Coupled ecological and economic models to project climate-induced changes in estuarine habitat and aquaculture production

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Acknowledgements: Paul Fackler, Shannon Hood, Marvin (Trey) Mace, and Matt Parker. Errors and omissions are solely the responsibility of the authors.
This work was supported by National Oceanic and Atmospheric Administration grants NA15NOS4780184 and NA18NOS4780179.
Prepared for: CLIVAR 2022, Woods Hole, MA, USA, April 12-14.

Why Develop Coupled Ecological and Economic Models for Oysters?

A persistent challenge in forecasting climate effects on ecosystems is linking expected biogeochemical and physical changes to effects on organisms.

Commercial aquaculture of the eastern oyster (*Crassostrea virginica*) in Chesapeake Bay may be economically vulnerable to climate change as a result of projected biogeochemical changes, including ocean acidification, salinity variability, and temperature increases.

Projecting effects on cultured and harvested organisms and the associated economic effects and social vulnerability is needed for meaningful application of forecasts. The coupled models include strategic firm behavior to demonstrate some of the benefits of improving ecological forecasts for mitigating risk.

The Models

Coupled Hydrodynamic-Biogeochemical Models: Physical and biogeochemical models (ROMS-RCA-CC; Shen et al. 2019) were used to quantify contemporary (1990s-2000s) and future (mid-century) variability and spatial distributions of multiple physiological stressors, including warming, salinity variability, food alterations, and estuarine acidification.

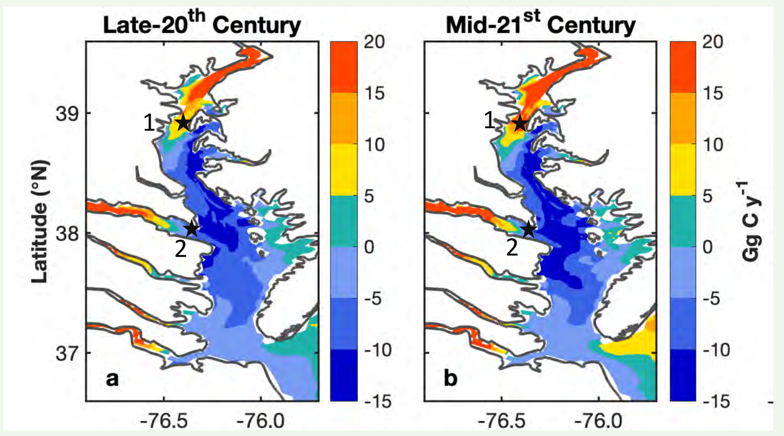

Figure 2: Contemporary and Mid-Century pCO_2 distributions in CB, with location of example study sites 1 & 2 indicated by stars

Oyster Growth and Survival Models: Modeled environmental variations were used to simulate tissue and shell growth of oysters using a bioenergetics model. Oyster survival modeling was adapted from Maryland DNR (2021) and Southworth et al. (2017).

