ARTICLE IN PRESS

Ecosystem Services xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Ecosystem Services

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

Diet composition uncertainty determines impacts on fisheries following an oil spill

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ARTICLE INFO

Article history:
Received 28 September 2017
Received in revised form 24 April 2018
Accepted 7 May 2018
Available online xxxx

Keywords:
Oil hydrocarbons
Food web
Uncertainty analysis
Gulf of Mexico
Atlantis ecosystem model

ABSTRACT

Oil spills can disrupt marine and coastal ecosystem services leading to reduced employment opportunities and income. Ecosystem models can be used to estimate the effects of oil pollution; however, uncertainty in model predictions may influence damage assessment. We performed an uncertainty analysis for the Atlantis ecosystem model of the Gulf of Mexico (Atlantis-GOM), under a scenario simulating the effects of the *Deepwater Horizon* oil spill. Atlantis-GOM simulates major biophysical processes, including the effects of oil hydrocarbons on fish growth and mortality. We used all available fish stomach content data to inform parameter distribution for the Atlantis-GOM availability matrix, which represents predator total consumption potential and diet preference. We sampled the fish diet composition distribution and analyzed the variability of functional group biomass and catch predicted by Atlantis-GOM simulations to changes in the availability matrix. Resulting biomass and catch were then used to fit statistical emulators of the ecosystem model and predict biomass and catch given the complete diet parameter space. We used simulated and emulated data to assess changes in recovery time to oil spill effects. Uncertainty in diet composition had large effects on model outputs and may, therefore, influence damage assessment of oil exposure on economically important species.

1. Introduction

Human survival and well-being depend on marine and coastal ecosystem services (Costanza et al., 1997); and thus are also dependent on management and conservation of the ecosystems that provide these services (Liquete et al., 2013). Marine and coastal systems provide a variety of ecosystem services including provisioning (e.g., fisheries), regulation and maintenance (e.g., coastal storm and flood protection), support (e.g., primary production), and cultural services (Millenium Ecosystem Assessment, 2006; Liquete et al., 2013). Importantly, fisheries provide some of the most important and lucrative ecosystem services through the production of seafood. Human-related stressors threaten food provisioning; oil spills, in particular, can cause catastrophic damages because they are unpredictable in space and time and the people and equipment necessary to minimize their negative impacts might not be readily available (Silliman et al., 2012). Accidental oil spills have caused extensive economic impacts to fisheries through massive fish and invertebrate die-offs, fishery closures, or decreased consumer confidence in seafood quality or safety (Committee on the Effects of the Deepwater Horizon Mississippi Canyon-252 Oil Spill on Ecosystem Services in the Gulf of Mexico et al., 2014). As offshore, deep-water oil exploration expands, large oil spills are likely to occur in the future and lead to long-lasting and unexpected ecosystem-level effects (Pettingill and Weimer, 2002).

Furthermore, the exposure of marine organisms to oil may lead to sublethal effects such as carcinogenicity, mutagenicity, cellular damage, endocrine disruption, and reduced survival (Larsen et al., 2016). These effects may all occur even at very low oil concentrations (Nahrgang et al., 2016). Oil-derived compounds may penetrate the marine food web when organisms ingest oil droplets or oil-coated food, or when oil contacts respiratory surfaces (Farrington et al., 2016). However, analyses of stable isotope ratios,

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https://doi.org/10.1016/j.ecoser.2018.05.002

which represent time-integrated information on consumers' diet, have found that oil assimilation in animal tissues was limited in areas affected by oil spills (Han et al., 2015). Nonetheless, oil exposure may lead to structural food web shifts, favoring species that can readily metabolize hydrocarbons (Passow and Hetland, 2016), and hydrocarbons might slow the growth of marine animals, increase their mortality rates, and propagate toxicity effects across the food web (Perhar and Arhonditsis, 2014). The indirect food web effects of oil exposure, determined by resource availability (Passow and Hetland, 2016), may lead to disturbances at higher-trophic levels and to trophic cascades, where predators reduce prey abundance, which then releases the prey's food from control (Peterson et al., 2003).

End-to-end ecosystem models that can simulate direct mortality events, bioaccumulation of oil-related contaminants, and the indirect effects of oil pollution on ecosystem components via ecological interactions can be used to understand the long-term effects of oil pollution on ecosystem structure (De Laender et al., 2011). A variety of existing ecosystem modeling platforms combine physicochemical and oceanographic processes with trophic interactions and, therefore, have the ability to simulate the effects of natural and human-related stressors (see Plagányi, 2007, O'Farrell et al., 2017 for a review). However, ecosystem models are fraught with uncertainty, including parameter uncertainty (Link et al., 2012); these models require hundreds to thousands of parameters which, in most cases, cannot be measured exactly or are unknown (Grüss et al., 2016). Consequently, any decisions or management actions taken based on ecosystem model predictions will be highly uncertain and be accompanied by associated tradeoffs. It is therefore important to understand and quantify the sources of uncertainty in ecosystem model predictions, including how uncertainty in model outputs relates to uncertainty in model inputs (Saltelli et al., 2008), such that the conclusions drawn from ecosystem model predictions are robust and transparent (Urrego-Blanco et al., 2016). Uncertainty analysis can be used to determine the variability (prediction imprecision) in the outcome variable that is due to the uncertainty in estimating the values of the input parameters (Iman and Helton, 1988); while a sensitivity analysis extends the uncertainty analysis by identifying which input parameters are important in altering the value of the outcome variable (Blower and Dowlatabadi, 1994). End-to-end ecosystem models are generally highly complex and use large volumes of simulation data such that it is rarely feasible to conduct detailed uncertainty or sensitivity analyses for them (Allen and Fulton, 2010; but see Köhler and Wirtz, 2002; Niiranen et al., 2012; Lassalle et al., 2014; Morris et al., 2014; Mateus and Franz, 2015). However, statistical emulation can be used to model the input-output relationships of an ecosystem model in a computationally-efficient manner; this technique creates a surrogate ecosystem model which acts as a fast approximation of the original model and can be employed to explore parameter uncertainty (Mattern et al., 2013).

