Chapter 24
Farm-Scale Production Models

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Abstract Farm-scale production models of bivalves have been used for site selection, optimization of culture practices, and the estimation of ecosystem goods and services. While all farm models require physical forcing through hydrodynamic models, the input of measured or modelled bivalve growth drivers, and a bioenergetic growth model which predicts individual growth and farm yield as a function of husbandry practices, some models are also embedded in a GIS system to allow for a "point and click" ability to test different locations and production strategies at various locations within the modeled domain. More generic Web-based models such as the Farm Aquaculture Resource Management are relatively simple to use, provide a link to larger ecosystem models, and provide direct estimates of ecosystem services. More detailed models, such as *ShellGIS,* may be more data intensive and require detailed bathymetry, spatial velocity fields, information about boundary layer and aquaculture structure hydrodynamics and particle depletion. However, these models provide the detailed spatial and temporal results that can optimize farm productivity and assess benthic impacts. New approaches using high resolution remote sensing satellites and powerful physical-biogeochemical models using unstructured grids to link farm scale models with ecosystem models in a GIS platform have potential to provide improvements in the utility of farm scale models for the estimation of bivalve aquaculture ecosystem goods and services.

Abstract in Chinese 摘要:养殖场规模的双壳贝类产量评估模型已经被广泛应用于养殖选址,养殖配置优化以及生态系统产品和服务评估。大部分的养殖场规模模型都需要通过水动力模型提供驱动,使用实测或模拟的贝类生长数据作为初始和驱动条件,并通过个体生长预测模型及产量评估模型进行结

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A. C. Smaal et al. (eds.), *Goods and Services of Marine Bivalves*,
https://doi.org/10.1007/978-3-319-96776-9_24

果的验证和应用。一些模型还可以嵌入到GIS系统中，允许通过“点选”来测试在模拟区域内，对不同位置进行不同生产策略的组合所产生的效果。一些基于网络的通用模型(比如养殖水域资源管理系统)的使用相对简单，这些系统可以通过网络链接到位于服务器上的大型生态系统模型，通过调用模型结果从而对生态系统服务进行直接评估。一些更加具体的模型(如ShellGIS)，可能需要更多的数据(如详细的地形， 边界层信息)来进行获取相应的结果(如养殖设施周围流场结构和示踪粒子扩散分布情况)。虽然这些比较复杂且要求数据较多，但是他们提供了养殖水域内更详细的物理环境状况，模型结果可以用于优化养殖布局以及进行底质环境的评估。利用高分辨率遥感卫星和非结构化网格的物理-生物地球化学耦合模型可以将养殖场尺度模型与GIS平台中的生态系统模型联系起来，这种新技术有助于推动养殖场尺度模型在双壳贝类养殖生态系统优势和生态服务评估方面发挥重要作用。

Keywords Farm-scale bivalve production models FARM · Geographical Information Systems · Particle depletion · Computational fluid dynamics · ShellGIS · Bivalve growth

关键词 养殖场尺度贝类生产模型(FARM) • 地理信息系统(GIS) • 粒子扩散 • 计算流体力学 • ShellGIS • 双壳贝类生长

24.1 Introduction

The role of bivalve farms in the provision of ecosystem goods and services has been reviewed by Ferreira et al. 2011, using the Farm Aquaculture Resource Management (FARM) model (Ferreira et al. 2007), and stressing the importance of bivalve farms in mitigating the consequences of nutrient loading. The application of dynamic biogeochemical, bivalve ecophysiological, and physical oceanographic models to predict bivalve growth have been reviewed by Grant and Filgueira (2011). In this chapter, we concentrate on bioenergetic and mechanistic mass balance models which predict farm production and regulating services, as opposed to statistical models which utilize hypothesized or measured relationships among variables in a specific data set such as the statistical relationships between clam growth, the flux of seston and bottom characteristics (Grizzle and Lutz 1989).

Production models for marine bivalve farms may be used for site selection for new farms, to determine the production capacity and optimal seeding density for farms, as well as to predict benthic and water column interactions and regulating services. While there have been numerous studies of bivalve carrying capacity and bay scale production capacity, relatively few have dealt with smaller scale aquaculture farm models. One of the difficulties in assessing farm-scale production models is that they rely on environmental drivers of production related to larger, bay-scale and ecosystem-scale processes. These large scale dynamics are connected to farm-scale models simulating local oceanographic conditions and culture practices that affect food availability, feeding and growth of the bivalves on the farms. Some approaches also use coupled physical-biogeochemical models and animal growth models to investigate farm and ecosystem interactions (Ferreira et al. 2008; Guyondet et al. 2010; Filgueira et al. 2014), and the effects of husbandry practices on both local and system scales (Smaal et al. 1997; Saurel et al. 2014). Reviews of the types of models available for aquaculture site selection and carrying capacity are presented in McKindsey et al. (2006), Ross et al. (2013), and Filgueira et al. (2015).

