on difference scores, with a 20% trimmed mean as the location estimator (Wilcox, 2003). The same analysis was used to compare the days to harvest at Stations 09 vs. H2, and use of surface vs. bottom POM at these same offshore stations. Chlorophyll *a* concentrations in 'good' years vs. 'bad' years were compared using a bootstrap-based modified T-test. Bootstrap-based methods have the advantage of no assumptions of normality or heteroscedasticity, and are generally more robust than classical statistical methods.

3. Results

3.1. Interpretation of FARM model results

The FARM model output of interest to this study is the time (days) it takes for one (2.54 cm) seed oyster to reach the three in (7.62 cm) legal size for harvest. Based on expert knowledge of long-term Connecticut

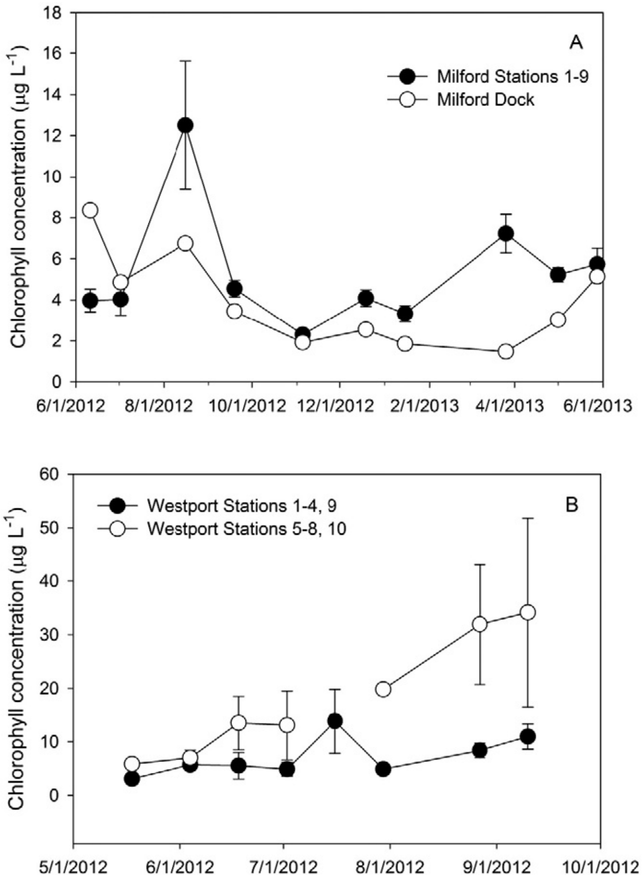

Fig. 3. a) Monthly chlorophyll *a* data for Milford Dock station (10) and average of Milford Harbor Stations 1–9 and b) Average of monthly chlorophyll *a* data for two Westport Harbor station groups (stations 1–4, 9 and stations 5–8, 10; see Fig. 1 for station location). Error bars represent one standard deviation. Note the Dock station was a single station, thus no error bars are plotted.

shellfish lease holders, growers, and aquaculture specialists we knew that a one in oyster typically takes two years but can take up to four years to reach harvest size. In order to most accurately represent 'realistic' conditions with our study results for both the simulated culture cycle as well as the categories assigned as indicative of growth potential, the scale included the possibility of 1500 days or four years of growth. Beyond four years, there is potential to lose oysters to disease or predation, thus locations where time to harvest was ≥1500 days were considered 'Not suitable' for aquaculture. Locations where oysters are able to grow to harvest size in less than 365 days are the most desirable and are classified as 'High growth.' Classifications between 1500 and 365 days were considered on a continuum of Low/slow growth to Moderate growth. These thresholds are based on expert knowledge of long-term shellfish lease holders (T. Getchis, Connecticut Sea Grant, Personal communication). The final thresholds and ranges for interpretation of FARM model results as number of days to reach three in (7.62 cm) harvestable size oyster from one in (2.54 cm) starting length were as follows, with the color coding that was used for the GIS layer representing 'potential oyster growth' in *The Aquaculture Mapping Atlas*:

High growth = <365 d (dark green)
Moderate growth = ≥365–1095 d (light green)
Slow/low growth = ≥1095–1500 d (yellow)
Not suitable for siting aquaculture = ≥1500 d (red)

All FARM model results presented below were characterized according to this scale based on days to harvest, with the color also indicated.

