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Spatially explicit assessment of estuarine fish after Deepwater Horizon oil spill: tradeoffs in complexity and parsimony

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Abstract

Evaluating long-term contaminant effects on wildlife populations depends on spatial information about habitat quality, heterogeneity in contaminant exposure, and sensitivities and distributions of species integrated into a systems modeling approach. Rarely is this information readily available, making it difficult to determine the applicability of realistic models to quantify

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population-level risks. To evaluate the trade-offs between data demands and increased specificity of spatially explicit models for population-level risk assessments, we developed a model for a standard toxicity test species, the sheepshead minnow (*Cyprinodon variegatus*) exposed to oil contamination following the Deepwater Horizon oil spill and compared the output with various levels of model complexity to a standard risk quotient approach. The model uses habitat and fish occupancy data collected over five sampling periods throughout 2008-2010 in Pensacola and Choctawhatchee Bays, Florida, to predict species distribution, field-collected and publically available data on oil distribution and concentration, and chronic toxicity data from laboratory assays applied to a matrix population model. The habitat suitability model established distribution of fish within Barataria Bay, Louisiana, and the population model projected the dynamics of the species in the study area over a five-year period (October 2009 – September 2014). Vital rates were modified according to estimated contaminant concentrations to simulate oil exposure effects. To evaluate the differences in levels of model complexity, simulations varied from temporally and spatially explicit, including seasonal variation and location-specific oiling, to simple interpretations of a risk quotient derived for the study area. The results of this study indicate that species distribution, as well as spatially and temporally variable contaminant concentrations, can provide a more ecologically relevant evaluation of species recovery from catastrophic environmental impacts but might not be cost-effective or efficient for rapid assessment needs.

Introduction

The estimated risk to a wildlife species from exposure to environmental contaminants can vary according to the temporal and spatial scales of available data and the scope of the

assessment (Maurer and Holt 1996, Landis 2003). Population models are a versatile tool amenable to exploring potential impacts from stressors in spatially and demographically specific context (Barnthouse et al. 2007). However, population-level risks are rarely assessed because the data requirements are prohibitive from a regulatory standpoint until guidelines and examples of best practices are established (Munns 2006, Forbes et al. 2009). Trade-offs between complexity and generality dictate a model's utility beyond the data from which it was developed (Bamford et al. 2009), and appropriately incorporating ecological effects into projections based on organismal-level response is crucial to meaningful model interpretation (Kramer et al. 2011, Kohler and Triebskorn 2013). For example, long-term impacts of sublethal contaminant effects might only be detected when population dynamics and habitat constraints are considered.

Alternatively, behavioral and ecosystem-level responses might compensate for minor reductions in populations over time. The utility of data-intensive, spatially-explicit population models requires an evaluation of uncertainty associated with measurement error and model predictions as well as intended management use (Van der Lee et al. 2006).

The Deepwater Horizon oil spill contaminated coastal and marine habitats within the Gulf of Mexico and prompted concerns about the long-term impacts on species throughout the area (Barron 2012, Cornwall 2015). Oiling from the spill was broad and heterogeneous in distribution, complicating ecological risk and damage assessments for species that interact to varying degrees with the different forms of oil contamination. Ongoing large-scale observation efforts qualitatively recorded coastal oiling after the spill, documenting oil severity along 1773 km of the Gulf of Mexico coastline, including the most impacted area of Barataria Bay, Louisiana (Michel et al. 2013). In spite of this effort and ongoing research, long-term effects of oiling on resident estuarine species are largely unknown (Cornwall 2015). Spatially explicit

population models provide a way of exploring potential scenarios that consider habitat availability, movement patterns, and seasonal variation in population dynamics while including ecological and behavioral processes that could have implications not observed at the organismal level (Fodrie et al. 2014). This data-intensive approach also permits evaluation of the most appropriate cost-benefit threshold of increased data demands for anticipating effects on wildlife populations.

