NCCOS Ecological Assessment to Support NOAA’s Choptank Complex Habitat Focus Area: Eutrophication and Shellfish aquaculture/restoration Ecosystem Services Modeling

Final report

A.M. Cubillo, S.B. Bricker, M. Parker, J.G. Ferreira

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Executive summary

This report describes the conceptual improvements and implementation of a model for individual growth and environmental effects for the Eastern oyster, *Crassostrea virginica*. The model was tested at four locations in the Chesapeake Bay, using *in situ* data for environmental drivers, and configured to reproduce the culture practice described by industry practitioners.

The individual model (AquaShell) is run by means of two separate applications: WinShell is used to examine the performance of one individual, and the mass balance of different substances of interest with respect to ecosystem services. The Farm Aquaculture Resource Management (FARM) model was updated to reflect changes to the individual model, and used to simulate cultivation at the four sites.

Major improvements to the modeling of Eastern oyster include (i) the implementation of functions to limit food intake, which in earlier versions could result in an overestimate of growth in eutrophic waters; and (ii) the simulation of diploid and triploid organisms.

A brief presentation of results for both the individual and population models is provided, together with comparisons of model outputs and measured data.

Overall, we believe the model performance to be adequate for describing oyster growth and harvest yield at the various locations in the Chesapeake Bay, and are confident that further use of the model by local managers and farmers will help develop sustainable shellfish aquaculture in the bay, and assist in a better understanding and valuation of ecosystem services.

The software applications and data files used for the simulations described in this report were made available for future use.

Introduction

Background

Eutrophication is among the most serious threats worldwide to the function and services supported by coastal ecosystems (Boesch et al., 2001). Attempts to reverse coastal eutrophication have centered on reducing land-based sources of nutrients, such as fertilizer applications and wastewater treatment plant dischargers. However, historical alterations in habitat quality, food webs, and community structure in coastal systems can alter nutrient processing, thus modifying the ecosystem response to reduced nutrient loads (Duarte et al., 2009).

A systems approach that integrates watershed load reduction programs with enhanced nutrient processing in coastal systems may prove more effective at restoring ecosystem services at less cost than load reduction programs alone. EPA's Office of Research and Development (ORD) has highlighted that research is needed to evaluate and model the nitrogen removal and ecosystem services provided by filter-feeding shellfish populations in estuaries (Compton et al., 2009).

There are several recent studies that suggest that shellfish aquaculture and restoration could provide water quality improvements through ecosystem services provided by filtration based removal of particulates and increased habitat that is provided by the three-dimensional structure of shellfish reefs (Lindahl et al., 2005; Ferreira et al., 2007; Ferreira et al., 2008; Kellogg et al., 2013; Pollack et al., 2013; Bricker et al., 2014; Kellogg et al., 2014; Rose et al., 2014; Bricker et al., 2015; Rose et al., 2015).

In particular, recent work by the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Environmental Protection Agency (EPA) highlights the usefulness of a modeling approach to investigate the role of enhanced food web processing of nutrients by shellfish through natural and engineered systems (Bricker et al., 2015). The valuation of the ecosystem services provided is part of the project approach.

Overview of activities

This work consisted in the evaluation of the potential removal of nutrients from the water through shellfish aquaculture or restoration, and was subdivided into three work packages as detailed below.

Table 1. Overview of work packages and tasks.

WP description	Tasks within each WP
WP1 – Coordination	Task 1.1 – Team meetings Task 1.2 – Partner activities related to project data and information needs
WP2 – Individual and farm-scale modeling	Task 2.1 – Re-calibration and validation of the AquaShell and FARM models Task 2.2 – Application of models
WP3 – Products and Dissemination	Task 3.1 – Report and manuscript preparation Task 3.2 – Dissemination of project results

An individual model (AquaShell) for the target oyster species, *Crassostrea virginica* (Eastern oyster) was adapted in order to develop a generic simulation platform for oyster growth in Chesapeake Bay, and calibrated and validated for specific sites where good datasets existed for both environmental drivers of growth and for culture practice (Fig. 1).

The individual model was then integrated into a population model within the Farm Aquaculture Resource Management Model (FARM; Ferreira et al., 2007). FARM is a local scale model used to estimate shellfish growth and nutrient removal at a farm scale but can be up-scaled to provide an estimate of production and the ecosystem services of oyster aquaculture and restoration at a system scale. Comparison of local-scale and ecosystem model results in a previous study suggest that the local scale models provide a reasonable estimate of system wide benefits in places where system scale circulation models do not exist (Bricker et al., 2015).

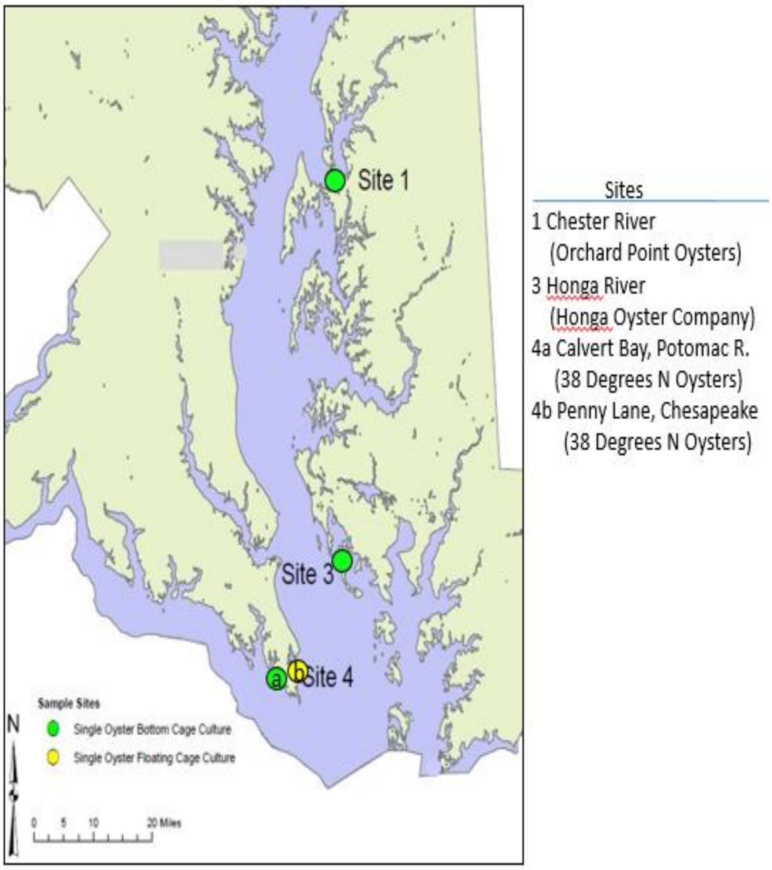


Fig. 1. Oyster farm sites used for calibration and validation of growth models

Modifications and enhancements to the existing models

Changes in conceptualization to the Eastern oyster individual model

Several changes were made to the Eastern oyster individual model in order to match the end-points, growth patterns and reproductive behavior observed in the Chesapeake Bay locations. These are summarized below.

Simulation of feeding physiology

- Limitation of the ingestion rate by establishing a maximum ingestion rate based on gut capacity and gut passage time.
- Estimation of pseudofaeces production by means of a Michaelis-Menten approach.

Simulation of reproductive behavior

- Addition of a triploid ‘switch’ to simulate growth for both diploid and triploid oysters.
- Implementation of multiple spawning events per year for diploids only since triploids do not spawn.

Simulation of feeding physiology

The changes to the feeding method were made at the ingestion rate (IR) and pseudofaeces production rate (PPR) components and are detailed below.

Clearance Rate and Filtration Rate

The clearance rate (CR) is determined by a maximum clearance rate modulated by various environmental limitation factors (temperature, salinity and chlorophyll-a concentration).

The maximum clearance rate (CR_{max}) is determined by means of an allometric formulation obtained from the field data found in (Riisgård, 1988 and Loosanoff 1958), where a weight exponent alters filtration rate based on individual oyster dry tissue weight (DW):

$$\mathrm{CRmax} = \mathrm{aCR}.\log(\mathrm{DW}) + \mathrm{bCR} \tag{1}$$

where aCR = 2.48 and bCR = 6.51

This clearance rate is then affected by limitations from temperature (T), salinity (S) and total particulate matter (TPM), which can be expressed as:

$$CR = CRmax.f(T).f(S).f(TPM) \tag{2}$$

CR_{max} is the maximum rate at which oysters can clear water (L ind^{-1} h^{-1}).

In this model, clearance rates (CR, L ind^{-1} h^{-1}) and filtration rates (FR, mg POM ind^{-1} h^{-1}) are considered synonymous. We acknowledge this assumption as a necessary simplification, as there is evidence for particle selectivity based on both size and food quality (e.g. Epifanio and Ewart, 1977; Haven and Morales-Alamo, 1970):

$$FR = CR.POM \tag{3}$$

where POM is the Particulate Organic Matter in mg L^{-1}.

