Ecological Modelling 347 (2017) 1–10

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Assessing the effects of ocean acidification in the Northeast US using an end-to-end marine ecosystem model

Gavin Fay[a,1], Jason S. Link[a,*], Jonathan A. Hare[b]

[a] National Marine Fisheries Service, Woods Hole, MA 02543, USA
[b] National Marine Fisheries Service, Northeast Fisheries Science Center, Narragansett, RI 02882, USA

ARTICLE INFO

Article history:
Received 16 June 2016
Received in revised form
14 December 2016
Accepted 23 December 2016
Available online 6 January 2017

Keywords:
Strategic ecosystem modeling
Fisheries management
Climate change
Atlantis
Northwest Atlantic
Ecosystem indicators
Acidification

ABSTRACT

The effects of ocean acidification on living marine resources present serious challenges for managers of these resources. An understanding of the ecosystem consequences of ocean acidification is required to assess tradeoffs among ecosystem components (*e.g.* fishery yield, protected species conservation, sensitive habitat) and adaptations to this perturbation. We used a marine ecosystem model for the Northeast US continental shelf to address direct and indirect effects of species responses to ocean acidification. Focusing on upper trophic level groups that are primary targets of fishing activity, we projected changes for systemic ecological and fisheries indicators. We modeled effects of ocean acidification as either fixed changes in mortality rate or production for select species groups over twenty years. Biomass and fishery yield of species groups that were modeled to have direct acidification impacts and groups that were not directly impacted both declined, due to both increased mortality/decreased growth and a decrease in availability of food for groups that prey on shelled invertebrates. Our analyses show that food web consequences of ocean acidification can extend beyond groups thought most vulnerable, and to fishery yield and ecosystem structure. However, the magnitude and precise nature of ocean acidification effects depend on understanding likely species' responses to decrease in pH. While predicting the effects of ocean acidification is difficult, the potential impacts on ecosystem structure and function need to be evaluated now to provide scientists and managers preliminary assessments for planning and priority setting. Scenario analysis using simulation models like ours provides a framework for testing hypotheses about ecosystem consequences of acidification, and for integrating results of experiments and monitoring.

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1. Introduction

Ocean acidification is the decreasing pH of ocean waters as a result of increasing concentration of dissolved CO_2 (Doney et al., 2009). Increase in ocean CO_2 is a direct result of the increase in atmospheric CO_2 owing to the burning of fossil fuels and other anthropogenic activities (Caldeira and Wickett, 2003; Doney et al., 2009) and is one aspect of climate change in marine systems (Hoegh-Guldberg and Bruno, 2010; Doney et al., 2012). Increasing dissolved CO_2 and decreasing pH are two related changes to ocean carbonate chemistry (Doney et al., 2009, 2012). Declines in pH over the past several decades have been documented in open ocean waters and on continental shelves providing observational evidence for ocean acidification (Bates and Peters, 2007; Feely et al., 2009). These declines in pH are expected to continue into the future as atmospheric CO_2 concentrations continue to rise (Caldeira and Wickett, 2003; Doney et al., 2009). Effective conservation and management of living marine resources under changes to ocean carbonate chemistry requires an understanding of how biological responses to ocean acidification (hereafter acidification) translate to impacts on ecosystem structure and function.

Societal impacts from acidification are likely to be high because many ecosystem services (such as food production from fisheries) depend on species thought vulnerable to acidification (Cooley and Doney, 2009). For example, in the Northeast US, calcifying marine organisms form the basis of valuable commercial fisheries and are also integral parts of the marine ecosystem (NMFS, 2014). Single-species modeling suggests declines in yield from the Atlantic sea scallop (*Placopecten magellanicus*) fishery resulting from ocean acidification (Cooley et al., 2015). Further, vulnerability assessments identify ocean acidification as one of the major climate related risks in marine ecosystems (Mathis et al., 2015; Hare et al.,

* Corresponding author.
E-mail address: Jason.link@noaa.gov (J.S. Link).
[1] Present address: Department of Fisheries Oceanography, School for Marine Science & Technology, University of Massachusetts Dartmouth, Fairhaven, MA 02719, USA.

http://dx.doi.org/10.1016/j.ecolmodel.2016.12.016
0304-3800/Published by Elsevier B.V.

2016). The mechanisms for the effects of ocean acidification on living marine organisms are diverse and the effects on life history parameters variable (*e.g.* Fabry et al., 2008; Kroeker et al., 2013, Busch and McElhany, 2016). Overall, calcifying algae, corals, and mollusks are negatively affected (*e.g.*, calcification impacted), while macro-algae and diatoms are positively affected (*e.g.*, photosynthesis enhanced). Certainly there are nuances to the effects of acidification, in terms of taxa impacted, the magnitude of response, and the degree of extrapolation across pH levels from the laboratory to the field and modeled responses (Kroeker et al., 2013; Busch and McElhany, 2016). Species-specific studies reinforce a range of responses across species (Ries et al., 2009) but in general, information is lacking for many exploited fish and shellfish species. Information on the effects of ocean acidification in the context of other pressures on marine ecosystems (including human pressures such as fishing) is also necessary to understand food web and ecosystem consequences of acidification on ecosystem productivity structure, and function.