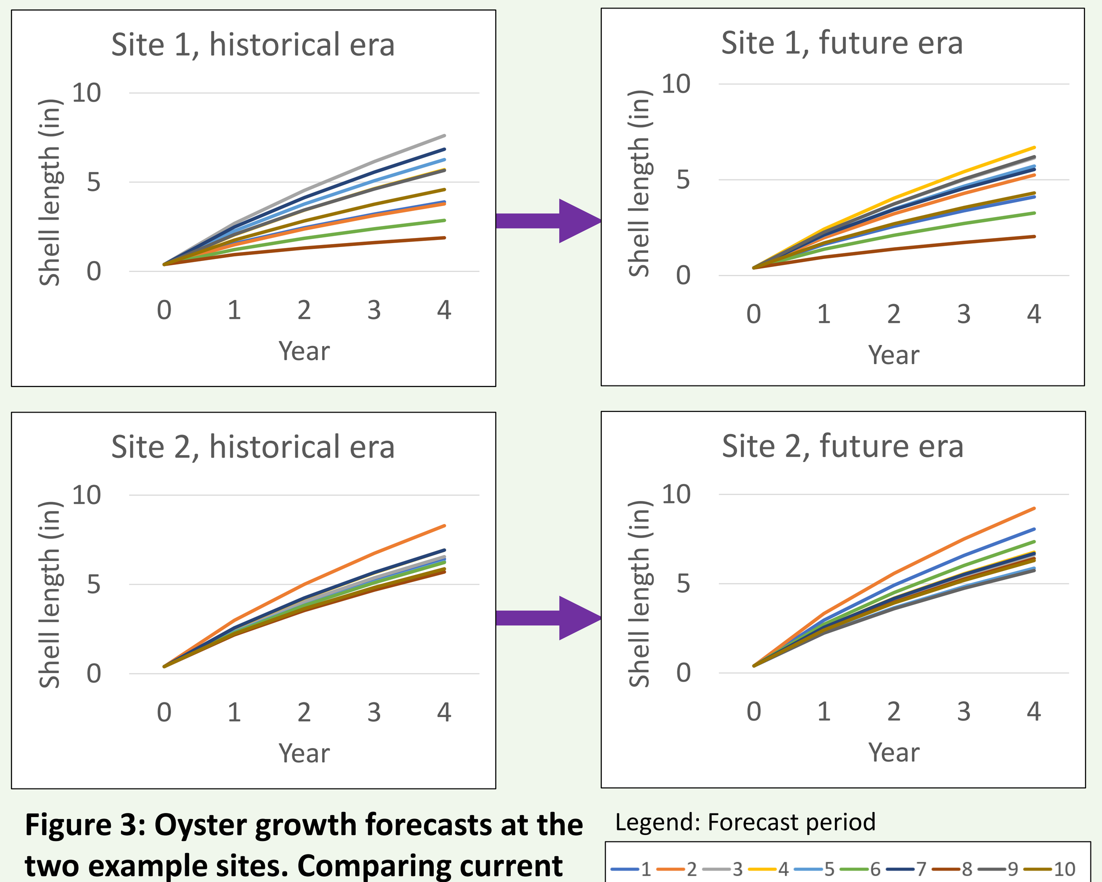

Figure 3: Oyster growth forecasts at the two example sites. Comparing current and future eras, the means and standard deviations shift in different ways. We found that the effects of future climate on the oyster growth were complicated by compensating and disproportionate impacts of warming versus acidification and salinity reductions.

Coupled Modeling Framework

We linked downscaled climate projections for Chesapeake Bay to drive contemporary and future simulations of biogeochemical variables important for growth of the eastern oyster.

The biogeochemical models were used to drive simulations of oyster survival and growth.

The oyster growth outcomes under climate change were used to guide a simulation of oyster aquaculture costs and operation regimes.