3.2. Spatial variability

3.2.1. Within an embayment

Fig. 3a shows monthly concentrations of chlorophyll *a* and of POM for all Milford Harbor stations. Chlorophyll *a* concentrations at the Dock station were 1.00–2.00 $\mu g\ L^{-1}$ less on average than at other stations, while average annual POM concentrations were similar at all ten stations. The FARM model simulation results for Milford (Harbor stations 1–9 and Dock station 10) showed that time to harvest ranged from 301 to 364 d (average 333 d), among the Harbor stations which was classified as High growth, but the Dock time to reach harvest size was 645 d, considered Moderate growth (Table 4).

Monthly averages for available summer chlorophyll *a* data at Westport Harbor stations are shown in Fig. 3b. There was a statistically significant difference in chlorophyll *a* concentration and POM between stations near the harbor outlet (Fig. 3b; stations 1, 2, 3, 4, and 9) when compared to the stations in the upper reaches of the harbor (stations 5, 6, 7, 8, 10; both $p < 0.001$), with stations further away from the harbor outlet having both higher chlorophyll *a* and POM. For this reason, sampling data were combined and used together to represent upper and lower (near the harbor outlet) Westport Harbor. Samples for winter months in Westport and Mystic stations were not available, FARM model results for these locations are described below in Section 3.3 (Temporal variability).

3.2.2. Surface vs bottom

The results of FARM model simulations for each year in the time series using surface data for station H2 show a range of 604 to >1500 d to reach harvest size with an average of 956 d (Table 4). Using bottom data shows a range of 388 to >1500 d to reach harvest size with an average of 852 d. At Station 09, the surface simulations show a range of 341 to >1500 d to reach harvest, average of 717 d. The Station 09 bottom samples show a range of 308 to >1500 d to reach harvest size, with an average of 725 d. A pairwise comparison of days to harvest for each year yielded no significant difference when surface or bottom POM was

Table 4
FARM model results for Milford, Westport and Mystic study sites, Stations H2 and 09 surface and bottom (Station 09 average 1995–2012; Station H2 average 1995–2010).

Site	FARM model result days to harvest average (range)	Key to interpretation of results
Milford Harbor (average and range of 9 stations)	333 (301–364)	≥*1500 d not suitable for siting aquaculture* (*red*)
Milford Dock	645	
Mystic Station 14, Ram Point	524	≥1095–1500 d Slow/low growth (yellow)
Mystic Station 9, Mystic Shipyard	337	
Westport Stations 1, 2, 3, 4, 9	353	≥365–1095 d Moderate growth (light green)
Westport Stations 5, 6, 7, 8, 10	282	
Station H2 (average and range using surface data)	956 (604 - > 1500)	<365 d High growth (dark green)
Station H2 (average and range using bottom data)	852 (388 - > 1500)	
Station 09 (average and range using surface data)	717 (341 - > 1500)	
Station 09 (average and range using bottom data)	724 (308 - > 1500)	
Milford Harbor measured + EcoWin model data	343	
EcoWin data only	601	

used at Station 09 ($p = 0.506$). A significant difference in days to harvest was detected at Station H2 ($p = 0.004$), with use of bottom POM resulting in predictions of faster time to harvest. Results for surface and bottom simulations fell into the same category at both sites in 32 of 34 comparisons, thus we felt confident using surface POM values for the FARM model simulations.

3.3. Temporal variability

3.3.1. What to do if there are no winter data

Results show little difference between simulations using the Milford Harbor station measured data (333 d to harvest) and measured data + EcoWin data (343 d to harvest) while using EcoWin data only (601 d to harvest) results in almost double the estimated time to harvest size (Table 4).

Based on the results for Milford Harbor, we were confident using data from the EcoWin model to replace the missing winter data for stations in Westport Harbor and Mystic River. The FARM model results, using the combined modeled and measured data for these sites, show High growth for the two groups of stations in Westport (stations near the mouth of the harbor 1–4, 9, 353 d; upper Stations 5–8, 10, 282 d; Table 4). The Mystic River Ram Point station results show potential for Moderate growth (524 d) while the Mystic Shipyard station result shows potential for High growth (337 d; Table 4).