Ingestion Rate

We have limited the intake of food into the gut by means of two new parameters: the maximum gut capacity (GC, mg or mm^3) and the time needed for food particles to pass through the gut, or gut passage time (GPT, h), following Scholten and Smaal (1998, 1999).

At each time step, a maximum ingestion rate (IR_{max}, mg POM ind^{-1} d^{-1}) is calculated as the ratio of the gut capacity and gut passage time:

$$IR_{max} = \frac{GC}{GPT} \tag{4}$$

The gut volume is related to oyster dry tissue weight by means of an allometric equation (Hawkins et al., 1990):

$$GV = aGC.DW^{bGC} \tag{5}$$

where aGC = 16 and bGC = 0.4 (parameterized according to Duarte et al., 2010).

The gut passage time depends on food quality (measured as the organic fraction in ingested material or POM:TPM ratio) and is delimited by minimum (GPT_{min}) and maximum (GPT_{max}) experimental values, according to Scholten and Smaal (1999):

$$GPT = \left(\frac{POM}{TPM}\right)^{0.3} \; (GPT_{min} - GPT_{max}) + GPT_{max} \qquad (6)$$

with GPT_{min} and GPT_{max} as 2 and 9 h, respectively, according to experimental values found in (Bayne et al., 1989).

The flow of ingested food through the gut is thus small for high quality food and large for low quality food, enabling the mussel to absorb relatively constant amounts of energy (see Hawkins and Bayne, 1992). Although the original work of Hawkins and Bayne (1992) used blue mussels, this physiological adaptation is applicable also to oysters and other filter feeders.

IR_{max} sets the maximum amount of food that can be ingested for a particular oyster size and food concentration. Thus, if IR > IR_{max}, the ingestion rate used by the model is set to IR_{max}.

Pseudofaeces production

Ingestion is also limited by the production of pseudofaeces (Pseudofaeces Production Rate: PPR, mg POM ind^{-1} d^{-1}), which in this model is estimated in different ways based on the ingestion rate: (i) as the difference between the filtration rate and the maximum ingestion rate –when the maximum ingestion rate limits food intake–; or (ii) as a function of particulate organic matter (POM) and a half-saturation constant for rejection (K_c), through a Michaelis-Menten formulation. The threshold for initiation of pseudofaeces production was set as 3 mg POM L^{-1} according to Bayne et al. (1993), and increased with increasing POM concentration following Bayne et al. (1993), Bayne and Worrall (1980), and Foster-Smith (1975). Pseudofaeces are not produced below 3 mg POM L^{-1} (Fig. 2).

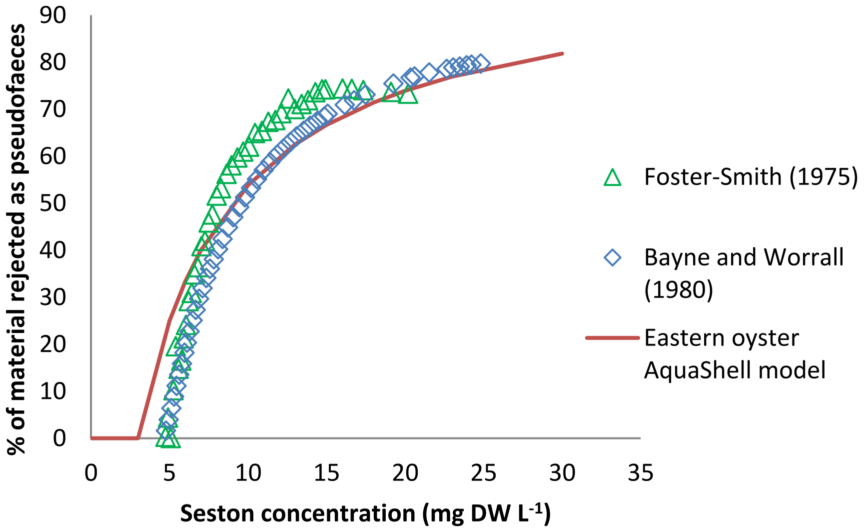


Fig. 2. Percentage of cleared material which is rejected as pseudofaeces. Points are observed values in Bayne and Worrall (1980) and Foster-Smith (1975), the line represents the predicted Eastern oyster AquaShell values.

The establishment of a maximum gut capacity together with the production of pseudofaeces limits the food intake by the oyster, based on oyster size, food quantity and food quality. This limitation mechanism has been used by other modelling approaches, such as EMMY (Scholten and Smaal, 1998, 1999) or DEB (Kooijman, 2000) and is based on physiological data (see e.g. Willows, 1992, for gut fullness or Bayne and Worrall, 1980, Bayne et al., 1993, and Kooijman, 2006, for pseudofaeces production).

Simulation of reproductive behavior

Growth simulation for diploid and triploid oysters

The individual growth model was modified to allow the user to select either diploid or triploid oysters, in order to simulate growth differences for diploid and triploid oysters, and the reduction in fitness observed for triploid oysters, which leads to underperformance of juveniles (Fig. 3).

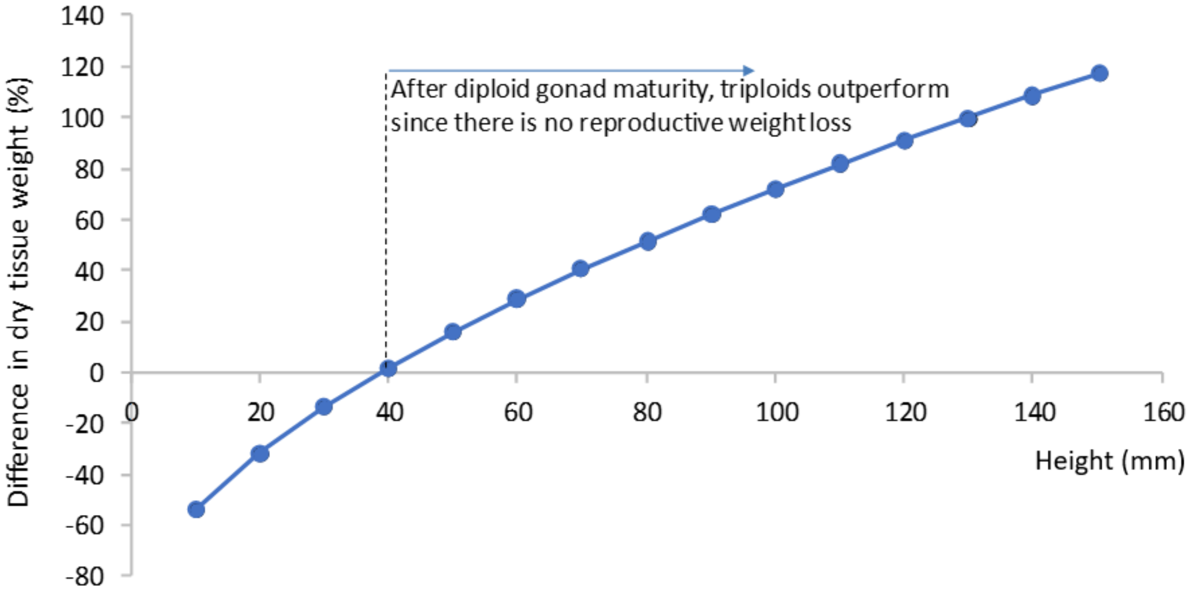


Fig. 3. Relative growth performance (dry tissue weight) of diploid and triploid oysters in Chesapeake Bay recalculated from oyster BMP panel data supplied by Bricker (pers. com.). Shell heights at 10 mm intervals were considered, and regression equations for tissue dry weight for diploids and triploids were used to calculate percentage differences in dry tissue weight.

When triploid mode is active, oysters do not allocate energy into gonadic tissue, and there are no tissue losses due to spawning. The lower growth performance of triploids before spawning was implemented by introducing an empirical fitness factor (0.99 of the diploid fitness) which reduces the absorption efficiency in triploids by 1%. The underlying premise is that organisms which differ genetically from a 'normal' oyster will have a slightly lower fitness for somatic growth. This lower growth performance is in place throughout the triploid oyster growth cycle, but is masked by the greater weight increase of non-spawning animals, when compared to diploid spawners.

Implementation of multiple spawning events

The individual growth model now allows oysters to spawn several times per year. According to Thompson et al. (1996), the Eastern oyster undergoes one spawning event in the northern waters of its distribution, typically from mid-June to mid- August, and three spawning events in southern waters, in spring, summer, and early fall.

Oysters are not trickle spawners, so they will lose their gonad content at once when spawning occurs. According to Choi et al. (1993), spawning takes place when the gonadosomatic index (GSI, measured as the ratio of gonad tissue weight to somatic tissue weight) exceeds 20%. For these reasons, two variables were added to deal with multiple spawning events per year: (i) a variable that limits the maximum number of spawning events per year, which would be set to 3 for diploids and 0 for triploids; and (ii) a counter for the number of spawning events, that ranges between 0 and 3 for diploids, and is set to 0 at the beginning of each year.