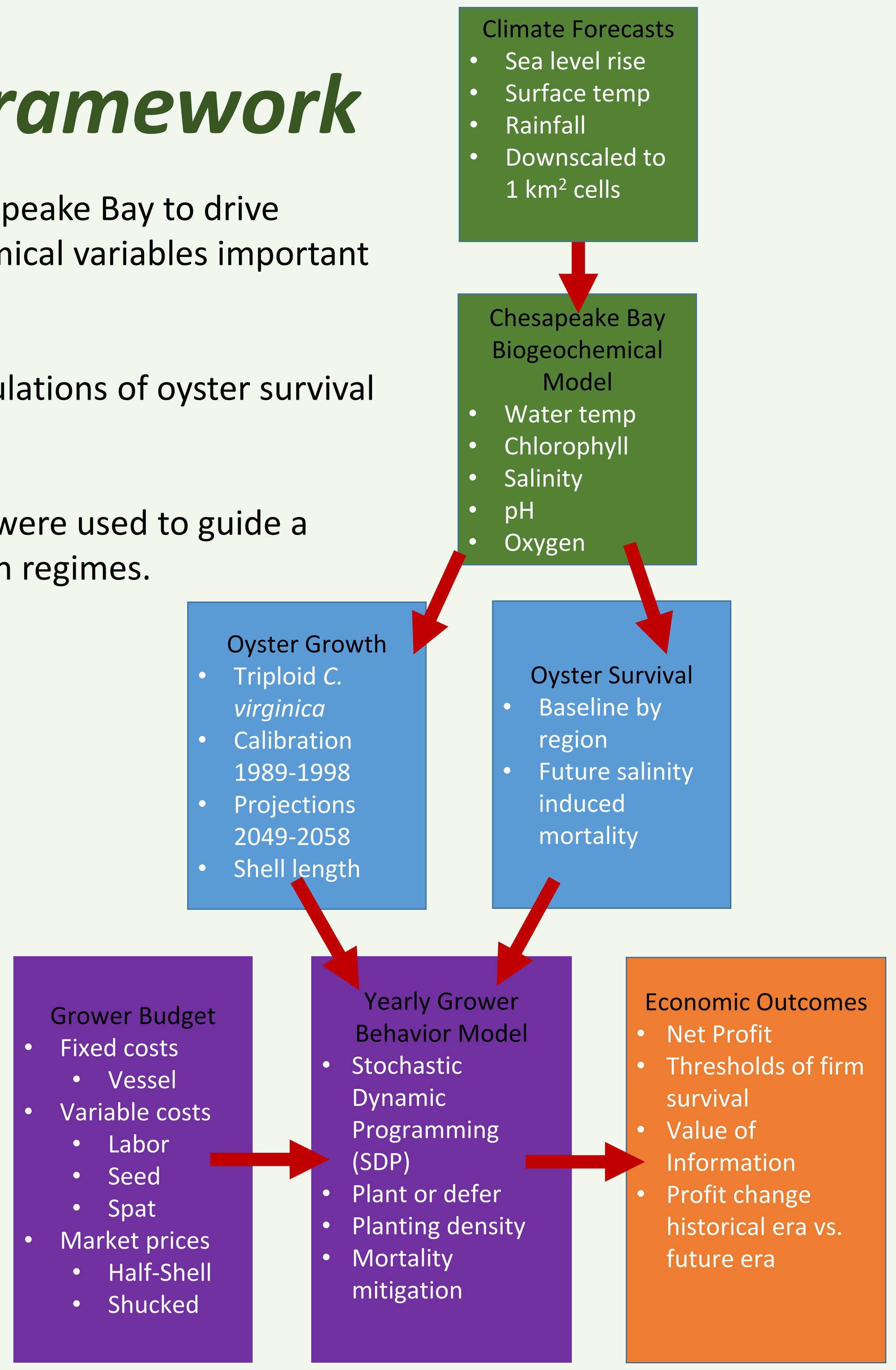

Figure 1: Conceptual diagram of models implemented, relevant variables, and the coupling between them

Oyster Aquaculture Decision Model: Expected distributions of growth and survival became inputs for an oyster aquaculture decision model for a representative grower. The decision model is in a yearly Stochastic Dynamic Programming (SDP) framework coded with open source software MDPSolve (Fackler, 2011). The SDP model yields an optimal set of grower actions for any combination of state variables. Performance outcomes of applying the optimal solution can then be simulated using Monte Carlo simulation (here, 10K draws) to characterize uncertainty. Year-to-year adaptive grower actions tested:

1. Purchase mitigation, e.g. more resilient brood stock
2. Plant or defer 1 period until conditions improve
3. Vary planting density, up to 3x expected harvest

Grower budgets were developed from multiple sources (e.g. Parker et al., 2016, Engle and van Senten, 2018) and recalibrated to track costs per oyster handled per time period. First-order Markov models were generated to predict next year size based on current size.