3.3.2. Use of a single year of data for site comparison

A pairwise comparison of FARM model results of time to harvest (using surface samples) from one in (2.54 cm) seed at Stations H2 and 09 each year from 1995 to 2010 indicated a statistically significant difference between the two stations, with time to harvest at Station 09 consistently shorter than at station H2 ($p = 0.03$; Table 4). The differences in time to harvest between the two stations are plotted in Fig. 4. Despite considerable inter-annual variability in days to harvest (543 to >1500 d), in 11 of 16 years, growth was faster at Station 09, there was no difference in two years, and faster growth at Station H2 was observed in only three of 16 years (with one of those three years yielding a three-day difference in time to harvest).

3.3.3. Good vs bad year

Annual averages of chlorophyll *a* and POM, and FARM model simulation results (days to harvest size) for Stations 09 and H2 are shown in Fig. 5. POM concentrations were consistent from year to year while

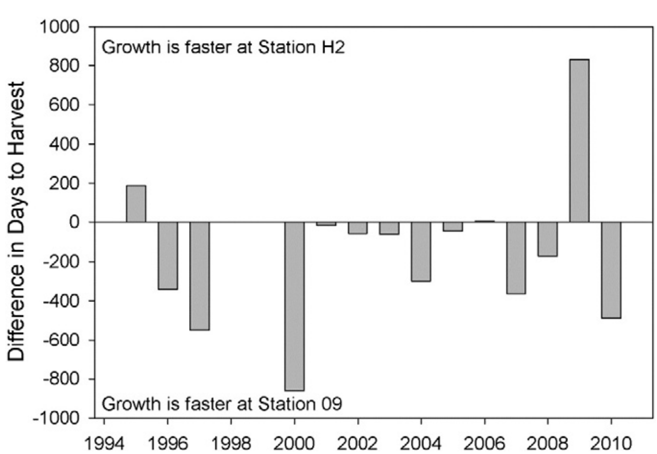

Fig. 4. Comparison of FARM model results, time to harvest, using surface samples at Long Island Sound Study stations H2 and 09 (see Fig. 1 for locations) for a 1500 day cycle simulation. The plot represents the difference between the time to reach harvest size where negative values represent years when growth is faster at Station 09 and positive values represent years when growth is faster at Station H2.

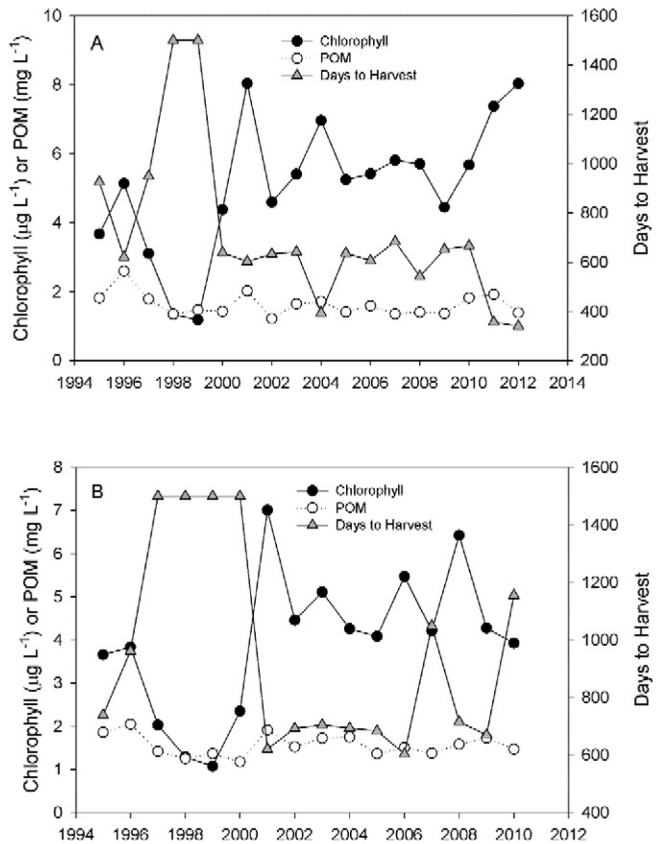

Fig. 5. Plot of annual average of measured chlorophyll *a* (µg L^{-1}), particulate organic matter (POM, mg L^{-1}) and FARM simulation results of days to reach harvest size at Long Island Sound Study long-term monitoring stations: a) Station 09 (1995–2012) and b) Station H2 (1995–2010). Note that below annual average chlorophyll *a* concentrations of 4.50 µg L^{-1}, days to harvest are considered a 'bad year' for growth (see text and Table 5).

chlorophyll *a* concentrations varied with lower concentrations in the mid to late 1990s at both locations. Time to harvest also varied showing slowest growth coincident with years of lowest chlorophyll *a* concentrations.