The ecological and biogeochemical models influencing bivalve food production (phytoplankton and detritus) such as the Simulation Model for the Oosterschelde (SMOES; Scholten and van der Tol 1994), ECOWIN (Ferreira 1995), RMA (King 2003), Row-Column Advanced Ecological Systems Modeling Program (RCA; Testa et al. 2014), General Aquaculture Model for Bivalve Equilibrium Yield (GAMBEY; Nunes et al. 2003) and others (Grant et al. 2008) are not usually considered in farm scale models due to a mismatch between the spatial scale of the typical application (i.e., bay or ecosystem scale) and the scale of an aquaculture farm (10–100's of meters). Filgueira et al. (2014) used an ecosystem model, a biogeochemical model, and a bivalve growth model to determine oyster carrying capacity in subareas of a region of complex geomorphology in New Brunswick, Canada, but not individual farms within each of these subareas. Since the consumption of food by bivalves occurs at relatively small spatial scales, the processes are important when coupling farm scale production models to the surrounding ecosystem, since local particle flux and consumption can influence bivalve growth and regulating services. This is especially true when food availability for bivalves on the farm is affected by particle depletion as occurs within dense populations of bivalves. Particle depletion is also affected by farming practices, or husbandry. Ultimately, the inclusion of husbandry is an important distinguishing feature of farm-scale models. For example, there models can account for the time of year seeded, the seed genetic origin and size, stocking density, animal biomass (Ferreira et al. 2007), nursery and grow-out gear type, and placement, spacing and orientation of gear on the farm (Bacher et al. 1997, 2003; Campbell and Newell 1998; Comeau et al. 2008; Drapeau et al. 2006; Duarte et al. 2008; Rosland et al. 2011; Newell and Richardson 2014).

The purpose of this chapter is to compare the advantages and disadvantages of different farm-scale production models, and to highlight promising new approaches which can improve the predictive value of farm-scale production models for ecosystem goods and services, and to suggest areas for future research.

24.2 Farm-Scale Models

There are two fairly well established farm-scale models in use today: *FARM* and *ShellGIS*. The *FARM* model (Ferreira et al. 2007) allows for the input of farm dimensions, species, density, cultivation period, temperature, water velocity, chlorophyll-a, particulate organic matter (POM), total particulate matter (TPM) and dissolved oxygen (DO) to calculate growth and harvestable biomass, using a growth model such as *AquaShell*™ (Silva et al. 2011; Saurel et al. 2014). *ShellGIS* (Newell et al. 2013) is a GIS system which also calculates growth and harvestable biomass, using the shellfish growth model *ShellSIM* (Hawkins et al. 2013a, b), and georeferenced growth driver data (temperature, salinity, chlorophyll-a, POM, TPM, DO) as well as water velocity from a flow model. Both shellfish growth models are a mechanistic function of the concentrations and quality of food particles either forced by monitoring or model data (no feedbacks) or embedded in a farm scale model with feedbacks on the environment. The *FARM* model scale is entered by the user, and consists of the farm dimensions (length, width, and depth). In *ShellGIS*, the scale of the flow model (50 m) defines the smallest scale (one cell), but results from multiple grids can be selected by the user by drawing a rectangle in the system. In the FARM model, water velocity and water quality data are entered for each farm. In ShellGIS, the program uses water velocity generated from each grid point and water quality data from georeferenced water samples, water quality model output, or interpolated values from nearby locations.

The *FARM* model produces growth rates, total harvest biomass, biomass seed to harvest ratio, profit, nitrogen credits, and an Assessment of Estuarine Trophic State (ASSETS) eutrophication score. *FARM* outputs are customized to provide direct estimates of bivalve ecosystem goods and services.

ShellGIS has been customized primarily to optimize farm production. *ShellGIS* walks the user through a list of frequently asked questions that determine target species, culture type (bottom or suspended), density (for bottom culture), angle of flow (degrees), stocking density (for suspended), start date, and period to run, including the following:

- What space is available to grow shellfish? (site selection)
- How does water flow through the system? (site selection)
- How do temperature and salinity vary through the system? (site selection)
- How fast will shellfish grow? (production)
- How to minimize time to market? (production and husbandry)
- How to maximize yield and profit? (production)
- How do variations between growing years affect yield? (production)
- What is the hydraulic zone of influence around the farm? (regulation)
- Results from farm or entire embayment (site selection)

While *ShellGIS* does not provide summary information for ecosystem services, *ShellSIM* can be used to plot not only growth but also physiological rates such as oxygen consumption, clearance rate, ammonium excretion and biodeposition rates at any location or time. These data could be integrated into a calculation of ecosystem services through improvements in the software if regulators or growers demonstrated interest. A comparison among *FARM* and *ShellGIS* is presented in Table 24.1.

Table 24.1 Comparisons between the FARM and ShellGIS farm scale models using the criteria of Nath et al. 2000

	FARM	ShellGIS
Objectives	Site selection, optimization of culture practice, ecological effects	Site selection, optimization of culture practices
Target audience	Regulators, growers	Growers
Analytical methods	Simple mass balance model Model forcing is constant Does not include turbulent mixing Shellfish growth model Economic model ASSETS score	GIS-based interactive model Model forcing varies spatially and temporally Includes turbulent mixing in benthic boundary layer and structure models Shellfish growth model Economic model
Analytical methods and results	Bioenergetic growth model Economic model Eutrophication assessment	Bioenergetic growth model GIS layers of bivalve growth drivers Aquaculture structure model Economic model
Geographic area and scale	Farm dimensions and embayment	Embayment and 50 m in GIS framework
Actual use	Extensive	Limited
Comments	Available on the web	Requires running high resolution flow model and collection of bivalve growth drivers
Scale of physical forcing	Single velocity	Spatial velocity fields

24.3 Geographic Information Systems (GIS)

The utility of farm models for decision-making is facilitated by a GIS platform, where specific areas of the farm and culture structures are georeferenced. While farm models have not extensively been embedded in GIS frameworks, this section is included because the future development of bivalve ecosystem goods and services models will be improved by advances in remote sensing and GIS.

