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Accounting for multiple stressors influencing living marine resources in a complex estuarine ecosystem using an Atlantis model

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ABSTRACT

Many external stressors influence marine and coastal ecosystems. Understanding effects of these stressors is important for managers concerned with living marine resources (LMR). Historically, analytical methods for understanding these effects have been limited to a relative few stressors being modelled. Recent work has shown that multiple stressors may commonly have non-additive or cumulative effects, so accounting for the interactions of such stressors on LMR populations may be important. Coastal and marine ecosystems, which are often important for early life stages of many LMR populations, have a wide variety of stressors, yet analytical approaches accounting for the dynamics of multiple stressors have been used infrequently in these types of systems. For this work, we simulate the effects of individual and multiple stressors on a complex estuarine system, the Chesapeake Bay (USA), to demonstrate the range of conclusions about the effects of stressors on LMR populations that might be reached if stressors are considered singly versus in combination. Temperature increase has the greatest effect on productivity in our simulations, and appears to be the dominant stressor currently affecting this system. Consequently, we suggest it may be important for future work focusing on the effects of other factors to also consider the effects of expected temperature increase in this system, or important non-additive trends could be missed. With recent improvements in processing speed, full system models like Atlantis have become effective tools to provide resource managers with the information regarding non-additive effects of multiple stressors that they need for sound decision making.

1. Introduction

Many external factors may influence the trends in abundance and distribution of organisms in coastal and marine ecosystems. Resource managers, charged with decision-making to ensure sustainable use of living marine resources (LMR), need to understand the influence of their actions on marine ecosystems and populations in the context of a changing environment. The need to consider the interaction of multiple stressors (e.g., ongoing habitat loss and modification, changing climate, fishing pressure on multiple stocks) on ecosystems is at the core of an Ecosystem Approach to Fisheries Management (EAFM; Garcia et al., 2003), and more broadly, Ecosystem Based Management (EBM). Crain et al. (2008) identify the urgency of accounting for stressor interactions for conservation planning, but it remains a challenge for ecologists to understand how non-additive effects scale up to natural communities and ecosystems (Darling and Côté, 2008). Resource managers usually rely on statistical analysis and mathematical models to assess population status and trends and to project future status and trends, one population at a time, at times without consideration of environmental effects. However, we contend that full-system ecosystem approaches like Atlantis need wider application if EAFM is to be implemented effectively, since such an approach allows individual population dynamics to be estimated in the context of their environment.

Analytical tools used for population assessments of LMR were historically limited to accounting for one or a few external factors. Recent work, however suggests that population trend estimates made in the context of a single environmental factor or fishing alone may provide misleading information in a complex ecosystem (Kaplan et al., 2010; Maunder et al., 2006; Nye et al., 2013). In one example, effects of climate change on harvested populations in the northwest Atlantic Ocean show synergistic effects when workers account for temperature change and harvest of top predators

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together (Nye et al., 2013). Moreover, in reviews of hundreds of laboratory experiments, Crain et al. (2008) and Darling and Cote (2008) suggest that the non-additivity of stressor effects is the norm rather than the exception in such experiments. If this is the case in ecosystems as well, distinctly non-linear (Sugihara et al., 2012) and non-intuitive effects of multiple stressors should be expected, rather than linear and intuitive effects. Vasslides et al. (2016) suggest that such an approach is especially important in a complex, estuarine system.

Much of the recent work has been focused in marine ecosystems where fishing is usually a primary driver influencing populations (Fu et al., 2012). However, in coastal and estuarine systems other human impacts besides fishing may be major drivers of LMR populations. A US Environmental Protection Agency Report (2006) assessed 28 estuaries in the United States and identified excessive nutrients, habitat loss, and alteration of freshwater flows as major factors influencing coastal ecosystems. Estuaries are important for the early life history stages of many LMR populations (Beck et al., 2001). It is important for managers to have tools that allow for the synergistic, antagonistic, or additive interactions among stressors to be accounted for when considering future LMR population status. In addition, tools that improve understanding of how management actions might drive unanticipated changes are necessary.

One of the goals of this work was to determine if multiple system stressors, when modelled singly, would predict the same effects as when they are modelled together. We focus on the Chesapeake Bay as a case study as it is a complex system with a diverse array of external factors influencing LMR populations, and because an Atlantis model for the Chesapeake has already been developed (Ihde et al., 2016). The Atlantis software is a tool that readily enables a user to model external drivers of an ecosystem, while also capturing the essential dynamics of the interacting populations in space and over time.