4. Discussion

4.1. Overall results

All sites were considered suitable for expanded or new aquaculture based on model results. The time to harvest at the Westport, Mystic and Milford study sites and Stations 09 and H2 in Long Island Sound all fell within the Moderate or High potential growth category for Eastern oysters (Table 4). In general, the higher the annual average chlorophyll *a* concentrations, the faster the oysters reached harvest size. Comparison among results in the three Harbors showed a range of times to harvest, from High growth (282 d) in upper Westport Harbor stations to Moderate growth (645 d) at the Milford Dock station (Table 4). The most desirable location to site an oyster farm based solely on time to harvest size would be in upper Westport Harbor. The offshore stations both showed Moderate growth and would also be considered suitable for siting, and in fact, there are already aquaculture leases at and/or near those stations (Fig. 2). Integration of these results into Connecticut's *Aquaculture Mapping Atlas* consisted of a GIS layer with dark green to indicate High growth for all inshore stations except the Milford Dock and Mystic Ram Point locations. Those stations were indicated as Moderate growth with a light green GIS layer, as were the two offshore stations (Table 4; Fig. 6).

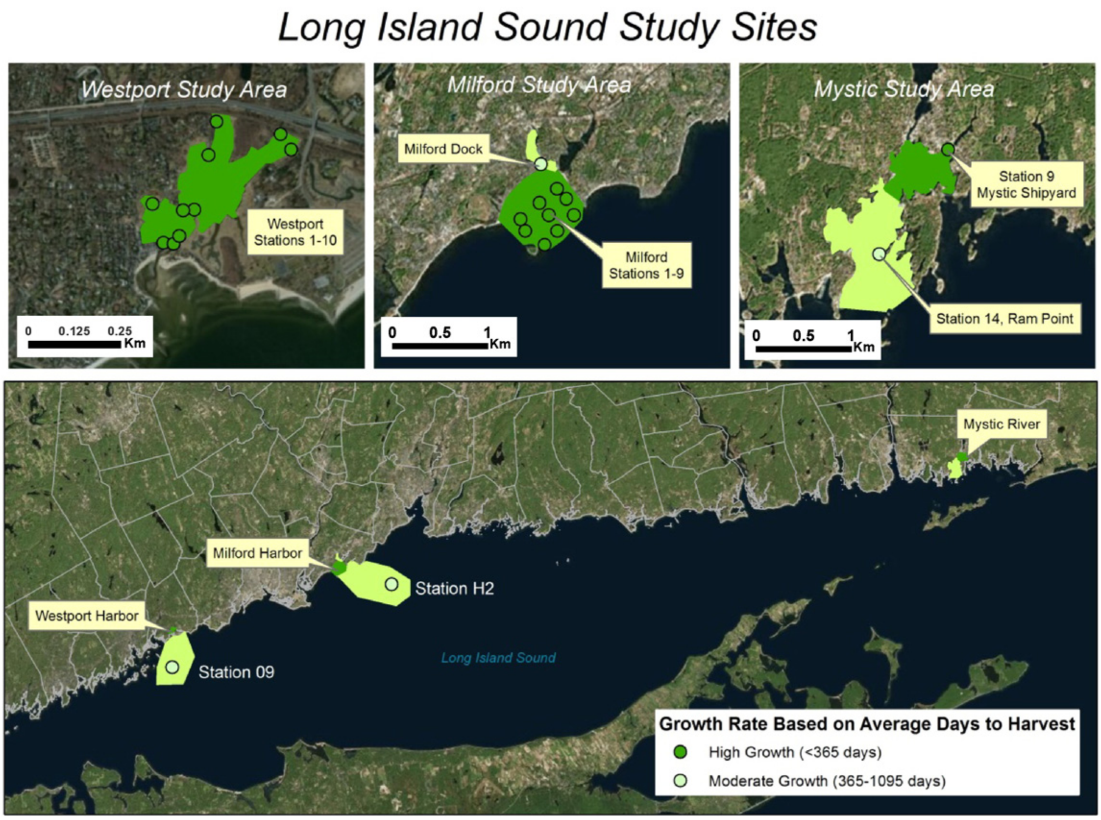

Fig. 6. GIS layers to be added to the Connecticut *Aquaculture Mapping Atlas*. The layers depict areas of High and Moderate 'potential oyster growth' based on FARM model results.