Nath et al. (2000) listed GIS platforms and compared the use of GIS systems in aquaculture decision-making, in a number of case studies according to the following criteria:

- Objectives
- Target decision support audience
- Geographic area and scale of analysis
- Analytical methods and results
- Actual use for decision making

GIS systems range from large to fine scale for a variety of purposes including site selection, environmental impacts, and farm productivity estimates for both finfish and shellfish. On a large scale (km), Buitrago et al. (2005) used 20 variables to choose optimum oyster raft sites in Venezuela in a Multi-Criteria Evaluation (MCE). In the intertidal zone, Congleton et al. (1999) used a GIS system to combine intertidal height and water velocity for soft clam mariculture siting, and Arnold et al. (2000) used multiple water quality and benthic habitat criteria to identify sites for hard clam aquaculture. Radiarta et al. (2008) used satellite imagery of chlorophyll-a and temperature, a weighted bio-physical, social-infrastructural and constraint criteria and model builder in ArcGIS to identify the best sites for scallop grow-out. Thomas et al. (2011)) also utilized satellite imagery to predict mussel growth in Mont St.-Michel Bay in France using a Dynamic Energy Budget (DEB) model, with 1 km resolution. Longdill et al. (2008) used a GIS approach to identify Aquaculture Management Areas (AMA's) in New Zealand, which combined residual water velocity, benthic habitat, primary productivity, marine protected areas and constraints and conflicting uses using MCE techniques. Tissot et al. (2012) integrated multiple spatial and temporal environmental data into a GIS based productivity model for oyster farms. Improvements in web-based and GIS-based tools, are likely to improve appropriate siting of farms, but smaller scale models utilizing fine scale hydrodynamics, biomass, and density distribution within the farms are required to provide greater insight into optimization within the farms themselves. In all of these GIS approaches, the presentation of data and model results are only as good as the resolution of the underlying data. Higher resolution ($\leq$100 m) satellites such as Landsat 8 have promise in providing data on temperature, chlorophyll-*a*, and turbidity for site selection and growth drivers for farm scale models (Snyder et al. 2017), especially if they are combined with bivalve growth and aquaculture structure models. If satellite data can be made available at a high enough frequency and resolution, it could be eventually used to provide environmental drivers of production for farm-scale models.

24.4 Farm Model Components

Farm models all have components which simulate water movement (hydrodynamic models) and bivalve growth (growth models) using forcing functions for growth (environmental growth drivers like food and temperature), a description of husbandry practices, and a process for accounting for food particle depletion within the farm. Depletion (reduction in the particulate phytoplankton and detritus, or seston) is a function of food supply (concentration × flow rate) and food demand (filtration by the bivalves). Biogeochemical feedbacks and nutrient cycling on the farms also are important in relation to bivalve biodeposition and excretion, regulating services of the farms. Specifically, bivalves do not simply clear the water of suspended particulates (Newell et al. 1989), but rather they participate in nutrient recycling and are involved in benthic/pelagic coupling.

24.5 Physical Models

Physical models are essentially advection-diffusion equations that predict water velocity at the farm-scale (*i.e.*, 50–100 m) or in the embayment or ecosystem (100–1000 m). The models require data on bathymetry, as well as the meteorological (e.g., wind and precipitation), river, and tidal drivers of circulation. Although the following list is far from exhaustive, some of the more common models are Delft-3D (Delft Hydraulics 2006), the Regional Ocean Modeling System (ROMS; Wilkin et al. 2005), MIKE 21 (Warren and Bach 1992), and the Finite Volume Community Ocean Model (FVCOM; Chen 2012). Some models (*i.e.*, Computational Fluid Dynamic (CFD) models, Hirt and Nichols 1988), although more computationally intensive, can also include aquaculture structure hydrodynamics (*e.g.,* suspended longlines, rafts, trays, racks and bags) as well as benthic boundary layer flow and benthic-pelagic coupling. Hydrodynamic-structure interaction modeling requires detailed physical representations of the aquaculture structures used on the farms (e.g. Plew et al. 2005; Stevens et al. 2008; Delaux et al. 2011; Newell and Richardson 2014; Tseung et al. 2016). The effects of the farms themselves on circulation can be estimated using farm drag coefficients (Grant and Bacher 2001; Pilditch et al. 2001; Plew 2011). A simple representation of water velocity as uniform throughout the site, both in the benthic boundary layer, and in and around aquaculture structures, is not representative of conditions on the farms. The ease of use of a simpler model (*e.g., FARM*) is a trade-off with greater complexities in a more detailed flow model approaches (*e.g., ShellGIS*). In *ShellGIS*, the choice of the type of husbandry (e.g., bottom culture, floating cages, rafts) activates a physical model which incorporates the aquaculture structure hydrodynamics to model food supply and seston depletion (below) more effectively. Finally, wave models such as the Simulating Waves Nearshore model (SWAN; Booij et al. 1997) can be used to model the height of waves which can disrupt bivalve feeding, growth, and farm yield, especially for suspended cultures, due to oscillating high velocities (Dewhurst 2016) and bottom resuspension that can inhibit feeding (Newell et al. 1989).

24.6 Organism Growth Models

Biological models predict organism growth as a mechanistic function of the concentrations and quality of food particles either forced by monitoring data or model data (no feed-backs) or embedded in a farm scale model with feed-backs. Bioenergetic growth models such as ShellSim (Hawkins et al. 2013a, b), Ecophysiological Model of *Mytilus edulis* (EMMY; Scholten and Smaal 1998), MUSMOD (Campbell and Newell 1998), Oyster-DEB (Pouvreau et al. 2006) and AquaShell™ (Silva et al. 2011) are used in farm models to predict bivalve production, including shell growth and tissue growth, and they can also be used to estimate regulating services of farms (carbon sequestration and nitrogen removal on harvest). Recently, Filgueira et al.