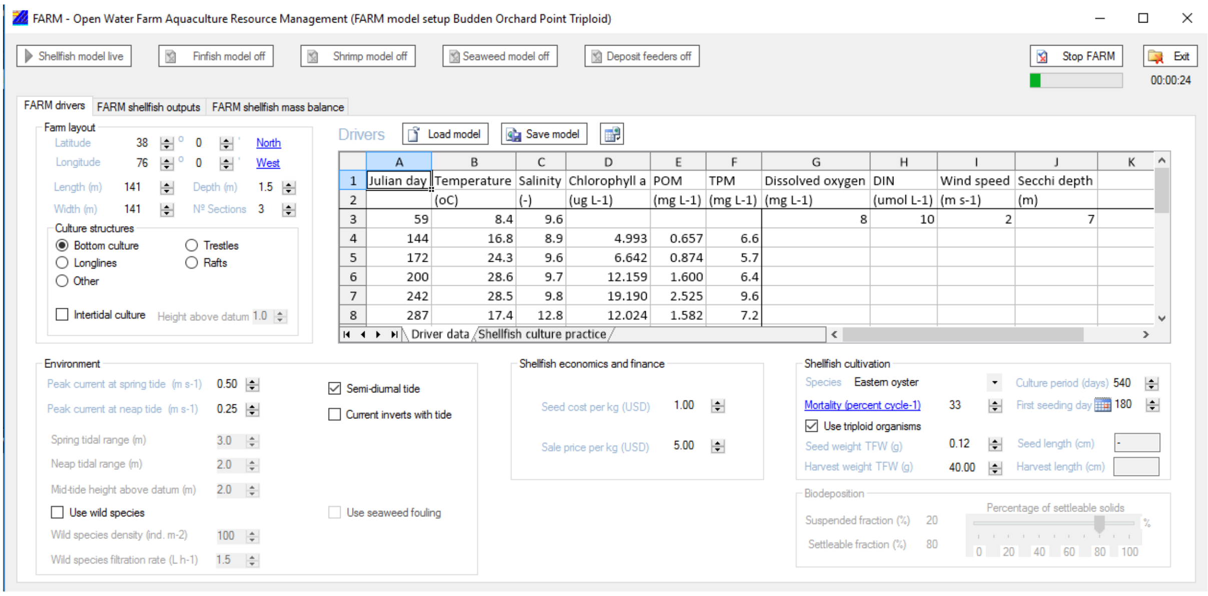
In addition, a threshold variable is required to set the minimum GSI needed for spawning. According to Choi et al. (1993), oysters become ready to spawn when gametes account for about 20% of total dry weight.

Other conditions that must be fulfilled for an Eastern oyster to spawn are:

- A minimum size for reproduction or maturity size, set at 0.2 g dry tissue weight (about 35mm)[1];
- Temperature higher than 15°C (modified from Shumway, 1996, and Wallace et al., 2008);
- Positive Scope for Growth (SFG), or net energy gain.

Adaptations to WinShell and FARM

The software for running AquaShell at the individual (WinShell) and population (FARM) scales was rebuilt to deal with ploidy options. In the case of WinShell, the combination *CTRL + Left Mouse Click* on the *Run* button displays the triploid option in the *Shellfish species* box, but does not run the model.



FARM - Open Water Farm Aquaculture Resource Management (FARM model setup Budden Orchard Point Triploid)

00:00:24

Farm layout
Latitude 38 ° 0 ' North
Longitude 76 ° 0 ' West
Length (m) 141
Depth (m) 1.5
Width (m) 141
Nº Sections 3

Culture structures
● Bottom culture
○ Trestles
○ Longlines
○ Rafts
○ Other
☐ Intertidal culture
Height above datum 1.0

	A	B	C	D	E	F	G	H	I	J	K
1	Julian day	Temperature	Salinity	Chlorophyll a	POM	TPM	Dissolved oxygen	DIN	Wind speed	Secchi depth	
2		(oC)	(-)	(ug L-1)	(mg L-1)	(mg L-1)	(mg L-1)	(umol L-1)	(m s-1)	(m)	
3	59	8.4	9.6				8	10	2	7	
4	144	16.8	8.9	4.993	0.657	6.6					
5	172	24.3	9.6	6.642	0.874	5.7					
6	200	28.6	9.7	12.159	1.600	6.4					
7	242	28.5	9.8	19.190	2.525	9.6					
8	287	17.4	12.8	12.024	1.582	7.2					

Environment
Peak current at spring tide (m s-1) 0.50
Peak current at neap tide (m s-1) 0.25
Spring tidal range (m) 3.0
Neap tidal range (m) 2.0
Mid-tide height above datum (m) 2.0
☐ Use wild species
Wild species density (ind. m-2) 100
Wild species filtration rate (L h-1) 1.5
☑ Semi-diurnal tide
☐ Current inverts with tide
☐ Use seaweed fouling

Shellfish economics and finance
Seed cost per kg (USD) 1.00
Sale price per kg (USD) 5.00

Shellfish cultivation
Species Eastern oyster
Culture period (days) 540
Mortality (percent cycle-1) 33
First seeding day 180
☑ Use triploid organisms
Seed weight TFW (g) 0.12
Seed length (cm) -
Harvest weight TFW (g) 40.00
Harvest length (cm)

Biodeposition
Percentage of settleable solids
Suspended fraction (%) 20
Settleable fraction (%) 80

Fig. 4. Screenshot of FARM running with the Orchard Point triploid input file.

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[1] the size at which Eastern oysters reach sexual maturity is extremely variable latitudinally and heavily dependent on where they reside within an estuary. According to some authors, Eastern Oysters typically reach sexual maturity as males at a shell size of 50 mm or 2 in in length (http://safinacenter.org/documents/2015/01/eastern-oyster-u-s-full-species-report-2.pdf). On the other hand, female oysters in Georgia reach sexual maturity at a size of approximately 25.4 mm, e.g. 1 inch (http://nsgl.gso.uri.edu/gaus/gauss12002.pdf). Other studies show that first sexual maturity can be attained at 31 mm (~1 year of age) (Galtsoff 1964; Rothschild et. al 1990). Thus, an intermediate size of 35 mm was chosen as threshold for reproduction, and this length corresponds to 0.2 g dry tissue weight in WinShell.

The triploid checkbox can be checked to run the model in triploid mode, but the user choice is not presently saved. Clicking the combination above will hide this option, but the ploidy choice remains active.

In FARM, the *Use triploid organisms* checkbox is permanently displayed in the *Shellfish cultivation* group box, but as in WinShell, the saved model input file always has the box unchecked.

In both cases, this (disabled) save option was chosen to provide backward compatibility of input files. However, for both applications, if a model is loaded while the ploidy status is set to triploid, the newly loaded model will run triploids without further selection.

Data for calibration and validation

The data used for environmental drivers and culture practice, were provided for four farms belonging to different growers. These farms are located at Chester River, Calvert Bay (Potomac River), Penny Lane (Chesapeake Bay), and Honga River (see Fig. 1 for locations)

The tables below show these data in the form they were used to set up the WinShell and FARM models.

Chester River

Table 2. Environmental drivers for the WinShell (first 6 columns) and FARM models at the Orchard Point Oysters farm at Chester River.

Julian day	Temperature	Salinity	Chlorophyll a	POM	TPM	Dissolved oxygen	DIN
	(°C)	(-)	(μg L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})	(μmol L^{-1})
59	8.4	9.6	6.35	4.0	8.4	11.91	
144	16.8	8.9	4.99	2.9	6.6	7.85	8.58
172	24.3	9.6	6.64	3.1	5.7	7.55	3.11
200	28.6	9.7	12.16	4.4	6.4	6	4.61
242	28.5	9.8	19.19	4.8	9.6	7.23	0.61
287	17.4	12.8	12.02	4.0	7.2	10.24	9.93
313	13.3	13.3	5.95	2.5	6.0	9.89	1.22
354	2.9	12.2	6.87	3.6	16.0	11.82	1.34

Table 3. Culture practice for the WinShell model for individual growth at the Orchard Point Oysters farm at Chester River.

	Site 1 (diploid)	Site 1 (triploid)
	Chester R.	Chester R.
	(Orchard Point Oysters)	(Orchard Point Oysters)
Model specifications		
Shellfish species	Eastern oyster	Eastern oyster
Start day for growth	180	120
Number of animals	1	1
Runtime (days)	540 - 720	480 - 600
Box volume (m^3)	1	1
Triploids	No	Yes
Seed size		
TFW (g)	0.12	0.12
Height (cm)	1	0.7

For all the FARM model setup files, the number of sections used in the model was 3, regardless of the data entered in the culture practice tables herein, because large numbers of sections force the model to run unreasonably slowly, to maintain numerical stability (the FARM model time step cannot be greater, and is parameterized automatically as somewhat smaller, than the time required for the water current to move water properties from one section to another).

Table 4. Culture practice for the FARM model for local-scale carrying capacity at the Orchard Point Oyster farm at Chester River.