4.2. Spatial variability

4.2.1. Within an embayment

The FARM model simulations demonstrated little difference in model results (i.e. days to harvest) among stations within Milford Harbor. The average days to harvest were 333, with a range from 301 to 364 d, and all stations fell within the High growth category. However, time to harvest was estimated to be almost twice as long at the Dock station (Table 4), perhaps due to a combination of the consistently lower chlorophyll *a* concentrations over the course of the year (Fig. 2a) and slower current speeds (Table 3). These results suggest that the Milford Harbor stations, excluding the Dock station, could reasonably be treated as a group representative of the whole harbor, and could be represented in the Connecticut *Aquaculture Mapping Atlas* as a continuous GIS layer without losing any resolution. The Harbor stations GIS layer was color coded dark green to represent estimated High growth potential at those sites, while the layer representing the Dock site was light green to represent Moderate growth potential (Fig. 6).

The FARM model results for Westport (Table 4), using a combination of measured and modeled (for the winter months) data, showed that growth for both groups of stations was High with estimated days to harvest at the stations near the mouth of the harbor being slower (353 d) than at upper harbor sites (282 d). For this Harbor the GIS layer was color coded as High growth (dark green) for all stations (Fig. 6). The higher growth at the upper harbor sites was likely due to greater food availability, with annual averages of both chlorophyll a and POM higher at the upper harbor sites (Stations 5, 6, 7, 8, 10; 11.8 μg L^{-1} and 2.35 mg L^{-1} chlorophyll *a* and POM respectively). At the same time, there was ample food available at the stations near the mouth of the harbor (Stations 1, 2, 3, 4, 9; annual averages of 8.50 μg L^{-1} chlorophyll *a* and 1.51 mg L^{-1} POM), plus greater flushing, and a sandier bottom type than the mud/silt bottom type found at the upper harbor stations (Dick Harris, HarborWatch, personal communication). The flushing and bottom type likely make the stations near the mouth of the harbor overall better locations for siting of an oyster farm.

Estimated growth at two stations at the Mystic location showed a difference in potential growth of oysters of 524 d with the Ram Point (Station 14) in the Moderate, and the Mystic Shipyard (Station 9) within the High growth category (337 d; Table 4). The Mystic Shipyard station at the Mystic study site had a GIS layer of the dark green color indicating High growth while the GIS layer for the Ram Point station is colored light green indicating Moderate growth (Fig. 6).

4.2.2. Surface vs bottom samples

Comparison of the time to harvest results using surface and bottom data for FARM simulations at the long-term offshore monitoring sites (Stations 09 and H2; Table 4) show that there was not a consistent or large difference between results. For the 18 years of data at Station 09 the difference ranged from 0 to 300 d, with an average difference of <1%, and differences in outcomes with surface or bottom POM were not statistically significant. While the differences in days to harvest between bottom and surface samples at Station H2 were statistically significant, most of the differences were relatively small, with differences ranging from 0 to 292 d, average 8.2%. It is worth noting that in only two of 34 comparisons did the use of bottom or surface POM change the category of potential oyster growth, e.g. High, Moderate, Slow/low, Not suitable. This provided confidence that surface samples of POM and TPM could reasonably be used for modeling to represent bottom cultivation. However, these results suggest that in some locations, use of surface POM may result in an overestimation of days to harvest for bottom-cultivated oysters.

4.3. Temporal variability

4.3.1. What to do when there are no winter data

Based on the comparison of modeled and measured results in Milford Harbor, it was determined that October–April data from EcoWin2000 could be used with reasonable confidence to fill in missing winter data for the Westport and Mystic sites. EcoWin2000 data were taken from the bottom boxes closest to the sites and the combined data were used for FARM modeling in the Mystic and Westport study sites. While results suggest that ecosystem level data output can be used to fill in missing data, using only model results would not be recommended given the great difference in results.