(2011) and Larsen et al. (2014) compared bioenergetic scope for growth (SFG, Bayne and Newell 1983) and dynamic energy budget (DEB, Van Haren and Kooijman 1993) bivalve growth models. While both models do a reasonable job of predicting bivalve growth, there are limitations related to the use of chemical proxies of food availability (chlorophyll-*a*, particulate organic matter (POM) and particulate organic carbon and nitrogen (POC, PON) as growth drivers for bivalves since the consumption and absorption of seston is related to its biochemical composition and digestibility.

In these models, growth is represented as a function of the concentration and quality of food particles. However, in farm scenarios, populations of bivalves may locally deplete food concentrations within the culture structures, within the farms, and within the embayments (see Sect. 24.8 below). While the removal of suspended particulates by the bivalves is considered an ecosystem service, it impacts the growth rates of bivalves if there is not a careful consideration of food supply and demand on the farm. Bacher et al. (2003) gave a more realistic approach to modeling scallop growth in Sungo Bay, China over a range of stocking densities when they included particle depletion by the bivalves and the influence of the structures on water velocity.

Some models also may include density dependent growth rates within the "culture units" such as a suspended ropes, pegged ropes, trays, bags, or bottom "patches" of bivalves (Campbell and Newell 1998). Organism growth may also be influenced by space as well as food (Frechette and Lefaivre 1990).

24.7 Environmental Growth Drivers

Bivalve growth drivers include the environmental conditions, water quality parameters and the live phytoplankton, detritus, and other suspended particles which contribute to bivalve feeding and growth. For each species, there are different requirements for these growth drivers, based on the feeding behavior and particle size retention efficiency of the ctenidia, and sensitivity to parameters such as temperature and salinity, including direct effects of water velocity on feeding (Wildish and Miyares 1990; Newell et al. 2001), red tides (Shumway 1990), hypoxia and pollutants. Growth models often use chlorophyll-*a* and POM as bivalve food, but POM can vary in quality (Newell et al. 1998) so the deterministic mussel growth model MUSMOD (Campbell and Newell 1998) utilized phytoplankton biovolume to carbon conversions and detrital carbon (and the detrital N/C ratio) to characterize bivalve food and model mussel growth (Campbell and Newell 1998). ShellSIM uses a chlorophyll-*a* to carbon conversion to quantify food quality as *selected organic matter* (SELORG; the phytoplankton-based carbon), and *remaining organic matter* (REMORG; Hawkins et al. 2013a, b).

Even within a farm, food quality can vary depending on the location of the bivalves. Muschenheim and Newell (1992) found that mussels on the edge of a bottom bed had enhanced access to benthic diatoms and organic detritus in water from

0–10 cm off the bottom, whereas mussels further in the farm relied on water being mixed from surface. It is known that bivalves grow faster on some kinds of algae than others (Epifanio 1979), so chemical measures of food concentration (*i.e.,* chlorophyll-a) have their limitations. Recent (unpublished) data has shown that American oysters (*Crassostrea virginica*) have increased clearance rates and absorption efficiencies with a natural diet dominated by large ciliates than with chain-forming diatoms a few weeks later.

24.8 Depletion Models

Depletion models are used to predict water column effects of bivalve farms, both in modifying available food within the farms, and also quantifying ecosystem services of reducing turbidity, grazing down phytoplankton blooms and benthic pelagic coupling. Simple models of food supply and demand in marine bivalve aquaculture systems are based on mass balances. For example, Incze and Lutz (1980) investigated the flux and consumption of particles for a mussel long-line system based on a predicted filtration rate of 2.4 l h^{-1} per mussel. Rosenberg and Loo (1983) used the approach of Incze and Lutz (1980) to estimate the food ration and flow speed necessary to supply food to a variable number of longlines in Sweden. Both studies concluded that food supply was a function of both current velocity and ambient particle concentration. Carver and Mallet (1990) examined the carrying capacity of a Nova Scotia inlet for mussel longline culture in a similar way, as did Ferreira et al. (2007) with the FARM model. Simple box models generally cannot incorporate the effects of different aquaculture structures on flow, benthic boundary layer dynamics for bottom culture, or density dependent growth rates within culture units.

More complex models of seston depletion consider the characteristics of aquaculture structures and benthic boundary layer dynamics, where reduced velocities are observed from bottom friction or physical drag (Plew 2005). Depletion models of food resources in rafts, longline cages, and benthic free planted bivalves can provide a more realistic picture of localized food concentration than the simple models described above. The following test cases illustrate the importance of aquaculture structure hydrodynamics and particle depletion models in determining the food availability at local scales to bivalves. Ultimately, these dynamics control bivalve growth rate on the farm scale.