Occupying a broad range of habitats, the sheepshead minnow (*Cyprinodon variegatus*) is a euryhaline, eurothermic fish commonly found in estuarine areas along the Atlantic coast and in the Gulf of Mexico (Haney 1999). It is most abundant in inner spartina marshes in low densities (Rozas and Zimmerman 2000) and vulnerable to oiling events because of their close association with near shore sediment, including burial behavior from larval through adult life stages (Bennett and Beitinger 1997, Chitty and Able 2004). It is also a model species for which a broad base of experimental toxicological data exists and for which population models have been developed based on laboratory observations and experiments (Raimondo et al. 2009). As such, models developed for sheepshead minnow habitat and population dynamics could be useful for a large and diverse geographical range and include stage-specific effects for various contaminants. Long-term simulations of these effects over the population's range can provide an ecologically relevant means of assessing risk within this species' natural environment.

Here we develop a spatially-explicit population model that incorporates four components: 1) habitat suitability, 2) contaminant distribution, 3) contaminant dose-response, and 4) a matrix population model. We use temporally and spatially variable estimates of contaminant concentration as input for dose-response curves of organism endpoints to modify vital rates within the population model in suitable estuarine habitat. The model is based on empirically

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determined effects of the contaminant, and includes movement and behavior relevant to the environment in order to compare different possible exposure scenarios and identify the costs of increasing data demands and benefits of reducing uncertainty with increased model complexity in assessment of population risk. The objectives of this study are to determine the utility of qualitative data to inform quantitative contaminant effects, to estimate long-term exposure effects on a population while including seasonal variability and spatial heterogeneity of a contaminant, and to evaluate different levels of complexity in assessing risk to an estuarine fish species.

Methods

Model Construct

Spatially explicit population models consisted of four basic parts: habitat suitability models determined likelihood of sheepshead minnow presence and movement patterns, monthly classifications of Shoreline Cleanup and Assessment Technique (SCAT) data categorized coastal oiling severity within Barataria Bay, population models included seasonally appropriate population dynamics based on temperature-specific vital rates, and dose-response curves determined through experimental exposures were used to adjust population parameters according to location-specific oil exposure effects. Barataria Bay, in southeastern Louisiana, was one of the areas most heavily impacted by the Deepwater Horizon spill, with the highest and most variable levels of coastal oiling throughout the bay, making it an opportune location to examine the effects of spatial heterogeneity in contaminant exposure. The area was divided into 65544 grid cells at a resolution of 90 m for simulations, based on spatial resolution of available habitat data (described below).

Habitat Suitability

The habitat suitability layer was developed based on data collected from sites selected within the Pensacola Bay, Santa Rosa Sound, and Choctawhatchee Bay classified as “Estuarine or Marine Wetland” by the National Wetland Inventory Project (<http://www.fws.gov/wetlands/>). We used these data to parameterize a habitat model for sheepshead minnow based on the variables available for Barataria Bay, rather than developing a site-specific model *de novo* following the spill. Using package “spsurvey” (Kincaid and Olson 2015) in R (R Core Team 2015), we identified 300 potential sample sites per season in Pensacola Bay (October 2008, February, April, and July 2009) and Choctawhatchee Bay (April 2010), using a Generalized Random-Tessellation Stratified (GRTS) design with a higher proportion of marsh sites than shoal sites based on *a priori* expectations of habitat suitability.

Fish presence or absence at each site was determined using drop traps to ensure lower variability in catch efficiency (Rozas and Minello 1997). At each site, a 1m² aluminum trap was deployed, and net sweeps collected any fauna within the trap until ten consecutive sweeps failed to retrieve fish. Preliminary recapture tests indicated that this technique resulted in capture of 96% (SD = 5.7%) of marked fish that had been released in the trap (Raimondo, unpublished data). All vertebrates and macroinvertebrates within the trap were identified and released, and all plants were identified. Sediment samples were collected at each site in October 2008, February, April, and July 2009, and April 2010 as a homogenization of surface sediment from three locations within the sampling site.