	Site 1 (diploid)	Site 1 (triploid)
	Chester River	Chester River
	Orchard Point Oysters	Orchard Point Oysters
Farm layout		
Latitude	38	38
Longitude	76	76
Length (m)	140	140
Width (m)	140	140
Depth (m)	1.5	1.5
Number of sections	3	3
Culture structures	Bottom culture	Bottom culture
Intertidal culture?	No	No
Height above datum (m)	Not applicable	Not applicable
Environment		
Peak current at spring tide (m s^{-1})^2	0.5	0.5
Peak current at neap tide (m s^{-1})^2	0.25	0.25
Spring tidal range (m)	Not applicable	Not applicable
Neap tidal range (m)	Not applicable	Not applicable
Mid-tide height above datum (m)	Not applicable	Not applicable
Semi-diurnal tide?	Yes	Yes
Currents inverts with tide?	Yes	Yes
Use wild species?	No	No
Wild species density (ind m^{-2})		
Wild species filtration rate (L h^{-1})		
Shellfish economics and finance		
Seed cost per kg (USD)	1	1
Sale price per kg (USD)	5	5
Shellfish cultivation		
Species	Eastern oyster	Eastern oyster
Stocking density (ind m^{-2})	1.5	33.2
Mortality (percent $cycle^{-1}$)	33	33
Seed weight TFW (g)	0.12	0.12
Harvest weight TFW (g)	40	40
Culture period (days)	630	540
First seeding day	180	120
Seed height (cm)	1	0.7
Harvest height (cm)	7.62	7.62

Stocking densities were estimated from the reported data as total number of oysters seeded divided by the lease area. Data on tidal currents were obtained from the NOAA website (https://tidesandcurrents.noaa.gov): data from Chesapeake Channel LLB 92 was used for Chester River, data from Piney Point for Calvert Bay and Penny Lane, and data from Bishops Head for Honga River.

FARM default values were used for the seed and harvest financial data. These can be adapted for local use as required, in conjunction with the farmers who provided data.

For the models to work correctly in FARM, i.e. running the new individual growth model with the adaptations described above, the latitude and longitude of the farms must be stipulated as 38°N and 76°W. This instructs FARM to run a specific growth model, which is chosen by testing the combination of latitude and longitude, and avoids a proliferation of model options in the *Species* selection dropdown box in the *Shellfish cultivation* group. Although this approach is less than ideal, it avoids extended listings of spatially-tailored models for the same species, and may potentially be resolved if and when a single shellfish growth model for a particular species can be sufficiently generalized to apply across a broad range of regions. This has been an ambition of shellfish modelers since the early 1990s, and although closer to fruition, is not yet realized.

Calvert Bay (Potomac River) and Penny Lane (Chesapeake Bay)

Table 5. Environmental drivers for the WinShell (first 6 columns) and FARM models at the 38 Degrees North Oysters farm at Penny Lane (Chesapeake Bay).

Julian day	Temperature	Salinity	Chlorophyll a	POM	TPM	Dissolved oxygen	DIN
	(°C)	(-)	(µg L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})	(µmol L^{-1})
17	6.3	16.7	3.20	3.6	10.4	11.58	1.19
43	5	16	6.79	4.4	21.1	12.23	1.01
109	15.2	11.3	15.93	4.7	27.0	9.14	11.57
144	17.9	12	5.24	2.4	7.7	9.52	12.59
179	25.9	14	7.76	2.4	2.40	5.74	1.17
200	28.6	14.6	12.86	5.6	9.20	5.93	2.32
242	28.4	15.9	22.14	8	46.0	6.08	1.16
277	22.6	16.50	11.08	4.8	22.4	7.96	5.06
313	14.3	17.6	3.11	1.5	3.9	9.32	3.37

Table 6. Environmental drivers for the WinShell (first 6 columns) and FARM models at the 38 Degrees North Oyster farm at Calvert Bay (Potomac River).

Julian day	Temperature	Salinity	Chlorophyll a	POM	TPM	Dissolved oxygen	DIN
	(°C)	(-)	(µg L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})	(µmol L^{-1})
17	6.3	16.6	4.45	3.6	14.0	11.36	1.88
109	15.4	12.30	12.28	4.5	13.0	9.5	5.84
144	18.7	13.3	7.29	5.3	34.2	8.81	7.78
179	26	12	9.89	2.0	29.60	7.2	0.48
200	28.6	13	9.58	4.4	10.80	6.92	5.89
242	28.5	15.3	7.44	3.2	7.6	6.16	0.63
277	23.2	16.5	7.00	3.6	10.0	6.93	3.66
313	15.1	17.4	2.27	1.6	4.8	8.71	2.39

Table 7. Culture practice for the WinShell model for individual growth at 38 Degrees North Oysters farm (Calvert Bay and Penny Lane culture sites).

	Site 4a (triploid)	Site 4b (triploid)
	Calvert Bay (Potomac River)	Penny Lane (Chesapeake Bay)
	38 Degrees North Oysters	38 Degrees North Oysters
Model specifications		
Shellfish species	Eastern oyster	Eastern oyster
Start day for growth	180	180
Number of animals	1	1
Runtime (days)	360 - 540	240 - 450
Box volume (m^3)	1	1
Triploids	Yes	Yes
Seed size		
TFW (g)	0.12	0.12
Height (cm)	1	1

Table 8. Culture practice for the FARM model for local-scale carrying capacity at 38 Degrees North Oysters farm (Calvert Bay and Penny Lane culture sites).

	Site 4a (triploid)	Site 4b (triploid)
	Calvert Bay (Potomac River)	Penny Lane (Chesapeake Bay)
	38 Degrees North Oysters farm	38 Degrees North Oysters farm
Farm layout		
Latitude	38	38
Longitude	76	76
Length (m)	114	296
Width (m)	114	296
Depth (m)	1.1	1.2
Number of sections	3	3
Culture structures	Floating cage culture	Bottom culture

Intertidal culture?	No	No
Height above datum (m)	0.2	0.2
Environment		
Peak current at spring tide (m s^{-1})^{2}	0.5	0.5
Peak current at neap tide (m s^{-1})^{2}	0.25	0.25
Spring tidal range (m)	Not applicable	Not applicable
Neap tidal range (m)	Not applicable	Not applicable
Mid-tide height above datum (m)	Not applicable	Not applicable
Semi-diurnal tide?	Yes	Yes
Currents inverts with tide?	Yes	Yes
Use wild species?	No	No
Wild species density (ind m^{-2})		
Wild species filtration rate (L h^{-1})		
Shellfish economics and finance		
Seed cost per kg (USD)	1	1
Sale price per kg (USD)	5	5
Shellfish cultivation		
Species	Eastern oyster	Eastern oyster
Stocking density (ind m^{-2})	154	45
Mortality (percent $cycle^{-1}$)	35	35
Seed weight TFW (g)	0.12	0.12
Harvest weight TFW (g)	40	40
Culture period (days)	450	330
First seeding day	180	180
Seed height (cm)	1	1
Harvest height (cm)	7.62	7.62

Honga River

Table 9. Environmental drivers for the WinShell (first 6 columns) and FARM models at Honga Oyster Company farm at Honga River.

Julian day	Temperature	Salinity	Chlorophyll a	POM	TPM	Dissolved oxygen	DIN
	(°C)	(-)	(µg L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})	(µmol L^{-1})
16	4.6	16.8	5.87	4.0	16.4	12.53	1.73
37	5.0	16.0	5.93	4.4	16.4	12.23	2.16
68	8.9	15.5	5.93	4.9	20.3	10.77	2.22
103	15.5	13.8	7.91	5.2	15.2	9.78	3.37
128	15.7	8.9	2.08	4.8	25.2	12.3	8.96
162	24.9	11.2	5.76	6.0	16.7	8.39	1.18
190	27.3	11.8	6.46	4.7	23.3	7.29	1.34
232	27.9	12.4	9.08	6.0	15.3	7.25	5.61
277	21.5	16.9	9.31	4.4	18.4	7.57	1.96
305	15.1	16.4	6.36	5.0	14.6	9.27	1.64
347	5.7	17.1	5.55	4.4	14.4	12.15	1.09

Table 10. Culture practice for the WinShell model for individual growth at Honga Oyster Company farm (Honga River).