24.8.1 Boundary Layer Depletion Models: Free-Planted Mussels

An advection-diffusion equation using water depth, initial phytoplankton concentration, vertical eddy diffusivity, phytoplankton uptake by mussels (*Mytilus edulis*) of known biomass or “filtration velocity” (w_{filt}) and downstream distance in the

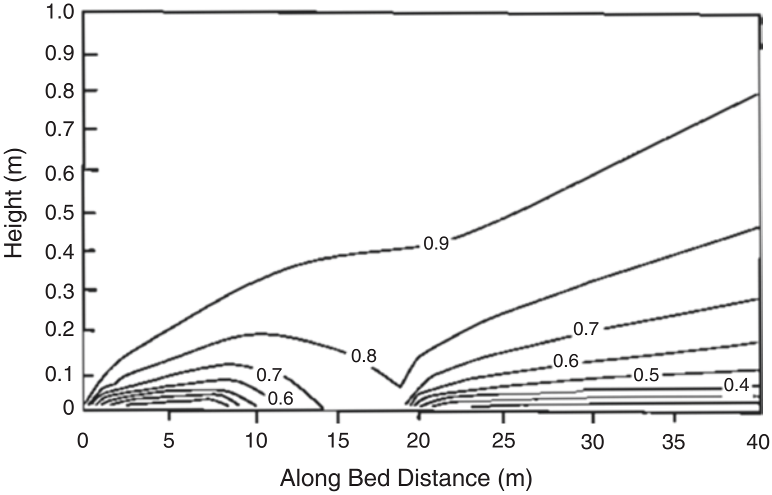

Fig. 24.1a Phytoplankton concentration along a patch of bottom cultured mussels due to boundary layer depletion. (From Newell and Shumway 1993, Fig. 26)

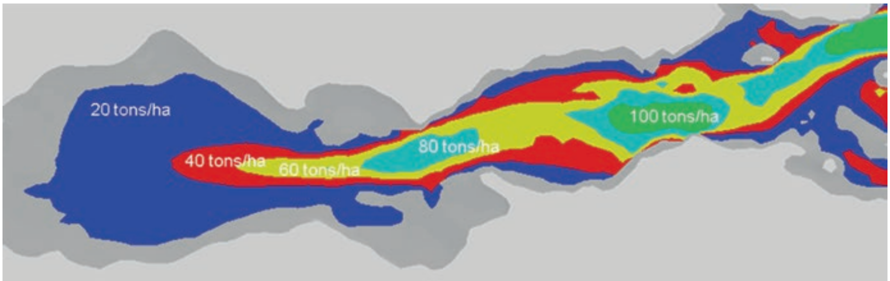

Fig. 24.1b Recommended seeding densities for Carlingford Lough, Ireland using MUSMOD. (Campbell and Newell 1998)

mussel patch, was used to model phytoplankton concentration at the height of ingestion by mussels (Fig. 24.1a), based on flume studies (Butman et al. 1994) and field work (Muschenheim and Newell 1992). In this case, the mussel beds are placed in two patches, from 0–10 m and from 20–40 m from the edge of a farm, and rapid particle depletion is observed in the benthic boundary layer just meters from the edges of both of these high density aggregations. This figure illustrates the importance of minimizing bottom patch size when spreading seed on the bottom in bivalve bottom culture.

The mussel growth model, MUSMOD, was developed for mussel bottom culture (Campbell and Newell 1998) in Maine in order to optimize mussel growth based on seeding density, the bottom shear velocity U* (Campbell and Newell 1998, Table 6), and boundary layer physics to estimate the food supply to bottom cultured mussels.

Using measured water velocities and a 2-d flow model, water samples and buoy temperature, salinity and chlorophyll-a data from Carlingford Lough, Ireland, MUSMOD estimated the best seeding densities for mussel farms (Fig. 24.1b) to maximize seed to harvest yields, mussel growth rates, and meat yields, assuming the mussels were spread well to eliminate density dependent "patch" effects (Newell 1990). The model simulations showed that areas of higher local velocity could support higher seeding densities, as long as the mussels were spread evenly and not in concentrated "patches". Using this type of approach, bottom culture farms could be optimized for production and ecosystem services instead of "trial and error" aquaculture which often results in lower meat yields, farm productivity, and seed survival.

24.8.2 Boundary Layer Depletion Models: Free-Planted Oysters

In this example, a boundary-layer algorithm was used to calculate food concentration in the middle of a benthic planting of 24 g live weight seed oysters (*Crassostrea virginica*) within a hypothetical "patch" of 100 × 100 m over a range of bottom densities from 50 to 1000 m^{-2}, based on water depth, oyster biomass, filtration rate, and free stream velocity from the 50 m resolution flow model ShellGIS (Newell et al. 2013). A reduction in food concentration in the benthic boundary layer was used in conjunction with ShellSIM to estimate the per cent reduction in oyster live weight in the middle of the hypothetical patch of mature oysters in the Damariscotta River, Maine, U.S.A. at two planting densities (100 oysters m^{-2} Fig. 24.2, left, and 500 oysters m^{-2}, Fig. 24.2, right). The color in each 50 × 50 m grid point shows the

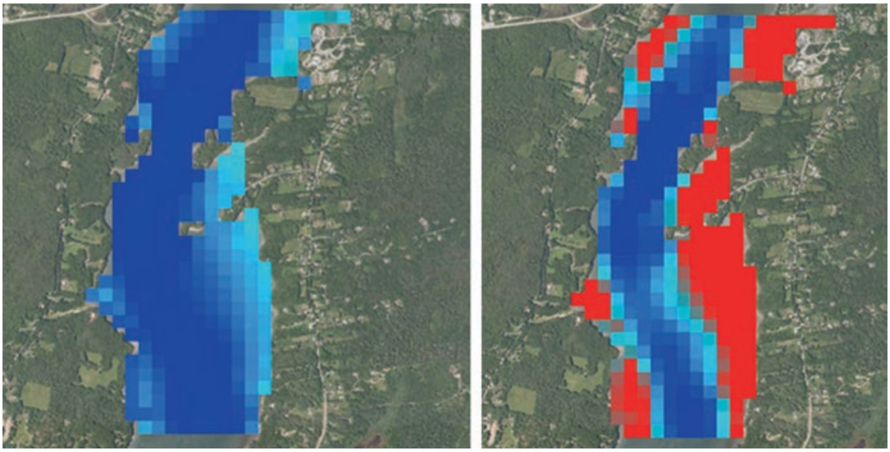

Fig. 24.2 Percent reduction of total fresh weight of oysters in the middle of a 100 × 100 m bottom planting after a year at 100 oysters m^{-2} (light blue is 25% reduction, left) and 500 m^{-2} (red is 50% reduction, right) using ShellGIS. (Newell et al. 2013)