Ecosystem models can be used to evaluate the likely system-level consequences of acidification effects and show tradeoffs among ecosystem components associated with other system drivers. The value of such integrated models is that the diffuse, indirect, cumulative, and second order effects can be detected that are often missed in more narrowly, singly focused taxa- or process-specific models. Modeling approaches provide tools to integrate the direct effects of a stressor such as acidification–which acts at physiological and ecological scales–to population and ecosystem responses (Le Quesne and Pinnegar, 2012). Fisheries and ecosystem modeling approaches that have included ocean acidification certainly have had both single-species and ecosystem focus. A coupled bioeconomic and population dynamics model was developed for red king crab (*Paralithodes camtschaticus*) that included the effects of acidification on pre-recruit survival. Expected yields and profits were projected to decline over the next 50 years due to decreasing ocean pH levels over time, but the impacts over the next 10–20 years were projected to be less and likely masked by other factors (Punt et al., 2014). Ecosystem models also have been used in the North Pacific to assess the effects of acidification on food webs at a range of spatial scales (Kaplan et al., 2010; Ainsworth et al., 2011; Busch et al., 2013). In Australia, the effects of ocean acidification were included in end-to-end models to evaluate the effects of ocean acidification along with ocean warming and fishing (Griffith et al., 2011, 2012), and other human and environmental stressors (Fulton, 2011). In the Northwest Atlantic, ocean acidification has been included in food web models for the Scotian Shelf (Guénette et al., 2014). While not explicitly exploring multispecies interactions, Cheung et al. (2011) demonstrated ecosystem effects of acidification on catch potential in the Northeast Atlantic. Although the complexity of responses to ocean acidification have typically been relatively simply represented in these approaches (but see Fulton, 2011; for an exception), food web and ecosystem modeling are appropriate tools to integrate information to assess the effects of acidification across a broad range of factors.

In this paper, we use an ecosystem model for the Northeast US continental shelf large marine ecosystem to address direct and indirect effects of species responses to ocean acidification. Acidification has already been documented to be a notable risk for factor several species of commercial and ecological importance in this ecosystem (Hare et al., 2016). Our goal was to use an extant, available model to explore hypotheses relating to the effects of acidification. We focus on the impacts to population/species group biomass and fisheries yields. We model the effects of ocean acidification by performing simulations that bracket plausible ranges of fixed increases in mortality or changes in production for selected species groups, primarily shelled benthic invertebrates and plankton. Certainly other processes or factors could be explored, but these seem to be some of the more dominant pathways of acidification effects (Busch and McElhany, 2016). We focus our analysis of results on the responses of upper trophic level groups that are the primary targets of fishing activity in the region, and associated changes in systemic ecological and fisheries indicators (Link, 2005; Shin et al., 2010; Large et al., 2013).

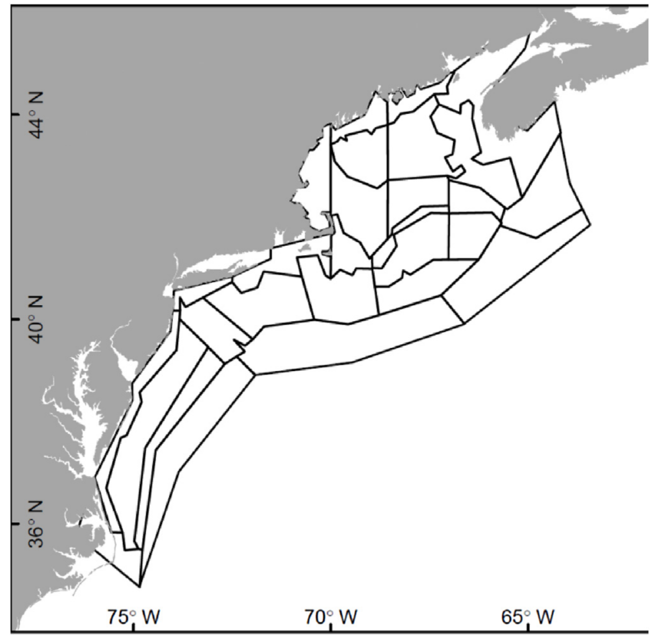

Fig. 1. Map of the Atlantis-NEUS model showing spatial domain and resolution. Each modeled area (box) divides the water column into up to four depth layers (0–50 m, 50–120 m, 120–300 m, and 300+ m), along with a epibenthic layer and a sediment layer.

2. Materials and methods

We applied the Atlantis model to the Northeast US large marine ecosystem using a set of model scenarios that included alternative hypotheses for the effects of ocean acidification on select species groups. We compared the results of simulations using this model to those obtained from a baseline when the effects of ocean acidification were not included. To demonstrate the approach, we used a simple fisheries management scenario whereby the fishing effort over the length of the simulations was fixed.

2.1. Atlantis model description

Atlantis (*e.g.* Fulton et al., 2011) is a deterministic, spatially explicit box model that links the output from a physical hydrodynamic model to a biophysical model of the food web to economic models describing human uses. Atlantis is suitable for conducting ecosystem-level management strategy evaluation, and has been used to rank alternative policy scenarios and quantitatively evaluate fisheries and ecosystem management strategies (*e.g.* Kaplan et al., 2010, 2012; Fulton et al., 2011, 2014). The Atlantis Northeast US model (Atlantis-NEUS; Link et al., 2010, 2011a) covers the area from Cape Hatteras to the Gulf of Maine, containing 22 dynamic spatial boxes stratified by depth (Fig. 1). The model uses output from the Hybrid Coordinate Ocean Model (HYCOM; http://www.hycom.org/) model to define transport and flows, and also to define water column properties (temperature and salinity). The ecological model comprises a food web of 45 functional groups, including phytoplankton and zooplankton, invertebrates, fish, and threatened and protected species such as marine mammals and seabirds.