	Site 3 (triploid)
	Honga River
	Cox Farm
Model specifications	
Shellfish species	Eastern oyster
Start day for growth	180
Number of animals	1
Runtime (days)	540
Box volume (m^{3})	1
Triploids	Yes
Seed size	
TFW (g)	0.12

Height (cm)	1

Table 11. Culture practice for the FARM model for local-scale carrying capacity at the Honga Oyster Company

	Site 3 (triploid)
	Honga River
	Honga Oyster Company
Farm layout	
Latitude	38
Longitude	76
Length (m)	284
Width (m)	284
Depth (m)	2.4
Number of sections	3
Culture structures	Bottom culture
Intertidal culture?	No
Height above datum (m)	Not applicable
Environment	
Peak current at spring tide (m s^{-1})[2]	0.25
Peak current at neap tide (m s^{-1})[2]	0.12
Spring tidal range (m)	Not applicable
Neap tidal range (m)	Not applicable
Mid-tide height above datum (m)	Not applicable
Semi-diurnal tide?	Yes
Currents inverts with tide?	Yes
Use wild species?	No
Wild species density (ind m^{-2})	-
Wild species filtration rate (L h^{-1})	-
Shellfish economics and finance	
Seed cost per kg (USD)	1
Sale price per kg (USD)	5
Shellfish cultivation	
Species	Eastern oyster
Stocking density (ind m^{-2})	18.5
Mortality (percent $cycle^{-1}$)	50
Seed weight TFW (g)	0.12
Harvest weight TFW (g)	40
Culture period (days)	540
First seeding day	150
Seed height (cm)	1
Harvest height (cm)	7.5 - 10

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[2] Data from the NOAA website; from Piney Point for Calvert Bay and Penny Lane:

https://tidesandcurrents.noaa.gov/ofs/ofs_station.shtml?stname=Piney%20Point&ofs=cb&stnid=8578240&subdomain=0

from Chesapeake Channel LLB 92 for Chester River:

https://tidesandcurrents.noaa.gov/ofs/ofs_station.shtml?stname=Chesapeake%20Channel%20LLB%2092&ofs=cb&stnid=cb1101&subdomain=0

and from Bishops Head for Honga River:

https://tidesandcurrents.noaa.gov/ofs/ofs_station.shtml?stname=Bishops%20Head&ofs=cb&stnid=8571421&subdomain=0

Model results

Individual model

The performance of somatic and gonad growth, as well as the number and intensity of the spawning events was verified by comparison with the field data provided and literature data.

Table 12 shows the endpoint live weight obtained with the AquaShell individual growth model for the four study locations using the environmental drivers and culture practice detailed above. WinShell is used as the application for running the model. All the input files for running these individual models have been supplied to NOAA as part of WP3 (Table 1).

For comparison purposes, a uniform culture practice was considered for all farms in both the WinShell and FARM models: a culture period of 540 days with Day 180 as the first seeding day (selected to represent the typical first day between May and July), a seed weight of 0.12 g TFW and 40 g TFW as harvest weight for both diploid and triploid based on data from the four oyster farms.

Table 12. WinShell growth outputs for diploid and triploid oysters grown at the different locations.

		Chester River	Calvert Bay (Potomac River)	Penny Lane (Chesapeake Bay)	Honga River
Diploids	TFW (g)	98.8	44.2	50.8	29.4
	Height (cm)	9.5	7.3	7.6	6.3
Triploids	TFW (g)	99.6	45.0	50.6	28.7
	Height (cm)	9.4	7.2	7.5	6.2

From the reported culture practice[3], we know that the average harvest weight ranges between 40 and 60 g TFW. Thus, the model may be overestimating oyster growth in Chester River and underestimating oyster growth in Honga River. When we compare both locations we observe that Chester River presents greater concentration of Chl-a and lower TSS than the Honga River. The food quality (POM/TSS) of Chester River is the greatest of all locations.

Sensitivity analysis for gut passage time

The growth model assumes the transit time of ingested food (GPT) to be based on food quality, and the gut volume calculation was taken from blue mussels, due to the lack of experimental data in oysters.

A sensitivity analysis (Eq. 7) was executed, considering a variation of ± 10% in gut volume at every model time step.

$$S = \frac{\Delta x}{x} \Big/ \frac{\Delta p}{p} \qquad (7)$$

Where:

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[3] Reported data on the four oyster farms is:

Honga River: Average harvest length is 3” (7.62 cm) and average harvest weight is 60-70g

Chester River: ~38g for small (2.5”-3”) and (3”-4”) for large oysters

Penny Lane and Calvert Bay: Between 43 and 85 g TFW depending on product quality

S = sensitivity (no units)

x = output metric (variable units, in this case total live weight in g)

p = parameter (variable units, in this case gut volume in ml)

Results for S were calculated for diploids (2.1 and -1.9) and triploids (2.2 and -2.0), which suggest the model sensitivity to this parameter is homogeneous (e.g. for diploids a 10% increase in gut volume leads to an 21% increase in end-point live weight and for triploids a 10% decrease in gut volume gives 20% less weight).

Overall, the model does not appear to be highly sensitive to this parameter. Gut volume can be recalibrated as necessary when data become available, and although variation of this parameter does not cause major changes to growth, laboratory evaluation of its allometric variation in the Eastern oyster is suggested.

Individual growth model validation against field data

The growth performance for diploid and triploid oysters was tested against reported data for the Orchard Point Oysters, Honga River Oysters and 38°C North Oysters farms (see Fig. 5, Fig. 6, Fig. 7 and Fig. 8 below).

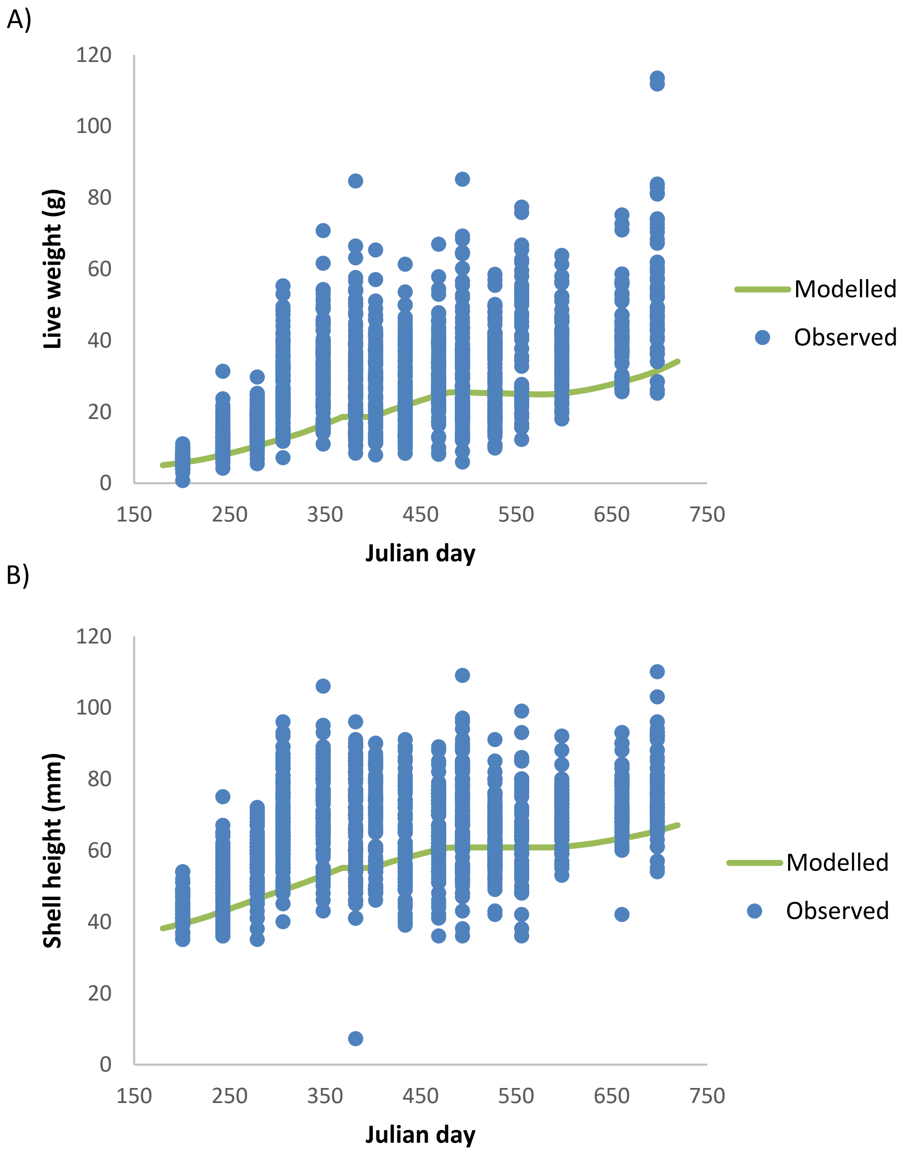


Fig. 5. Comparison of observed and predicted individual growth in A) live weight and B) shell height for Eastern oyster triploids at the Honga River Oysters Farm in the Honga River.