results of utilizing the conditions at that grid point (water velocity, temperature, salinity, chl a, POM) on how growth would be reduced in the middle of a 100 × 100 m patch with the center at that grid point, and does not consider interactions with other grid points (*i.e.,* uses a single 100 × 100 m farm).

The differences in growth rates are a function of different tidally driven water velocities in the system and reduced food in the middle of the oyster patches. The areas in red and light blue have lower production than the higher current dark blue areas, but they may be managed effectively using lower seeding densities. Output of the ShellGIS farm model results shown in Fig. 24.2 are facilitated by the ability to choose, by a point and click method, the results of any farm location within the model domain, and determine production at any point during the growing season.

24.8.3 Computational Fluid Dynamics (CFD) Depletion Models

Aquaculture structure models use CFD and a technique known as the Fractional-Area-Volume-Obstacle-Representation (FAVOR) method to represent the structures within a rectangular grid (Hirt and Sicilian 1985). The FAVOR method uses partial control volumes to provide the advantages of a body-fitted grid but retains the construction simplicity of ordinary rectangular grids. The method also allows for the calculation of flow through "porous" media. It is also used to model seston depletion if there is uptake (filtration) of particles by bivalves at any location within the model domain. While CFD methods are more complicated and require a detailed physical representation of the system and more high performance computing, they can provide great insight into not only the hydrodynamic characteristics of a culture system but also ways to optimize farm productivity. Generally, we observe that chlorophyll-depletion in aquaculture structures increases with shellfish biomass in those structures which matches the patterns in the flow modeling results. Including structure porosity in the models can be a valuable proxy for understanding the impact of biofouling on farm structures and demonstrates the value and optimal timing for farmers to reduce biofouling.

24.8.4 Husbandry Practices

One of the major utilities of farm scale models is the ability to assess different husbandry practices and determine how they might be optimized on a shellfish farm. Factors under control of the farmer include the time of year seeded, the seed genetic origin and size, animal stocking density and biomass (Ferreira et al. 2007), nursery and grow-out gear type, and the placement, spacing and orientation of gear on the farm for scallop longlines (Bacher et al. 1997, 2003), mussel rafts (Duarte et al.

2008; Newell and Richardson 2014), mussel bottom culture (Campbell and Newell 1998); and mussel longline culture (Comeau et al. 2008; Drapeau et al. 2006; Rosland et al. 2011).

24.8.4.1 CFD: Oyster Bags on Racks

As part of the Understanding Irish Shellfish Culture Environments (UISCE) project (Dallaghan 2009), we performed CFD analyses of flow and predicted chlorophyll-*a* concentration in pacific oyster (*Crassostrea gigas*) bags on bottom trestles in Dungarvan, County Waterford, Ireland. Water flow through bags and trestle systems show significant depletion (blue areas) when the orientation of the trestles to flow direction was 0 degrees (Fig. 24.3, left), but flow is significantly improved when the angle is from the side, effectively increasing the cross-sectional area of the bags (Fig. 24.3, right). We found similar patterns in chlorophyll-a depletion.

24.8.4.2 CFD: Mussel Rafts

Newell and Richardson (2014) used a CFD model of flow and chlorophyll-*a* depletion for individual and multiple mussel rafts in Maine to determine that the mean velocity going through a mussel raft was only about 20% of the ambient flow (*i.e.,* 30 cm s^{-1} outside raft = 6 cm s^{-1} inside) (Fig. 24.4), and that particle depletion could be minimized by changing raft orientation to flow direction. These simulations provided guidance for site selection for locations which would minimize depletion in rafts (*i.e.,* outside raft velocities over 25 cm s^{-1}), and allow for adjustments to food concentration experienced by mussels in the rafts as input to production models.

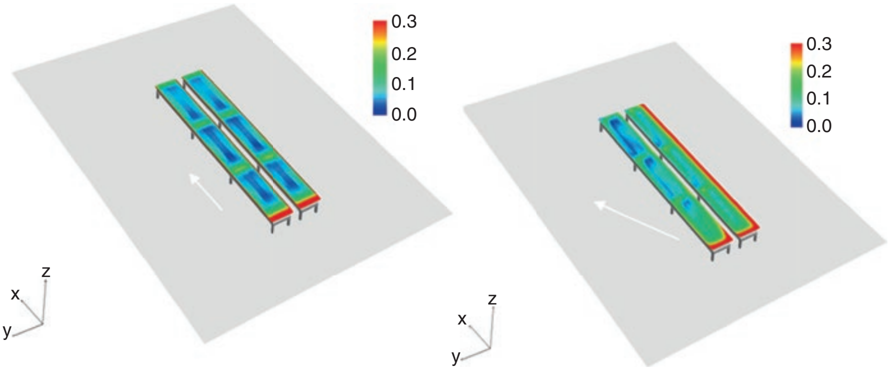

Fig. 24.3 Water velocity (m s^{-1}) in oyster bags on trestles with orientation at 0 degrees to flow direction (**a**) or 15 degrees to flow direction (**b**). (Richardson and Newell 2008)