4.3.2. Use of a single year of data for site comparison

The long-term data from stations H2 and 09 were used to determine the inter-annual variability in potential production, and to evaluate whether one year of data was adequate to accurately differentiate between sites. We observed large inter-annual variability at both sites (Table 4) varying from Slow/low to High growth over the course of the time series. However, results at Station H2 showed Moderate growth in 11 of 16 years (69% of observations) while Station 09 results showed Moderate or High growth in 15 of 18 years (83% of observations; Fig. 4). A direct comparison of the two sites in each year yielded a significant difference, with Station 09 having overall faster growth than Station H2; in only two of 16 years was growth substantially faster at Station H2 than Station 09 (Fig. 4). While comparison of the growth potential at the two sites is a reasonable approach for informing siting decisions, long-term data are not always available. The inter-annual variability is of concern in a comparison, and it appears from our analysis that it would not be appropriate to compare two or more sites based on data from different years. If there were data from sites for the same year, there is a reasonable expectation of successful prediction of which site would be the better location for siting a farm.

4.3.3. Good vs. bad years

We have used these data to determine the levels of environmental and water quality variables that result in 'good' (i.e. High and Moderate) vs 'bad' (Low/slow and Not suitable) growth years. Although no analysis was done to determine the sensitivity of FARM results to changes in food, temperature and turbidity, which are all drivers of the model, an analysis was made of the variation in food (chlorophyll *a* and POM) from 1995 to 2012 at the long-term Long Island Sound Study monitoring stations (H2 and 09) and resultant variation in time to harvest (Fig. 5). Both stations showed strong linkage between chlorophyll *a* concentrations and days to harvest; there was not a strong linkage to POM concentrations. Filgueira et al. (2014b) note several reasons that chlorophyll *a* should be used as a food proxy with caution (i.e. carbon: chlorophyll *a* ratio, phytoplankton assemblage variability, tidal influence of chlorophyll *a* concentration within an embayment). Additional research may be useful to address these potential issues. However, our results show for the 16–18 year timespan at these sites that the longest times to harvest, >1500 d, considered 'Not suitable for siting aquaculture,' were generally observed when average annual chlorophyll *a* concentrations dropped below 4.50 μg L^{-1}. High growth years, represented as shorter number of days to harvest, were observed at chlorophyll *a* concentrations above 7.00 μg L^{-1} at both stations.

Note that while we use chlorophyll *a* as a proxy for oyster food and it is thus a driver for growth and time to harvest, the results from the FARM model application are not actual harvests and are therefore not independent of chlorophyll *a* concentrations used in the model. However, estimated FARM model harvest results have shown good correspondence to actual harvest (i.e. Ferreira et al., 2009) and we use the model generated harvest results from the simulations in CT waterbodies with some level of confidence. The average concentration of combined chlorophyll *a* data from Stations H2 and 09 for years falling within combined High and Moderate growth categories was 5.25 ± 1.34 μg L^{-1} (n = 27).

Table 5
Results of analysis of risk based on concept of Filgueira et al. (2013b, 2014a) where annual average chlorophyll *a* – one standard deviation (2.69 μg L^{-1}) represents the sustainability threshold below which shellfish growth is not supported. The results include annual average chlorophyll *a* concentrations for long-term offshore stations H2 (1995–1010) and 09 (1995–2012), FARM model results as days to harvest, the growth category of FARM results and risk to growth (too low indicates that chlorophyll *a* concentrations are below the sustainability threshold).

Year	Station	Annual average chlorophyll *a* (μg L^{-1})	Days to harvest	Growth category	Risk to growth
2012	09	8.03	341	High	No problem
2011	09	7.37	358	High	No problem
2004	09	6.96	395	Moderate	No problem
2008	09	5.71	543	Moderate	No problem
2001	09	8.04	603	Moderate	No problem
2006	H2	5.47	604	Moderate	No problem
2006	09	5.42	607	Moderate	No problem
1996	09	5.14	621	Moderate	No problem
2001	H2	7.01	621	Moderate	No problem
2002	09	4.60	634	Moderate	No problem
2005	09	5.25	637	Moderate	No problem
2000	09	4.38	639	Moderate	No problem
2003	09	5.41	643	Moderate	No problem
2009	09	4.45	652	Moderate	No problem
2010	09	5.68	667	Moderate	No problem
2009	H2	4.28	670	Moderate	No problem
2007	09	5.81	684	Moderate	No problem
2005	H2	4.08	684	Moderate	No problem
2002	H2	4.46	693	Moderate	No problem
2004	H2	4.26	694	Moderate	No problem
2003	H2	5.11	705	Moderate	No problem
2008	H2	6.42	716	Moderate	No problem
1995	H2	3.66	739	Moderate	No problem
1995	09	3.68	926	Moderate	No problem
1997	09	3.11	950	Moderate	No problem
1996	H2	3.83	962	Moderate	No problem
2007	H2	4.21	1049	Moderate	No problem
2010	H2	3.92	1155	Slow/low	No problem
1997	H2	2.03	1500	Not suitable	Too low to support growth
1998	H2	1.29	1500	Not suitable	Too low to support growth
1999	H2	1.07	1500	Not suitable	Too low to support growth
2000	H2	2.35	1500	Not suitable	Too low to support growth
1998	09	1.35	1500	Not suitable	Too low to support growth
1999	09	1.19	1500	Not suitable	Too low to support growth