In the present study, we apply an uncertainty analysis to examine how uncertainty in diet composition of an end-to-end ecosystem model affects determination of oil spill impacts on food provisioning ecosystem services in the Gulf of Mexico, a Large Marine Ecosystem bordered by the U.S., Mexico and Cuba, using fisheries catch and recovery time of target fish biomass as indicators. We employed the Gulf of Mexico Atlantis ecosystem model (Atlantis-GOM), which is an application of the Atlantis modeling platform. Atlantis is a sophisticated, three-dimensional deterministic modeling platform which simulates oceanography, ecology, fisheries dynamics, human impacts, and resource management (Fulton et al., 2004a; Fulton et al., 2011). Atlantis outputs can be used to derive ecosystem indicators, quantitative measures that can be used to analyze the response of ecosystem services to simulated perturbations in a similar way as indicators in a real system (Smith et al., 2015; Reed et al., 2017). Because Atlantis is a deterministic model, the outputs are completely determined by the input parameters and structure of the model; the only uncertainty affecting the outputs is generated by input variation (Marino et al., 2008). The Atlantis-GOM model was primarily designed to assess the food web impacts of the *Deepwater Horizon* oil spill (Ainsworth et al., 2015), which, in 2010, released an estimated 4.9 million barrels of crude oil (±10%) from the base of the continental shelf in the Northern Gulf of Mexico (Murawski et al., 2016). Atlantis-GOM represents the state of the Gulf of Mexico in 2010 ('baseline conditions') and can simulate the direct effects of oil spills and their indirect effects via trophic interactions to ultimately determine the impact on ecological communities and ecosystem services decades after the spill (Coleman et al., 2014).

2. Methods

We evaluated the uncertainty in assessing the impacts of oil hydrocarbons predicted by Atlantis-GOM to the assumed food web structure. We incorporated new fish stomach content data to the Atlantis-GOM diet matrix, notably data originating from the northern and western Gulf of Mexico (Simons et al., 2013). We used this data to obtain robust diet composition estimates and associated errors for the Atlantis-GOM by bootstrapping aggregate fish diets from stomach sampling and online sources, and feeding the resulting data into a statistical model. We then employed the distribution of diet compositions and associated errors predicted by the statistical model to bound uncertainty in the Atlantis-GOM availability matrix. Previously, Ainsworth et al. (2018) explored the impacts of direct oil exposure on fish growth and mortality, the impacts of ichthyoplankton contamination on recruitment success, and the impacts of fishery closures on the GOM food web. We apply their worst-case scenario of direct oil exposure on fish growth and mortality to estimate how the effects of the oil spill on exploited species biomass, ecosystem indicators, and fisheries are influenced by diet composition uncertainty. We then employed statistical emulators that are less computationally demanding than the Atlantis model itself to examine the complete distribution of availability parameter estimates. Finally, we examine fish catch and recovery time of target fish biomass using simulated and emulated outputs.

Each of the abovementioned stages is described in detail below. All analyses were carried out in the R statistical framework (R Core Team, 2017); the packages used are described in Table S1. We employed virtual machines running on the Microsoft Azure cloud computing platform (Standard F16 series, 16 cores, 32GB memory) using Ubuntu 16.04; we ran parallel simulations using a total of 15 machines (for a total of 240 cores). The specifications to customize the virtual machines for Atlantis-GOM simulations and the R code used to generate the simulations and the statistical emulators, analyze data, and generate figures is freely available in GitHub https://github.com/hmorzaria/atlantis_gom_oil. The biomass and fish catch outputs from the Atlantis-GOM model simulations can be utilized to replicate our figures and are available from the Gulf of Mexico Research Initiative Information & Data Cooperative (GRIIDC) repository at https://data.gulfresearchinitiative.org/data/R6.x805.000:0002 [DOI: https://doi.org//10.7266/N71G0JSG]

2.1. The Atlantis modeling platform and the Atlantis-GOM model

Atlantis is an end-to-end ecosystem modeling approach that represents all trophic levels from bacteria to apex predators and humans. Atlantis process equations can be found in Fulton (2001), Fulton et al. (2004a,b); further information can be found