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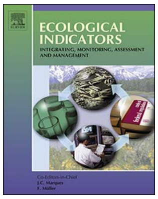

Original Articles

Hierarchical modeling assessment of the influence of watershed stressors on fish and invertebrate species in Gulf of Mexico estuaries

Jonathan Miller[a,*], Peter C. Esselman[b], Ibrahim Alameddine[c], Kristan Blackhart[d], Daniel R. Obenour[a]

[a] North Carolina State University, 208 Mann Hall, Raleigh, NC 27695, United States
[b] US Geological Survey, Great Lakes Science Center, 1451 Green Road, Ann Arbor, MI 48105, United States
[c] American University of Beirut, Bliss Street, PO Box 11-0236, Beirut, Lebanon
[d] ECS Federal, Inc. in support of National Marine Fisheries Service, 2725 Montlake Blvd East, Seattle, WA 98112, United States

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ABSTRACT

The northern Gulf of Mexico (GoM) spans five U.S. states and encompasses estuaries that vary greatly in size, shape, upstream river input, eutrophication status, and biotic communities. Given the variability among these estuaries, assessing their biological condition relative to anthropogenic stressors is challenging, but important to regional fisheries management and habitat conservation initiatives. Here, a hierarchical generalized linear modeling approach was developed to predict species presence in bottom trawl samples, using data from 33 estuaries over a nineteen-year study period. This is the first GoM estuary assessment to leverage Gulf-wide trawl data to develop species-level indicators and a quantitative index of estuary disturbance. After controlling for sources of variability at the sampling event, estuary, state, and sampling program levels, our approach screened for statistically significant relationships between watershed-level anthropogenic stressors and fish and invertebrate species presence. Modeling results indicate species level indicators with sensitivities to landscape stressor gradients. The most influential stressors include total anthropogenic land use, crop land use, and the number of toxic release sites in upstream watersheds, as well as agriculture in the shoreline buffer, each of which was significantly related to between 21% and 39% of the 57 species studied. Averaging the effects of these influential stressors across species, we develop a quantitative estuary stress index that can be compared against benchmark conditions. In general, disturbance levels were greatest in estuaries west of the Mississippi delta and in highly developed estuaries in southwest Florida. Estuaries from the Florida panhandle to the eastern Mississippi delta had less anthropogenic stress.

1. Introduction

Fishing is central to the social and economic well-being of the northern Gulf of Mexico (GoM) region of the United States (U.S.), making sustainable management of fisheries a regional priority. The seafood industry in the Gulf States of Florida, Alabama, Mississippi, Louisiana, and Texas (FL, AL, MS, LA, TX) contributed $7.9B to the 2012 U.S. Gross Domestic Product (GDP) and provided 160,000 jobs to coastal residents (NMFS, 2014), while recreational fisheries provided an additional $7.8B to the regional GDP in 2012 as a result of the activities of 3.1 M anglers (NMFS, 2014). Some of the most valuable species in both the commercial and recreational fisheries, including shrimps (Family: Penaeidae), Gulf Menhaden (*Brevoortia patronus*), and Spotted Seatrout (*Cynoscion nebulosus*), have strong affiliations to estuary habitats for a portion of their life cycles. The estuaries of the GoM are subject to disturbance from a wide range of anthropogenic activities, potentially putting commercial and recreational fisheries at risk. Understanding the spatial patterns and causes of degradation to estuary fisheries and fish habitats are important to the conservation of these economic, recreational, and ecological resources.

Environmental degradation in some areas of the GoM is already advanced due to anthropogenic disturbances that include hydrologic alteration, eutrophication, toxic pollution, and overfishing (NRC, 2000; Rabalais et al., 2002; Yáñez-Arancibia and Day, 2004, Howarth and Marino, 2006). Altered patterns of freshwater inflow to GoM estuaries have resulted from upstream damming, river channelization, and water abstraction (Harwell, 1997; Flannery et al., 2002), which have led to changed salinity regimes, reduced dilution of estuary pollutants, and

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* Corresponding author.
E-mail addresses: jwmille7@ncsu.edu (J. Miller), pesselman@usgs.gov (P.C. Esselman), ia04@aub.edu.lb (I. Alameddine), kristan.blackhart@noaa.gov (K. Blackhart), drobenour@ncsu.edu (D.R. Obenour).

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land subsidence (Day et al., 2000). Excessive runoff of nitrogen and phosphorus from fertilizers and urban activities in catchments has caused eutrophication, and in severe cases, low dissolved oxygen and fish kills (Rabalais et al., 2002; Diaz and Rosenberg, 2008; 2011). Toxic chemicals associated with industry, urban development, and agriculture are strongly concentrated in some areas and have been shown to negatively affect benthic organisms in the GoM (Brown et al., 2000). Some of these toxic releases originate from the petroleum industry, which is especially concentrated in coastal areas of LA and eastern TX (Adams et al., 2004). Estuarine fish and invertebrate species integrate habitat conditions differently over both time and space and can be helpful as biological indicators of larger trends in ecosystem degradation (e.g., Macauley et al., 1999).