A generalized linear model with binomial distribution and logit link identified habitat characteristics associated with presence of sheepshead minnows. Variables included in

development of the static habitat suitability layer were those available as spatial layers for Barataria Bay during the time of our field sampling, December 2010. We randomly selected half of the data from Pensacola and Choctawhatchee Bays in all five seasons as a training dataset and used the remaining half as a testing dataset. We used R package “MuMIn” (Barton 2015) to compare a fully parameterized model to simpler models by Akaike’s Information Criteria (AIC) and package “PresenceAbsence” (Freeman and Moisen 2008) to evaluate predictions of species presence by means of a receiver operating curve demonstrating sensitivity and specificity of model predictions by the area under the curve.

Estuarine bathymetry data from NOAA’s National Ocean Service provided gridded depth information for Barataria Bay at 90 m resolution and established the spatial scale for subsequent modeling scenarios. Salinity and dissolved oxygen layers were interpolated from data that were collected in situ using ordinary kriging in R package “gstat” (Pebesma 2004). At each bathymetry gridpoint, salinity and dissolved oxygen values were spatially joined in ArcGIS v. 10.2 (ESRI 2014). Parameters of habitat models were used to predict relative habitat suitability at each point in Barataria Bay. Spatial data were manipulated using R packages “sp” (Pebesma and Bivand 2005) and “spatstat” (Baddeley and Turner 2005).

Oiled Site Categorization

Each gridpoint within Barataria Bay was assigned a category of oiling severity for each month of the simulation period based on the nearest SCAT observation recorded for that period. We used SCAT categories to define the concentration of the total of 57 parent polycyclic aromatic hydrocarbons (tPAH; Supplemental Information) at each site in two distinct ways. First we created five hypothetically discrete intervals of tPAH concentration within the range of

the maximum observed tPAH concentration reported for Barataria Bay sediment (355.74 mg/kg; Turner et al. 2014a). We evenly divided the five SCAT categories within the observed field range of tPAH and used the midpoint of each category as the tPAH concentration to estimate effects of reduced embryo survival and delayed maturity (no oil observed = 0 mg kg⁻¹, very light = 106.72 mg kg⁻¹, light = 177.87 mg kg⁻¹, moderate = 249.02 mg kg⁻¹, heavy = 320.17 mg kg⁻¹). The second quantification of tPAH for SCAT classifications of each location was determined by resampling empirical tPAH concentrations from sediment collected in Barataria Bay and coastal Louisiana following the spill. We collected sediment samples from 52 sites around Barataria Bay to estimate the range of petroleum hydrocarbon concentrations for each SCAT category. Sample sites were determined using a GRTS design to identify randomly distributed sites from each of the five categories of SCAT classifications (no oil observed, very light, light, moderate, heavy). Sediment samples were collected from each site using metal spoons, stored in Teflon sealed glass jars, and frozen at -20° C until compositional analysis, as described below. These data were augmented with tPAH concentrations detected in surficial sediment samples collected by NOAA and accessed via the Deepwater Horizon Information Management Portal (www.noaanrda.org; accessed 17 Feb 2015). We included only samples within a year of the spill for resampling, during which time we expected to have sufficient representation of SCAT categories as well as better concordance between visual representation of oil severity and tPAH concentration.

Sediment collected in Barataria Bay as part of the present study was analyzed for total petroleum hydrocarbons (TPH), tPAH, and alkyl homolog groups using gas chromatography and mass spectrometry with selected ion monitoring (GC/MS-SIM). Samples were also analyzed for a number of additional contaminants (metals, PCBs, organic contaminants and pesticides) to

identify potential influence of non-petroleum compounds. Sediment was prepared with an automated Soxhlet extraction and silica gel cleanup. A 2 mL sample of oil collected remotely from the Macondo wellhead was also analyzed for PAH analytes to confirm origin of petrochemicals identified in sediment samples. Organochlorine pesticide analyses included additional fluorisil and carbon cleanup. Sample collection, processing and analyses were conducted according to USEPA methods and the contract laboratory quality assurance protocols and are described in Raimondo et al. (2014) as are oiled sediment exposure assays.