Average of concentrations for years falling within the Slow/low and Not suitable growth categories was 1.89 ± 1.01 μg L^{-1} (n = 7). When chlorophyll *a* concentrations were compared between the High/Moderate growth years vs. the Slow/Not suitable years, the differences were statistically significant ($p < 0.001$).

Based on these admittedly limited results, with the noted caveat regarding linkage of chlorophyll *a* and FARM model estimated harvest results, we suggest that annual average concentrations of chlorophyll *a* might be a reasonable way to determine the growth potential for oysters, which is consistent with recent work by Pérez-Camacho et al. (2014). Chlorophyll *a* concentrations above 4.50 μg L^{-1} were associated with a 'good' year for growth and are at least suggestive of a threshold of chlorophyll *a* needed to support shellfish aquaculture (Table 5). This threshold concentration corresponds closely with the threshold of 5.00 μg L^{-1} marking the boundary between 'Low' and 'Moderate' chlorophyll *a* concentrations in various eutrophication assessment methods (e.g. Bricker et al., 2003; Borja et al., 2011, and others in Zaldívar et al., 2008), suggesting that 'Moderate' levels of chlorophyll *a* within an estuary are needed to support good growth at these sites. While there are several studies that explore the use of shellfish aquaculture as an eutrophication reduction method (e.g. Bricker et al., 2015; North et al., 2010; Rose et al., 2014, 2015), these results highlight that there is a balance whereby there must be adequate chlorophyll *a* available to support shellfish growth.

4.3.4. Sustainable shellfish aquaculture and ecosystem resilience

We carry the analysis further following the concept of Filgueira et al. (2013a, 2013b, 2014a) with respect to consideration of ecosystem health and carrying capacity within the context of natural variation (albeit influenced by human actions in this urban estuary) and ecosystem resilience. We include here a determination of the variation in chlorophyll *a* concentration at the two long-term offshore sites during the 1995–2012 period of record. Analysis of each site separately shows that there is site specificity with respect to a sustainability threshold. However, we have used combined data from the two sites for a more robust measure to illustrate the minimum concentration that is needed to support aquaculture at these locations. The average chlorophyll *a* concentration for the 18 years of data at the two sites is $4.56 \pm 1.87\ \mu g\ L^{-1}$. This gives a minimum threshold for support of oyster growth of $2.69\ \mu g\ L^{-1}$ which can also be considered the threshold for 'risk of failure of growth'. This threshold predicts, or at least is consistent with the 6 cases where FARM model results fall within the 'Not suitable for siting' category which each have annual average chlorophyll *a* concentrations below the threshold (Table 5). This is confirmatory of the GIS layer created with the FARM model results and thus is informative to growers, resource managers and permitting agencies who are working together to manage the future of oyster aquaculture expansion in Long Island Sound.

Note that the cause(s) of the low concentrations of chlorophyll *a* during the late 1990s and 2000, the years for which model results were considered 'Not suitable for siting' have not been established (M. Lyman, CT DEEP, Personal communication; Table 5). Relatively low chlorophyll *a* concentrations were observed Sound-wide during this time period. Long Island Sound is a naturally productive estuary that has historically supported large populations of shellfish (Kurlansky, 2006), the shellfish aquaculture industry in Connecticut is extensive, rather than intensive, and a recent study shows that present oyster aquaculture is within the range of carrying capacity in Long Island Sound (Bricker et al., 2015). For these reasons, it is unlikely that the shellfish industry caused depletion of food resources by overstocking.