A central challenge in biological assessment is to distinguish the responses of species to anthropogenic stress from the high levels of natural background variation common to ecological systems (Hawkins et al., 2010). This challenge is particularly acute in GoM estuaries where the daily and seasonal variability in temperature, salinity, and dissolved oxygen leads to annual variation in biological community composition and structure (Peterson and Ross, 1991; Akin et al., 2003; Baltz et al., 1993; Gelwick et al., 2001; Granados-Dieseldorff and Baltz, 2008). While high natural environmental variability can be stressful to many species, anthropogenic stress to estuaries has been shown to result in dominance by opportunistic habitat or trophic generalists, to the detriment of rare or specialized taxa (Felley, 1987; Chesney and Baltz, 2001; Lewis et al., 2011). Such findings suggest that some species may be particularly sensitive to human impacts, including even estuarine species adapted to high degrees of natural environmental variation. Many estuarine studies conducted to date have focused on responses by groups of species with similar life history or functional characteristics (i.e. community metrics; Macauley et al., 1999; Summers, 2001; Hughes et al., 2002; Meng et al., 2002; Jordan et al., 2010; Cabral et al., 2012). However, evidence from freshwater systems suggests that community metrics may obscure biological responses to stressor gradients that can be detected in species-specific indicators (Baker and King, 2010; King and Baker, 2010). Further, individual species indicators may also allow for more direct linkages to management by focusing on populations of economically valuable taxa or taxa with high conservation value.

Multiple approaches have been used to account for natural background variation in biological assessment. One approach is to define different biological indicators within discrete salinity zones (Coates et al., 2007; Breine et al., 2010; Cabral et al., 2012) or different types of estuaries (Harrison and Whitfield, 2006). Another approach is to screen for indicators that are sensitive to anthropogenic stress, but insensitive to natural gradients (Jordan et al., 2010). Moreover, models can be developed and used to account for the effects of natural variables before testing for indicator sensitivity (Engle et al., 1994). Multivariable models (e.g. multiple linear regression) have proven useful for predicting species or community responses to both natural and anthropogenic gradients (Lewis et al., 2007; Courrat et al., 2009; Delpech et al., 2010). By controlling for natural variation with model coefficients, biological responses to one or multiple ecological stressors can be predicted at different stressor levels which can be particularly helpful for judging whether current conditions differ from a benchmark or reference condition (Hawkins et al., 2010). Without benchmarks, little context exists for interpreting the measured value of an ecological resource, which can vary substantially with natural differences among sites.

Efforts to classify the ecological status of estuaries have occurred globally over the past two decades. In the U.S., studies have focused on characterizing estuaries based on their water quality, susceptibility to pollution based on geomorphologic and flow conditions, and watershed stressors such as land cover and point sources of pollution (Bricker et al., 2008; Greene et al., 2015). Some studies have classified U.S. estuaries based on their fish populations (Gleason et al., 2011; Hughes et al., 2014), but only a few nekton species in limited regions have been modeled to connect fish presence to estuary anthropogenic stress (Toft et al., 2015). In Europe, regional and country specific multi-metric indices have been developed based on biological communities to calculate overall ecological health (Breine et al., 2007; Coates et al., 2007; Delpech et al., 2010; Cabral et al., 2012; Harrison and Kelly, 2013), but limited progress has been made toward showing strong relationships between these indices and anthropogenic stressors (Pasquaud et al., 2013). Such analyses have been complicated by the additional effort required to "intercalibrate" the results from different studies in order to make intra-continental comparisons. In particular, setting regional benchmark conditions and comparing studies with different sampling protocols or metrics is an ongoing challenge not easily resolved (Poikane et al., 2014). Though much progress has been made in sampling and quantifying estuary ecological status, further efforts and techniques are needed to model species and biological communities across varying natural settings, link biological conditions to watershed stressors, and set benchmark conditions.

Hierarchical (or 'multi-level') modeling provides a potential methodology for linking watershed stressors and estuary biological condition, accounting for discrepancies among sampling programs and natural variability among estuaries. Hierarchical modeling accounts for variability among different groups of data at different spatial or organizational levels using regression coefficients (i.e., 'random effects') that vary by group as members of a common statistical hyperdistribution (Gelman and Hill, 2006). This extension of classical regression modeling accounts for intra-class correlation among data from common groups (i.e., estuaries, states, trawl programs), allowing for statistically valid hypothesis testing of group-level predictor variables (Gelman et al., 2014). Thus, for grouped data, hierarchical modeling is often an improvement over classical regression modeling in terms of both predictive performance and causal inference (Wikle, 2003a; Cressie et al., 2009; Qian et al., 2010), and these models have been used extensively to study environmental and ecological systems (Wikle et al., 1998; Wikle, 2003b; Clark and Gelfand, 2006; Bolker et al., 2009; Kashuba et al., 2010; Cuffney et al., 2011). In this study, hierarchical modeling is instrumental in controlling for the variability of species presence across different estuaries, states, and monitoring programs.

The aim of the current study is to identify key sources of watershed stress (i.e., stressors) that are related to species presence in GoM estuaries, and to aggregate these relationships to assess the relative intensity of watershed stress in each estuary using hierarchical generalized linear modeling. This new approach to assessing the biological health of estuaries allows us to: (1) combine nearly 70,000 trawl samples collected by separate research efforts; (2) control for natural environmental variation while identifying statistically significant estuary-level stressors affecting the presence of fish and invertebrate species; and (3) create an estuary stress index that quantifies the amount of anthropogenic stress affecting GoM estuaries as compared to benchmark conditions in the region.

2. Methods

2.1. Study area

Our study spanned 33 estuaries across the five U.S. GoM states (Fig. 1). Estuary habitats were classified to include open water and wetland classes from the Coastal Change Analysis Program (C-CAP) dataset (NOAA, 2006) and the National Wetlands Inventory (NWI; USFWS, 2012). To summarize landscape influence on each estuary, it was necessary to define their spatial extents and tributary influences. The seaward extent of estuaries was limited to the 4-m depth contour based on an examination of plots of salinity-at-depth. The salinities at the defined seaward depth did not generally drop below 32 practical salinity units (psu). The landward extent of the estuaries was drawn to include open water areas as well as estuarine emergent wetlands from