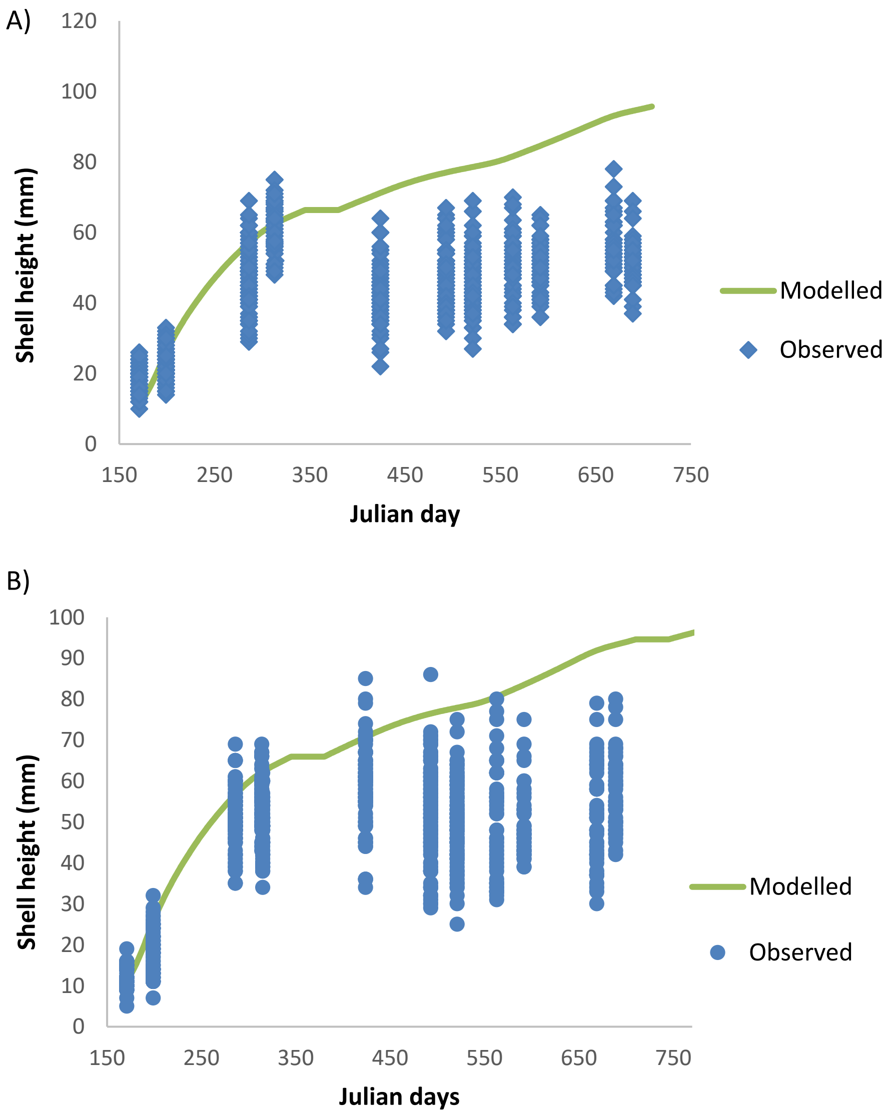


Fig. 6. Comparison of observed and predicted individual growth in height for Eastern oyster A) diploids and B) triploids at the Orchard Point Oysters farm in Chester River.

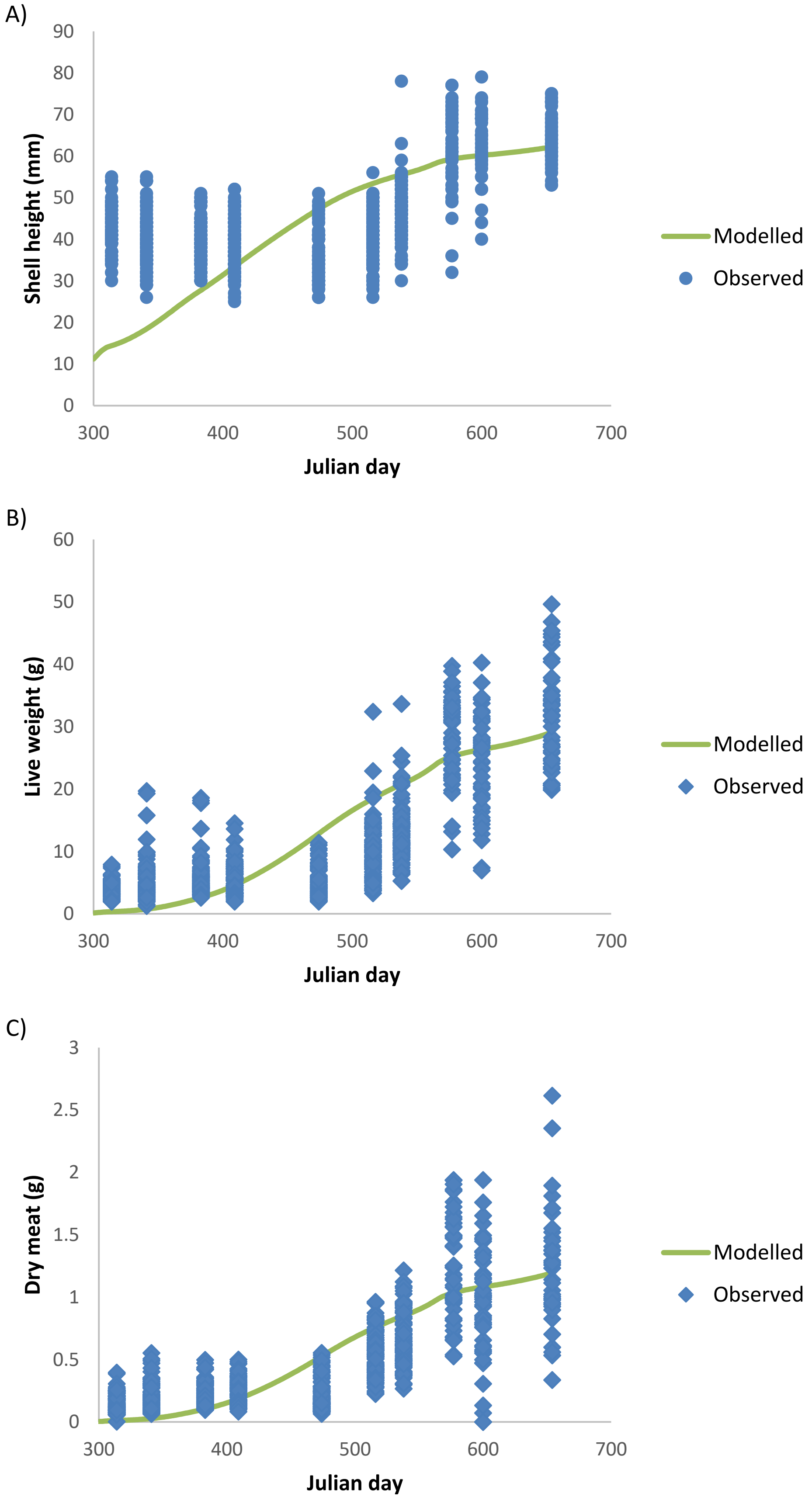


Fig. 7. Comparison of observed and predicted individual growth in A) shell height, B) live weight and C) dry meat weight for Eastern oyster triploids at the 38° North Oysters Farm in the Chesapeake Bay (Penny Lane).