The potential of depletion of food sources by over stocking has been demonstrated for several European and Canadian estuaries through modeling studies (e.g. Lysefjord, Filgueira et al., 2014a; Richibucto Estuary, Filgueira et al., 2014b; Tracadie Bay, Filgueira et al., 2014c; Bay of Bourgneuf, Tissot et al., 2012) designed to determine the carrying capacity and optimum placement of aquaculture operations to assure productivity while also avoiding use conflicts. In each case, chlorophyll *a* concentrations were used for simulations, for example, in Richibucto estuary, consistent high values across the estuary were taken as an indication that shellfish aquaculture is within the range of carrying capacity (Filgueira et al., 2014b). Two other studies show stocking density and food depletion as the probable cause of low condition index of oysters (CI; Filgueira et al., 2013b) and declines in mussel harvest (Smaal et al., 2013).

The results of these models and the global movement to expand aquaculture production highlight the balance that must be made in order to sustain ecosystem health while at the same time pushing the system to support aquaculture production. These results, while admittedly limited in spatial scale, suggest that in most years there is adequate chlorophyll *a* to support growth which bodes well for potential expansion of oyster aquaculture in Long Island Sound. We suggest that annual average chlorophyll *a* could be used as a simple screening tool to inform the site selection decision process, that above $4.50\ \mu g\ L^{-1}$ good growth would be supported while concentrations above $2.69\ \mu g\ L^{-1}$ would be necessary for sustainable support of shellfish aquaculture at these locations.

4.4. Limitations of this approach

While these results are promising, there are caveats to note with regard to the model and these findings. First, while the individual model for *C. virginica* that is used in the FARM model has been calibrated and validated for Long Island Sound (Bricker et al., 2015), the model results have not been validated for each of the study sites. Additionally, we know that the use of only peak neap and spring tides at a single location to represent each embayment may not provide the full measure of variability with respect to current speed and direction which vary seasonally as well as episodically with rainfall, wind and other climatic events (Longdill et al., 2008). This could impact the model simulation of food availability, and thus growth, as well as circulation and residence time thus introducing uncertainty to our model results (Filgueira et al., 2014b). Another possible limitation of this approach is that we use a local rather than ecosystem scale model thus we do not account for the possible food depletion by oyster growth in neighboring farms within the same embayment (Filgueira et al., 2014a, 2014b). This may lead to an overestimate of modeled oyster growth giving false information to growers about potential production, though a recent study shows that present oyster aquaculture is within the range of carrying capacity in Long Island Sound (Bricker et al., 2015). With desired expansion of cultivation in coming years, it will be important to consider waterbody scale carrying capacity (i.e. embayments and the whole of Long Island Sound) and sustainability thresholds. Understanding these potential limitations and how they might bias results is important. We believe that the simplified approach presented here may be more useful for growers, regulators and permitting agencies than the linked hydrodynamic – ecosystem – geospatial models that have burdensome data requirements requiring significant resources for measurement and application. In particular, this simplified approach could be most useful in areas where there is presently limited or no aquaculture but where available environmental data suggest it is possible.

5. Conclusions

- All stations, both nearshore and offshore, are considered suitable for aquaculture with demonstrated Moderate to High growth potential based on results of FARM model simulations. The results will be added as a GIS layer (dark green to indicate High growth and light green for Moderate growth potential) to the existing Connecticut *Aquaculture Mapping Altas*.
- It is worth noting that the results of this pilot study did not differentiate among locations in Connecticut (i.e., all stations were in the Moderate and High growth categories). This tool is likely most useful in locations with limited existing aquaculture or new industry, rather than distinguishing among locations in a waterbody already known to support good shellfish growth.
- This tool provides useful information to aid growers in the selection of an aquaculture site from those deemed suitable by the mapping tool, and for resource managers and regulators who are charged with permitting oyster lease areas.
- Where measured data are not available for a full year, particularly when winter data is missing and not data typical of the major growing season, model data can be used as inputs if an ecosystem scale model, such as EcoWin, with monthly data output is available.
- It is important when comparing among suitable sites to use data from the same year due to large interannual variability in many locations. Comparison of data from different sites and different years may give an incorrect determination of the most desirable site.
- Analysis of FARM results at long-term monitoring sites in Long Island Sound (H2 and 09) showed that there were specific chlorophyll *a* thresholds that were reasonable predictors of 'good' and 'bad' years for potential oyster growth. These results indicate a threshold of annual average chlorophyll *a* concentrations of $4.50\ \mu g\ L^{-1}$ above which growth is considered 'good' while an analysis of variation

over the time period of record suggests a sustainability threshold of 2.69 μg L^{-1}. It is possible that these thresholds would be a useful screening tool, though further research should confirm these threshold values.

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