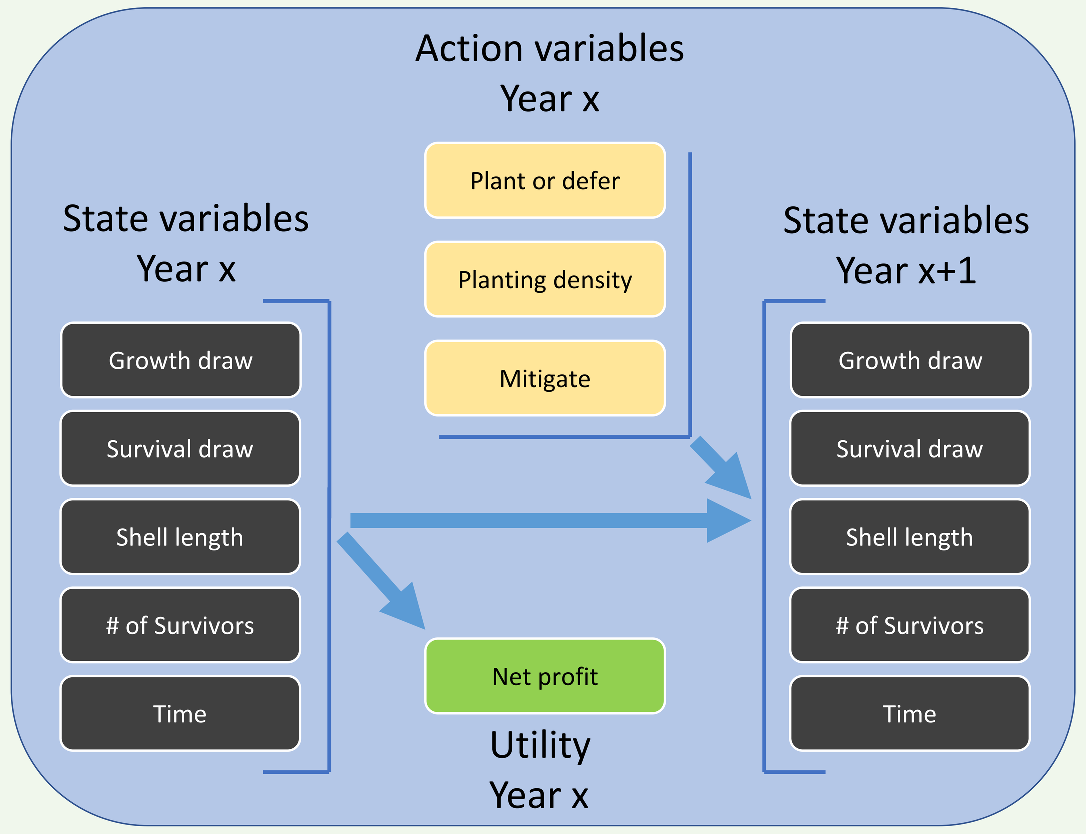

Figure 4: Grower decision model with the Stochastic Dynamic Programming framework

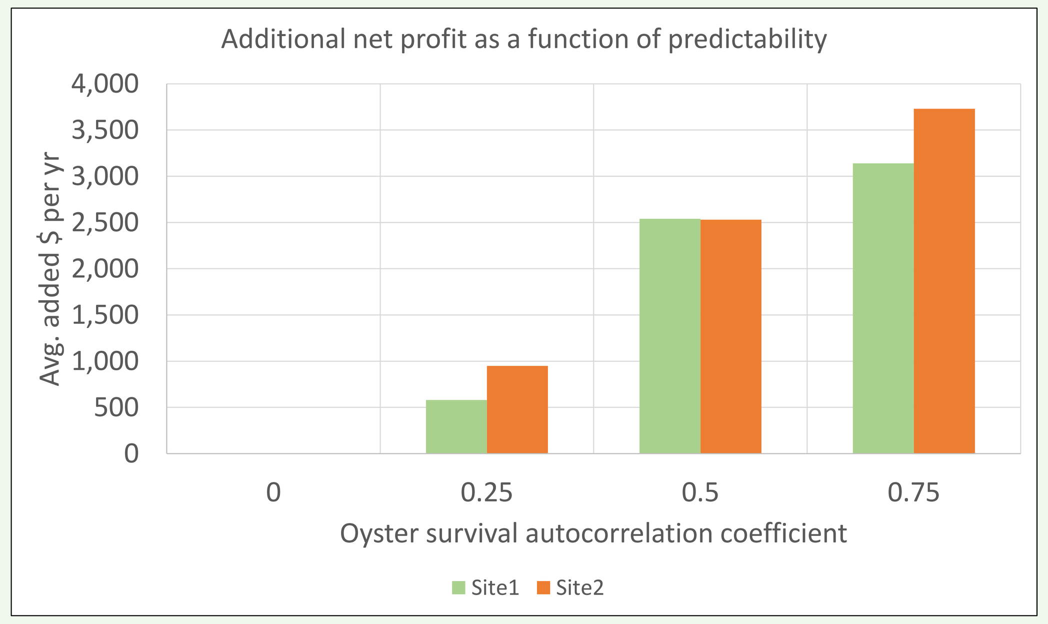

Figure 5: Preliminary results of average increased net profits with increasing predictability, where predictability was represented by survival autocorrelation (X axis)