Oil Concentration-Response

Effects of exposure to oiled sediment were determined via experiments that included a chronic life cycle exposure assay (larvae – reproduction) with the sheepshead minnow (Raimondo et al. 2015) and included a sediment embryo development assay using zebrafish as a proxy (*Danio rerio*; Raimondo et al. 2014) to fully account for early life stage effects. For both assays, reference sediment was collected from non-oiled Choctawhatchee Bay, Florida, based on low levels of contamination (metals, pesticides, PCBs) and similarity in grain composition to sediment in the most heavily oiled regions of Barataria Bay (Raimondo et al. 2014).

Concentration-response tests were performed with laboratory weathered South Louisiana crude oil, similar in composition to oil released from the Deepwater Horizon spill. Methods used for both the embryo and life cycle assays are documented in Raimondo et al. (2015).

Population Models

Sheepshead minnow population models were developed based on methods described by Raimondo (2012). Specifically, we used temperature-dependent vital rates to incorporate

seasonal variation in population dynamics in our simulations. The original matrix population model was modified to a two-week time step to be more consistent with the temporal resolution of available temperature data. Concomitant with modifying the time step, the model was adjusted to three life stages (larval, juvenile, and adult) distinguished by size thresholds of 1.5 and 2.6 cm (Nordlie 2000, Cripe et al. 2009). As described in Raimondo (2012), stage duration was determined by a temperature-dependent von Bertalanffy growth parameter, K, determined from fish growth at multiple temperatures and fit to a logistic growth function. Size-dependent mortality was modeled as a derivative of temperature-driven growth, calibrated using field-based mortality estimates for sheepshead minnow young of year and adults (Raimondo 2012). We used a pre-breeding census approach to estimate fecundity rather than the birth-flow model described by Raimondo (2012); however, fecundity estimates similarly incorporated the temperature-dependent embryo survival originally described by Kinne and Kinne (1962). Effects of oil exposure on stage duration and embryo survival were included as described below, based on results of laboratory experiments.

Concentration-response curves from laboratory assays described above were used to modify vital rates in the population model and simulate oil effects, based on the SCAT level of oiling recorded for that time period and/or location as applicable. These effects were modeled as reduced embryo survival and delayed maturation resulting from reduced growth rate. The proportional increase in the larval stage duration for sheepshead minnows, D_1 (from hatching until the observed growth exceeded 1.5 cm), resulting from oil reducing growth rate, was estimated based on three-parameter log-logistic model of larval stage duration for each measured concentration of tPAH:

$$D_1 = 0.485 / (1 + \exp \{-0.576 (\log (\text{tPAH}) - \log (3795.362))\})$$

Likewise, reduced growth of juvenile sheepshead minnows exposed to oil resulted in a lengthened juvenile stage duration (D_j ; period that length ranged from 1.5 – 2.6 cm), which also was calculated using a three-parameter log-logistic model based on the proportional increase in stage duration of oil-exposed sheepshead minnows relative to that of juveniles under control conditions for that temperature:

$$D_j = 0.145 / (1 + \exp \{-1.618 (\log (tPAH) - \log (98.607))\})$$

Reduced embryo survival (S_e) was determined by fitting survival data from the zebrafish embryo development assay to a three-parameter Weibull dose-response curve with the upper limit constrained at the estimated survival rate under control conditions (S_{control}) for that temperature:

$$S_e = S_{\text{control}} \exp \{-\exp \{1.919 (\log (tPAH) - \log (215.991))\}\}.$$