1.1. System description

The Chesapeake Bay is complex in its physical, chemical, and ecological dynamics. The Chesapeake is the largest estuary in the U.S. It is shallow (averaging only 7 m), but its physical environment is highly variable, and system behavior is complicated by the flow of eight major tributaries and Atlantic Ocean input through a wide, southern mouth. The system receives nutrient and sediment inputs from six states and major metropolitan areas that include: Norfolk, Richmond, and Charlottesville, VA; Washington, DC; Harrisburg, PA; Baltimore, MD; and Cooperstown, NY. There is a growing population of more than 17 million people, as well as a relatively large agricultural sector in its extensive (165,760 km^2) watershed, all of which contribute to exceptionally high nutrient loads to the system (Ihde et al., 2016). Chesapeake Bay waters are highly temperate and lows reach around 1 °C (Murdy et al., 1997), whereas the high in 2016 (Solomons Island, MD) was 31 °C. The system is trophically complex as well, where predators are attracted to a wealth of forage, and forage find refuge in its shallow, habitat-rich waters. Though historically-important oyster reefs no longer exist in most areas of the system, submerged aquatic vegetation (SAV), and emergent marsh habitats still provide refuge for many prey species.

1.2. System stressors

Living marine resource populations in the Chesapeake Bay are subject to many external stressors. Excessive nutrients and sediment from runoff, sewage treatment, human development, and atmospheric deposition degrade habitats in the bay (e.g., Kemp et al., 2005). SAV and emergent marsh grasses provide diverse habitat in many portions of the bay, but the loss of SAV and other structural habitat over the decades has potentially had a major effect LMR populations in the bay (Chesapeake Bay Program, 2004). On the other hand, some levels of increased nutrients may have had a positive effect on production of pelagic fish production (Breitburg et al., 2009). For the last three decades, efforts have been made to improve water quality and reduce SAV losses, with limited success. More recently, however, a Presidential Executive Order (Executive Order 13508, 2009) empowered the US EPA to enforce the implementation of nutrient and sediment management throughout the Chesapeake watershed. Consequently, the water column habitat is changing in the system as well. The nutrient and sediment pollution limits for each jurisdiction in the watershed is known as the Total Maximum Daily Load (TMDL) requirement.

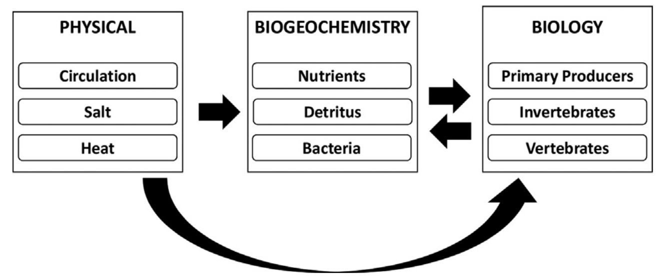

Fig. 1. The Atlantis Model uses output from a circulation model to provide physical forcing of circulation and transfer of heat and salt across model boxes. The physical forcing influences the biogeochemistry module as well as the biological module (based on preferences of biological groups). The biogeochemistry module simulates nutrient cycles (C, N, O, Si) which makes nutrients available for primary producers. The biology module simulates food web and habitat interactions.

In addition to these regional stressors, global stressors (i.e., climate change-associated sea level change and temperature change), are also likely to influence the bay's LMR populations. Sea-level rise is projected to result in a considerable loss of marsh habitat that is important as both food and refuge for LMR populations. Increasing water temperature is likely to influence LMR populations in both direct and indirect ways. Water temperature affects all trophic levels, with impacts ranging from basal metabolic rate (increases) to primary production effects (Nye et al., 2013).

We modelled the effect of each of these system stressors (i.e., temperature increase, habitat loss, and expected water quality change) both separately and in combination, in order to identify any potential cumulative effects of the changes expected in this system, and to determine which, if any of these stressors dominate the predicted dynamics of the Chesapeake Bay. This type of analysis is important for resource managers to understanding the effects of external stressors individually and as a whole. Multiple stressors have been shown to produce variable or even different effects (Crain et al., 2008; Darling and Cote 2008; Kaplan et al., 2010) when acting in combination compared to acting singly. Thus, consideration of cumulative effects can be crucial. Identification of dominant stressors can also be essential to identify what factors must be considered in future work, and to help set research priorities in an environment of increasingly limited funding.

2. Material and methods

2.1. The chesapeake atlantis model

The Atlantis ecosystem approach (Fulton et al., 2011; Fulton et al., 2004) was applied to model the Chesapeake Bay ecosystem in the context of its major physical, chemical, and ecological factors. Atlantis is a whole-ecosystem model that integrates a wide variety of information, including the physical (circulation of water, salt, and heat), the biogeochemical (nutrient input, detritus, and bacterial dynamics), and a full suite of biological characteristics (primary