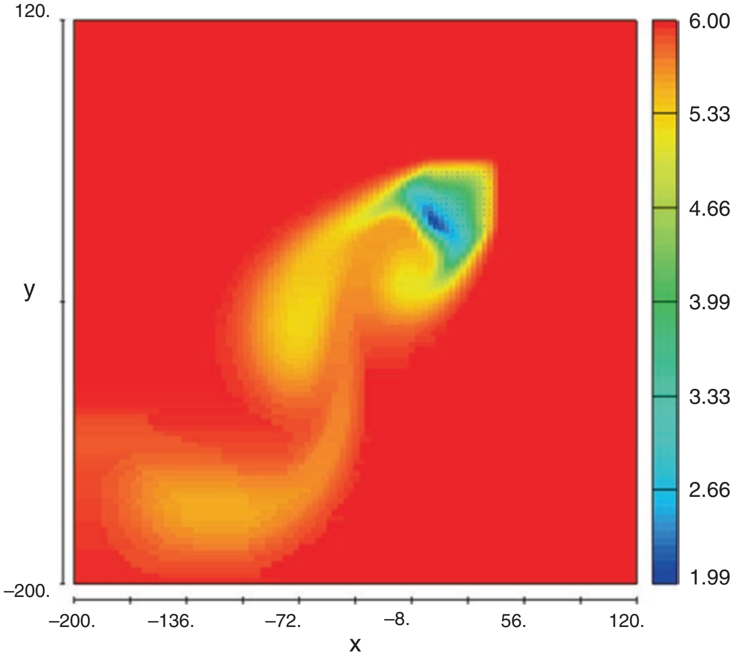

Fig. 24.4 Chlorophyll depletion at 15 cm s^{-1} flow in a Maine mussel raft with a 45° orientation to flow direction. Y-axis is chl-a µg l^{-1}. (Newell and Richardson 2014)

24.8.4.3 CFD: Oyster Rafts, Trays and Mussel Longlines

Oyster stick or tray rafts were modeled in Gorge Harbor, Cortes Island, British Columbia, Canada using Computer Aided Design (CAD) drawings of oyster trays and the CFD FAVOR method described above. Plan view and side view velocity models, combined with consumption estimates, were used to recommend spacing between multiple raft systems (4–5 raft diameters), and indicated that upwelling of deeper, chlorophyll-a waters would occur between the rafts if they were arranged in rows perpendicular to the current direction.

CFD models were also developed for OysterGro™ trays floating in longline systems, using CAD drawings of the trays and modeled velocity relative to orientation of the trays to flow direction (Fig. 24.5). A series of model simulations were used to predict the depletion of phytoplankton in arrays of suspended trays. At the high velocity areas (mean velocity over 20 cm s^{-1}), depletion was only significant in the oyster cages when the long-line system had a 0° orientation to the flow direction (Fig. 24.6).

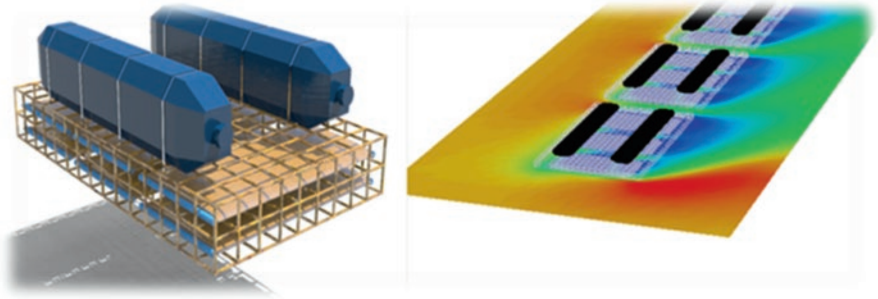

Fig. 24.5 Oystergro™ trays (left) and modeled velocity (right) with orientation of trays 45 degrees to flow direction in the Damariscotta River, Maine (ShellGIS oyster structure model)

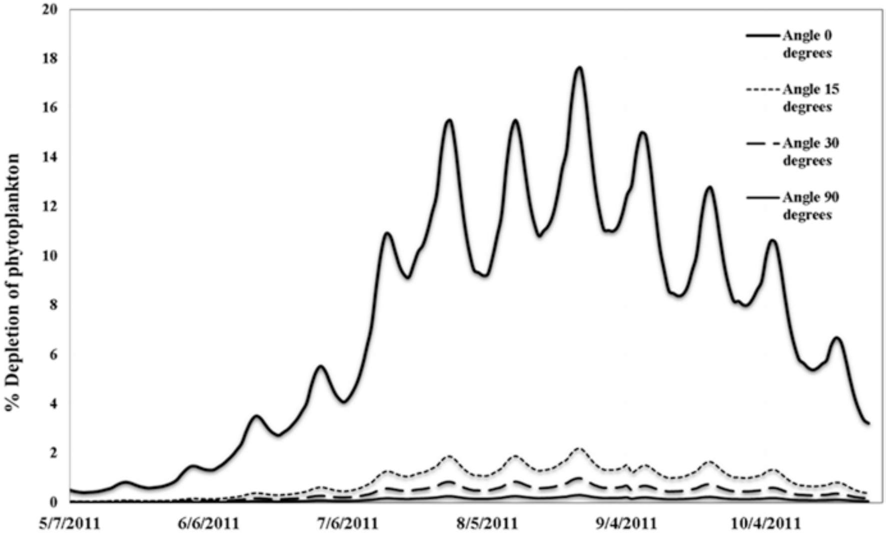

Fig. 24.6 Percent depletion of phytoplankton in surface Oystergro™ cages as a function of time of year and orientation of longline system to flow direction (ShellGIS oyster structure model)