In basic (“simple”; Table 1) matrix population models, without any spatial or temporal framework, deterministic values of population growth rate were calculated for each SCAT category at temperatures ranging from 10-35 degrees. To add a temporal perspective (“seasonal matrix model”), the three-stage matrix model then was modified sequentially based on oil effects representative of monthly changes in coastal oiling at a single point in Bay Jimmy, where the most severe oiling was observed (Cornwall 2015, 29.45°, -89.88°). Population growth rate, λ , was calculated, using package “popbio” (Stubben and Milligan 2007), to include seasonally fluctuating temperatures and oil exposure. This projection was contrasted with a “no oil” simulation that included the same seasonal population dynamics in the absence of oil.

To obtain a preliminary species distribution for spatially explicit population models (SEPM), we simulated fish population dynamics for a ten-year period in the absence of oil exposure and effects, using average biweekly temperatures from our dataset for the corresponding two-week interval. Temperature data were obtained from USGS National Water

Information System (<http://nwis.waterdata.usgs.gov/nwis>) for the five-year period of October 2009 (approximately seven months before oiling) to September 2014. Relative habitat suitability was determined at a resolution of 90 m, based on the available data for habitat variables and the habitat suitability model described above. Fish were first distributed at grids with a greater than average measure of habitat quality with an initial maximum density of 12,331 fish per occupied grid, based on an average of 1.52 fish per m² during July field sampling, when temperature and population growth are greatest (Raimondo 2012). Fish moved to neighboring cells of greater habitat quality until seasonal fluctuations in abundance stabilized. An exponential function of habitat quality determined the probability of a fish remaining at each location at each interval, based on documented sheepshead minnow movement rates in the field (Chitty and Able 2004). Following the simulation of baseline species distribution and population size, population growth was estimated for each two-week interval based on the average mid-day temperature for that period.

SEPM that incorporated the most spatial and temporal information available about population dynamics and oil distribution were used to simulate effects of oil exposure under four scenarios (no oil, SCAT oil, oil avoidance, and homogenous oil; Table 1) using the two separate contaminant estimate approaches described above (discrete SCAT categorizations of tPAH and resampling from empirical sediment tPAH values matched to the nearest SCAT categorization). We used both methods of assigning tPAH values to SCAT categories for each of the four scenarios to compare effects of potential spatial heterogeneity in oil exposure with actual differences in measured tPAH. All SEPM scenarios included temperature effects over time and habitat-dependent movement. Models did not include experimental density dependence functions that affected vital rates at much higher densities than observed in field populations

(Raimondo et al. 2013) but rather used the maximum density ceiling (12,331 fish per location) based on average number of fish m^{-2} in July as density dependent population limitation.

Simulations projected population growth and movement, and distribution was mapped using R package “ggplot2” (Wickham 2009).

The “no oil” scenario simulated population dynamics without oil-induced reductions in survival or growth and fluctuated according to seasonal temperature. The “SCAT oil” scenario included reduced survival and growth effects according to the SCAT category, determined by either the discrete categories or the resampling of empirical tPAH values, of the nearest observed coastline for that month and the corresponding dose-response relationship measured in the laboratory studies. A third spatially explicit scenario included behavioral response to oiling (“oil avoidance” scenario). We incorporated oil avoidance behavior by allowing movement only to less oiled neighboring areas of equal or improved habitat suitability as part of our movement criteria. In the fourth scenario (“homogenous oil”), the SEPM included limited information on contaminant distribution to determine the value of spatially explicit contaminant data. In this scenario, oil exposure and effects were represented evenly across Barataria Bay, reflecting the temporal changes in SCAT data for a single point located in Bay Jimmy (29.45° N, 89.94° W).