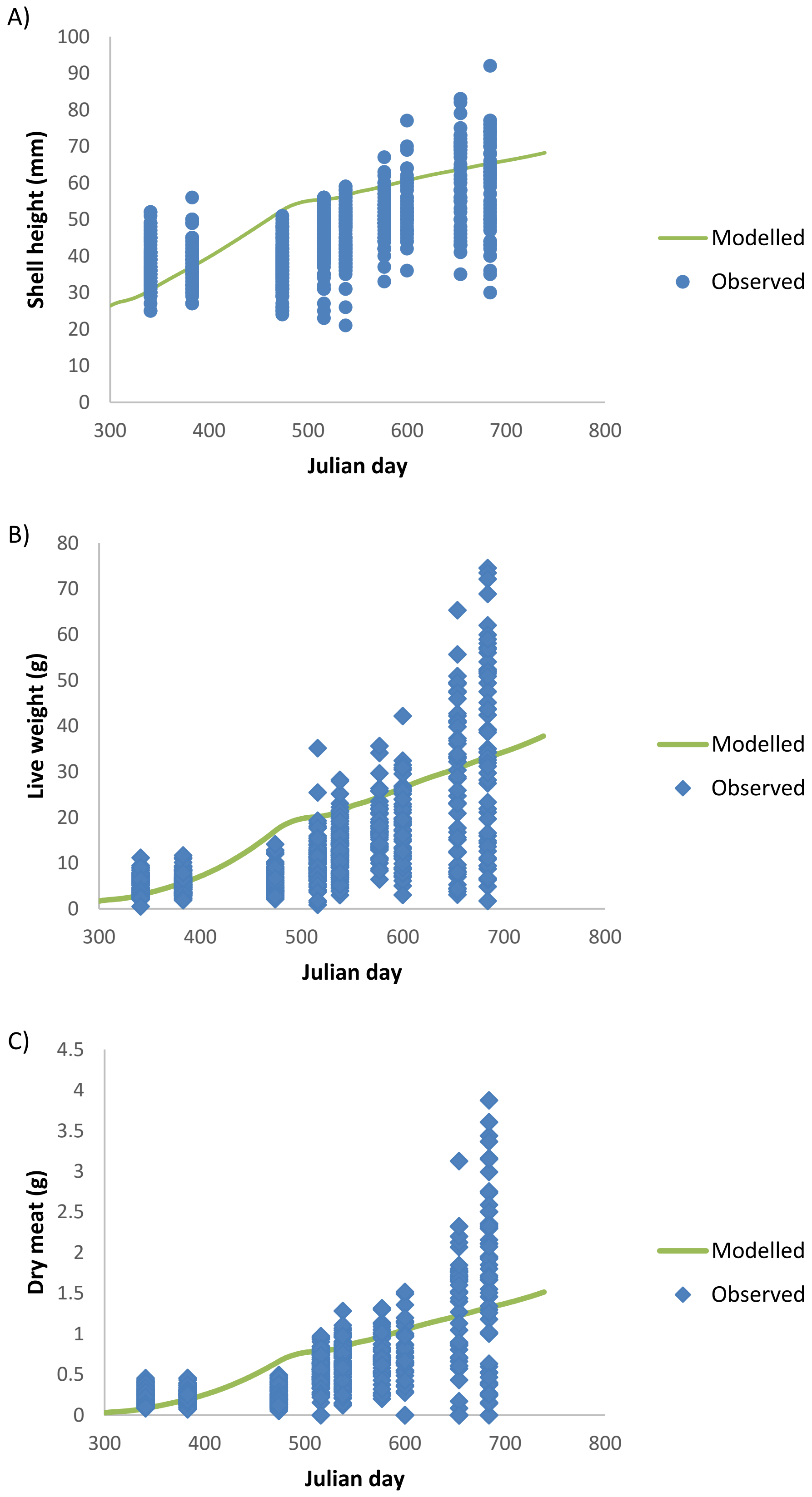
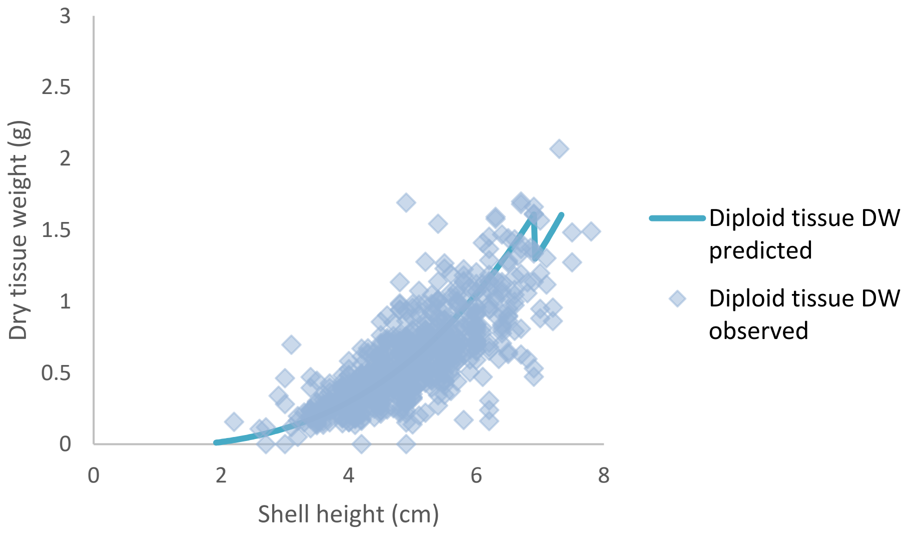


Fig. 8. Comparison of observed and predicted individual growth in A) shell height, B) live weight and C) dry meat weight for Eastern oyster triploids at the 38° North Oysters Farm in the Potomac River (Calvert Bay).



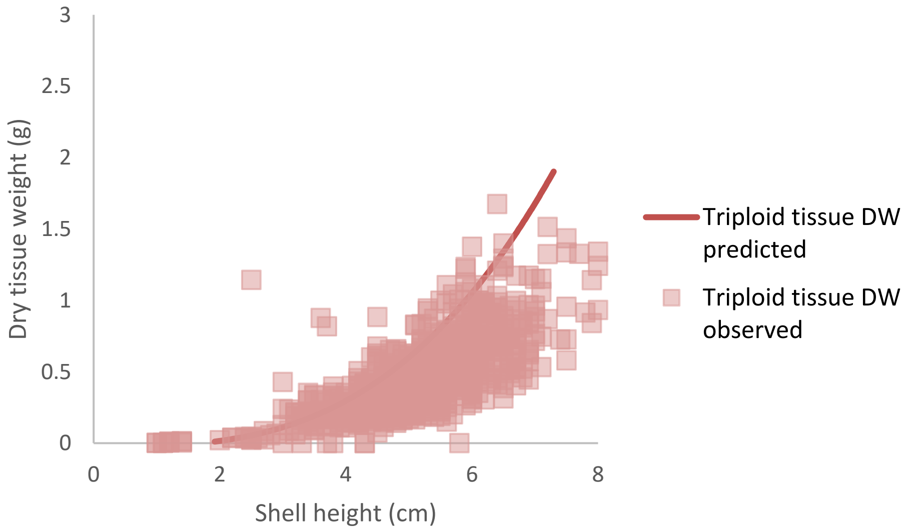


Fig. 9. Height-tissue dry weight allometry for simulated and field (Orchard Point Oysters) data.

Fig. 9 shows a good match for the relationship between height and tissue dry weight in upper Chesapeake Bay diploid and triploid oysters. Moreover, the data on triploid growth at Orchard Point indicate that for equivalent lengths, diploids systematically outperform triploids (see Table 14). Since the model is conceptualized to provide better overall growth for triploids (these will have a slightly lower genetic fitness, but tissue weight increases more rapidly since there is no investment in gamete production), the model curve follows the upper values of the data set until the animals are slightly over 5 cm in height, and then markedly exceeds the measured values.

Comparative growth performance of diploid and triploid Eastern oysters

The individual growth model successfully simulates the differences in growth between diploid and triploid oysters due to the absence of spawning losses in triploids (Fig. 10).

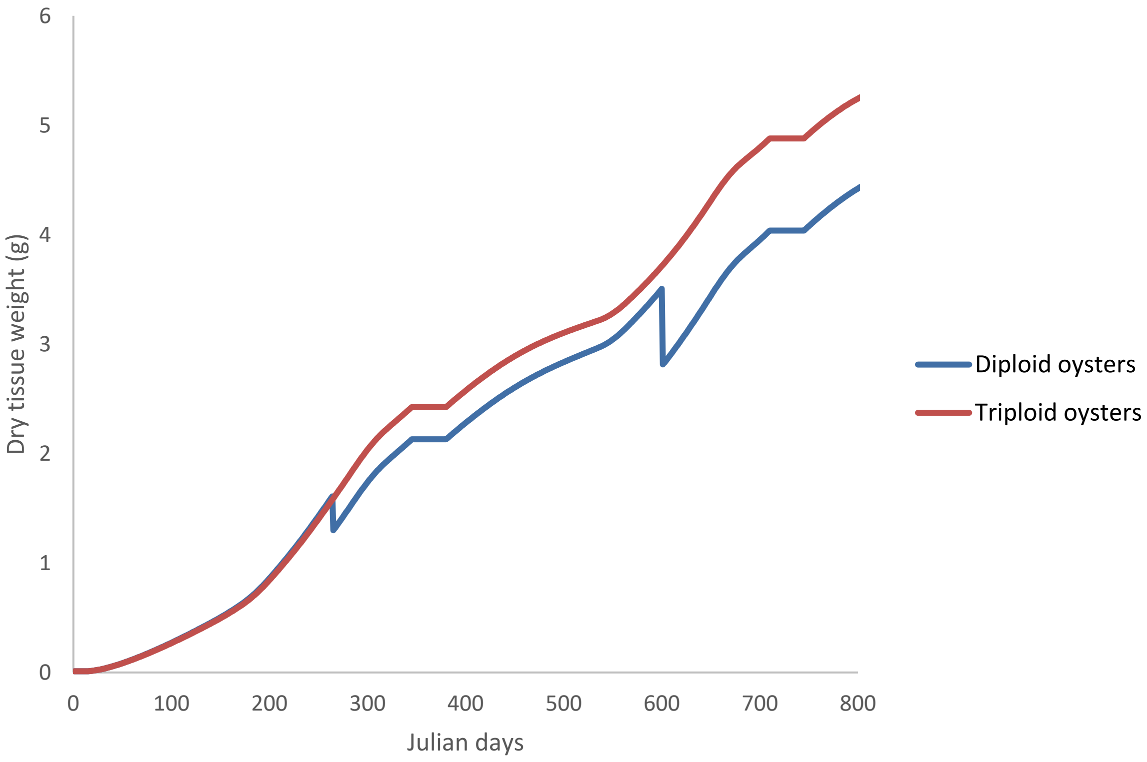


Fig. 10. Simulation of the growth performance for diploid and triploid oysters at the Orchard Point Farm in Chester River.