Outcomes for Grower Actions

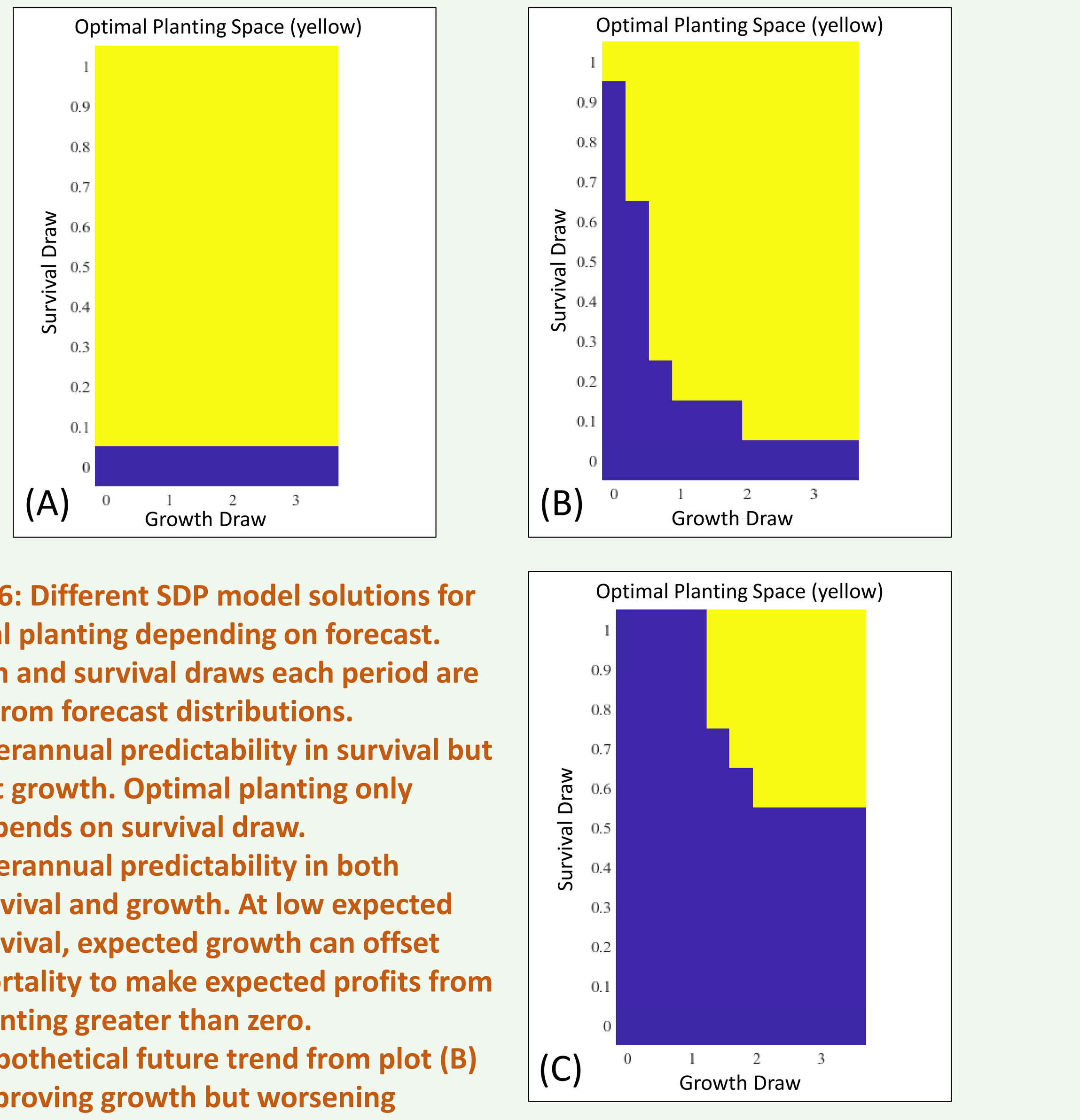

Figure 6: Different SDP model solutions for optimal planting depending on forecast. Growth and survival draws each period are taken from forecast distributions.

(A) Interannual predictability in survival but not growth. Optimal planting only depends on survival draw.

(B) Interannual predictability in both survival and growth. At low expected survival, expected growth can offset mortality to make expected profits from planting greater than zero.

(C) Hypothetical future trend from plot (B) improving growth but worsening mortality. It is only worthwhile to plant when growth and survival rates are projected to be high.

Conclusions & Next Steps

On average within Chesapeake Bay, future biogeochemical changes may increase oyster growth. However, mortality variability appears to be more important than growth in determining aquaculture harvest and net profits. Mortality may increase due to more frequent low salinity events (associated with major precipitation events), although increasing salinity resulting from sea level rise may mitigate this effect in some areas.

Oyster aquaculture growers in Chesapeake Bay can make marginal gains through flexible behavior informed by updated forecasts, but the relative improvements vary by region and which variables have improved forecasts.

Improved forecasting can take multiple forms, such as refined mean or standard deviation estimates, updated time trends, and strength of autocorrelation between years.

In ongoing biogeochemical work we plan to predict more detailed spatial patterns in oyster growth responses to climate change and the associated impacts on future aquaculture firm survival within the Bay.

For the coupled economic modeling we will expand the decision model to encompass both bottom culture and container culture operations, quantify the Value of Information for improving forecasts for different variables, and identify forecasts that cross thresholds of aquaculture viability.

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