As part of the UISCE project (Dallaghan 2009), we modeled depletion of chlorophyll-a through mussel longlines in Killary Harbor, Ireland, where field measurements and CAD drawings were used to develop a CFD depletion model for single dropper longline systems and an expert system for optimizing longline configuration. Longlines have also been modeled using CFD techniques by Delaux et al. 2011. Again, the depletion was very sensitive to the angle of orientation of the longlines, with little depletion when angles were more than 15 degrees from current direction (Richardson and Newell 2008).

24.8.5 Benthic Impacts

While some models have attempted to simulate benthic effects of bivalve organic matter deposition (Weise et al. 2009), it is often the site-specific balance between sedimentation of biodeposits, resuspension, burial and decay that results in benthic impacts (Testa et al. 2015), especially in shallow water. For example, using a mass-balance approach, Testa et al. (2015) calculated that wave induced resuspension within a Maryland, U.S.A. farm allowed tidal currents outside the farm to export the majority of nitrogen deposition (Fig. 24.7). Understanding the interplay between transport and biogeochemistry may represent the future of sustainable siting. Export of organic matter from the farm was dependent on estimated shear stress from tides and waves which in turn caused resuspension of the oyster biodeposits. Importantly, these dynamics were sensitive to local bathymetry.

The release of nutrients from biodeposits on shellfish farms may balance consumption indirectly (Asmus and Asmus 1991; Testa et al. 2015) by stimulating phytoplankton growth. In this case, the farms themselves may influence bay scale productivity. The flux of dissolved inorganic nitrogen, phosphate, and silica from the decomposition of bivalve biodeposits, and its stimulation of localized phytoplankton blooms is poorly understood, but may be important in maintaining phytoplankton concentrations near the farms when estuarine productivity is low. Organism growth models can also predict individual rates of water filtration and particle consumption, oxygen consumption, ammonium excretion, and biodeposit production,

Fig. 24.7 Erosional area from tides (light green) and waves (dark green) with the sedimentation rates indicated on an oyster farm, channel and control areas in Maryland, U.S.A. (Testa et al. 2015)

or be used in combination with hydrodynamics to predict deposition, resuspension and benthic impacts (Grant et al. 2005).

24.9 Conclusions

While there have been numerous studies on bivalve carrying capacity and bay scale production capacity, relatively few have dealt with farm models, and even fewer capture important small scale effects related to local bathymetry, aquaculture structures, and their orientation. A comparison between the FARM and ShellGIS models is presented in Table 24.1, using the criteria of Nath et al. 2000.

Perhaps one of the more interesting implications of the co-advances in both hydrodynamic-biogeochemical models and aquaculture structure models is the potential to more easily link these modeling platforms in the near future. For example, the Chesapeake Water Quality and Sediment Transport Model has been under continuous development since 1984 (Cerco and Noel 2013) and has moved from spatial resolutions on the order of kilometers to meters. Unstructured grids, such as FVCOM and SCHISM (Ye et al. 2016), are allowing for resolution at the farm scale in nearshore environments.

Better parameterization of the food supply of bivalves, both in terms of the concentration and quality of detritus, and the food value of different species of phytoplankton, will improve the fit of growth models with field data. In addition, understanding the time scales of nutrient cycling by bivalves related to phytoplankton growth and residence time of the water will help shed light on farm scale productivity and aquaculture-environmental feedbacks.

Improvements in web-based and GIS-based tools and advances in remote sensing are likely to improve appropriate siting of farms, but smaller scale models such as ShellGIS, utilizing fine scale hydrodynamics, biomass, and density distribution within the farms, and animal growth models are required to provide greater insight into optimization within the farms themselves or provide better production estimates for ecosystem models. While simplified web-based modeling tools such as FARM can provide quick insights into the results of different farm management scenarios, it is the specific conditions on the farms (bathymetry, localized water velocity, food resources, placement and arrangement of gear, local rope/bag/raft density and biomass, and structure hydrodynamics) which ultimately control the farm productivity and ecosystem services.

Applications that add aquaculture specific biogeochemical parameters, such as SPM, POM, and chlorophyll-*a* to new high resolution grids are also increasingly available (Xia and Jiang 2016; Testa et al. 2014). A challenge for coupling these models with aquaculture structure models with GIS capability, like ShellGIS, will be creating a data framework capable of transitioning model output into formats appropriate for estimating ecosystem goods and services and well as farm siting, and production modeling, based on the ability to nest the higher resolution farm scale models into a bay scale and ecosystem framework like the FARM model currently accomplishes.

Acknowledgements This chapter was supported in part by the National Science Foundation EPSCoR Cooperative Agreement IIA-1355457 to the University of Maine. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. It was also supported by research funded by the Bord Iascaigh Mhara U.I.S.C.E project (Republic of Ireland), the USDA Northeast Regional Aquaculture Center, the Maine Aquaculture Innovation Center, the NOAA National Sea Grant Program and the USDA SBIR program. We acknowledge the constructive remarks of two referees.

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