In order to compare the growth performance of our model with results from other authors (Paynter & Dimichele, 1990; Paynter & Malone, 1990; Paynter et al, 1992) we would need the environmental growth drivers at these locations, which are not provided by these authors. However, in Table 13 we can see that the simulated growth rates (from 2.9 to 4.7 mm month^{-1}) lie within annual growth rates from the literature (2.4 to 13.2 mm month^{-1}).

Table 13. Comparison of measured and simulated annual oyster growth rates.

Growth period	Growth rate (mm month^{-1})	Author	Culture system
Late June - October 1987	10-15	Paynter and Dimichele (1990)	Floating trays
November - May	No growth	Paynter and Dimichele (1990)	Floating trays
Late June - October 1988	8-10	Paynter and Dimichele (1990)	Floating trays
Annual	5.1	Paynter and Dimichele (1990)	Floating trays
Annual	3.75	Paynter and Dimichele (1990)	Floating trays
September 1989 - December 1990	4.4-5.7	Paynter et al. (1992)	Floating rafts
Annual range	8.3-16.7	Paynter and Mallonee (1990)	Floating rafts
Annual mean	13.2	Paynter and Mallonee (1990)	Floating rafts
Annual	2.4-3	Paynter (2008)	Subtidal mesh cages
Summer months	3.5-7.2	Paynter (2008)	Subtidal mesh cages
18 months from the 1st July	3.5	Simulated for Calvert Bay (Potomac River)	Floating cages
18 months from the 1st July	3.6	Simulated for Penny Lane (Chesapeake Bay)	Bottom culture
18 months from the 1st July	4.7	Simulated for Chester River	Bottom culture
18 months from the 1st July	2.9	Simulated for Honga River	Bottom culture

FARM model

Example outputs

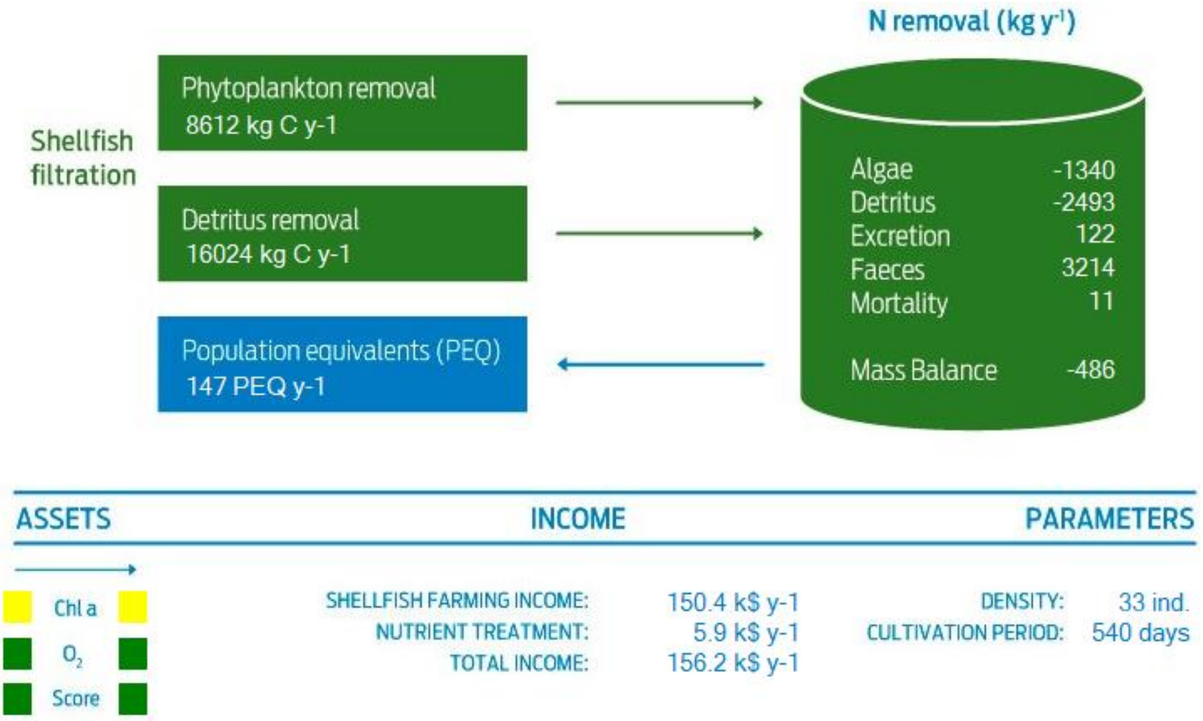
Table 14 shows the FARM model outputs for an Eastern oyster production cycle at the different locations in the Maryland part of Chesapeake Bay. The tons obtained at harvest, as well as the economic outputs are proportional to the seeding density. The Average Physical Product (APP) was highest at the Orchard Point Farm (Chester River) and lowest at the Cox Farm (Honga River).

At a culture density of 33 animals per square meter, oysters provide an annual ecosystem service of 147 population equivalents at the Orchard Point Farm (Fig. 11). FARM not only simulates the total mass balance of phytoplankton and organic detritus removed, but also the substitution cost of nutrient removal, which in this case corresponds to nearly $6,000 per year, using a valuation of 12.4 USD kg^{-1} N (Lindahl et al., 2005). Application of cost-equivalence coefficients obtained in the Long Island Sound and Great Bay Piscataqua Estuary bioextraction study (Bricker et al., 2015) would approximately triple the potential replacement cost, when considering point-source costs alone.

Table 14. Management level outputs for FARM runs at the different locations over a production cycle, considering 40 g live weight as minimum weight for harvest. Financial data are indicative only, since pricing data were not made available.

Location	Chester River	Chester River	Penny Lane	Calvert Bay	Honga River
Ploidy	Diploid	Triploid	Triploid	Triploid	Triploid
Stocking density (ind m^{-2})	1.5	33.2	45.6	154.4	18.5
Seed (tonnes)	0.03	0.65	3.95	1.99	1.5
Ind. weight (g TFW)	100.6	98.5	49.5	44.5	28.5
Height (cm)	9.46	9.37	7.44	7.18	6.20
Harvest (kg m^{-2})	0.10	2.24	2.91	9.61	0.65
TPP (tonnes)	2.0	44.5	255	125	52.1
APP (-)	68.0	68.0	64.6	62.6	34.8
Revenue (k$)	10.1	222	1277	624	261
Cost (k$)	0.03	0.65	3.95	1.99	1.50
Profit (k$)	10.1	222	1273	622	259
Nitrogen removal (kg y^{-1})	23	486	2081	1068	542
PEQ y^{-1}	7	147	630	324	164

The low yield for diploid culture at Chester River is due to the very low stocking density calculated. The growth performance is higher in diploid culture than in triploid culture (100.6 vs. 98.5 g TFW), which may be due to lower intraspecific competition for food resources at lower stocking densities.



SHELLFISH FARMING INCOME: 150.4 k$ y-1
NUTRIENT TREATMENT: 5.9 k$ y-1
TOTAL INCOME: 156.2 k$ y-1

DENSITY: 33 ind.
CULTIVATION PERIOD: 540 days

Fig. 11. FARM model annualized mass balance for Eastern oyster culture at Orchard Point Farm in Chester River (triploids).

This analysis is useful *per se*, since it can be used by managers and farmers to analyze potential issues with respect to the model, the environmental data, and the culture practice description. We tested the updated modelling approach with data from both Long Island Sound and a highly eutrophic farm area in the Potomac River, and found that the model appears to be robust in both cases, and does not produce overgrowth to any significant extent.

We do recommend caution when applying the model in a range of different environments, if the conditions are markedly different from the systems tested. Caution is always a recommendation when models are applied, and in this case, it means that when the model is run with a new set of field data, the outputs should be validated against measured growth – at the very least shell height, but also weight parameters such as dry tissue and total live weight. Because models simplify reality, we do not expect perfect matches unless a model is re-tuned for each bespoke dataset (thereby trading off generality and simplicity for accuracy and realism). Even in the case where such a bespoke model is developed, its application without due diligence to e.g. different years is unwise, because e.g. genetic variability in populations will lead to changes in growth rates, and in the case of diploids, spawning performance.

However, and with those caveats in mind, the present version of the model successfully simulates growth and environmental effects of Eastern oyster culture across a range of trophic conditions.

Products and dissemination

Software applications

The delivery to NOAA of two software applications forms an integral part of this contract, together with the files described above which were used to generate the results shown. This set has been made available digitally through a bespoke web link, and full instructions have been provided with respect to installation and operation of both WinShell and FARM.

Reporting

This report provides a brief account of the work done, with an emphasis on the methodological aspects that led to model improvements, and the presentation of example results. The software delivery aims to allow NOAA, in conjunction with local managers and industry, to take these results further by fine-tuning different aspects of the input data, and using local knowledge to provide appropriate interpretation of outputs, and definition of stakeholder-relevant development scenarios for testing.

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