Finally, we compared the results of the models of varying complexity to the deterministic risk quotient (RQ) method used in risk assessment (US EPA 1997) that does not take population dynamics, habitat availability, or seasonal variability into consideration. To calculate tPAH-based RQs for fish exposed via sediment, we used the maximum (5663 mg/kg) observed oil concentration on record for Barataria Bay sediment during the year following the spill as Expected Exposure Concentration (EEC). The acute RQ was calculated as the EEC divided by the lowest acute value for the most sensitive fish species exposed to oil via sediment obtained

from the literature (zebrafish 96 h EC50 = 87 mg/kg; Raimondo et al. 2014). The chronic RQ was the EEC divided by the lowest No Observable Adverse Effects Concentration (NOAEC) for the most sensitive endpoint for sheepshead minnow life cycle test described briefly above (50 mg tPAH/kg dry sediment; wet weight and standard length; Raimondo et al. 2015). Characterization of risk to fish from acute and chronic exposure was qualitatively evaluated against the US EPA designated Level of Concern (US EPA 1997).

Results

Habitat Suitability Model

The top model in our candidate modelset was the fully parameterized model with additive effects of salinity, dissolved oxygen and depth (Table 2). Using coefficients from the model and environmental parameter data from Barataria Bay, predicted sheepshead minnow habitat was in shallow areas with lower salinity and dissolved oxygen (Figure 1). The area under the receiver operating curve, 0.72, indicates satisfactory predictive capacity.

Oil Categorization

Sediment sampling locations included the full range of SCAT categories and covered a broad spatial range (Figure 2). Many of the sites we sampled in December 2010 were reclassified as minimal oiling observations in SCAT records shortly thereafter, suggesting a reduction in oiling severity during the time of sample collection. Among SCAT categories, concentrations of tPAH overlapped and were skewed low, contrary to our assumed representation of SCAT categories as distinct distributions of tPAH exposure hazard (Table 3). The samples ranged widely in tPAH concentration (Table 3) and did not align consistently with

SCAT categorizations either just prior or just following sample collection. For example, a site categorized as heavily oiled prior to sampling was classified as “no oil observed” shortly thereafter and had a tPAH concentration of 1.4 mg/kg.

Oil Concentration-Response

Exposure to oiled sediment greatly reduced growth rates within the early life stages of sheepshead minnow and embryo-larval survival in zebrafish. The highest concentrations of tPAH reduced zebrafish survival in the embryo-larval stage to 0 (Figure 3a). Reduced embryo survival had the greatest impact at temperatures of 20° C, when survival at this stage reaches 0.43 in control populations. Effects were of lesser magnitude at temperatures with lower embryo survival. Growth of larval and juvenile sheepshead minnow showed a significant decline at the highest tPAH concentrations measured (Figures 3b and 3c). Reduced larval growth rate interacted with temperature-dependent growth rates to increase the embryo-larval stage by as much as 100.9 days at lower temperatures (e.g., a potential stage duration of 373.3 d if temperatures were sustained at 10° C) and only by 1.77 d at higher temperatures (16.77 d at 35° C). Reduced juvenile growth also affected potential juvenile stage duration more at lower temperatures (from 155.7 d to 182.0 d at sustained temperatures of 10° C) than at higher temperatures (from 19.67 d to 23.0 d at 35° C).

Population Models

Oil effects on stage duration and embryo survival reduced population growth rates in simple population matrix models, when tPAH concentration was classified in discrete intervals (Figure 4a). At lower temperatures (< 17° C), high early life-stage mortality regardless of oil

exposure resulted in the longer stage duration and reduced embryo survival having negligible additional effect on population growth. The heaviest oiling category of exposure resulted in $\lambda < 1$, which is indicative of population decline, regardless of temperature. Oil effects made a qualitative difference in population decline ($\lambda < 1$) rather than growth ($\lambda > 1$), at temperatures above 18 degrees (typically during the months of March – November in Barataria Bay).

Including the temporal influence of temperature, seasonal population matrix models produced population growth rates that varied from 0.96 to 1.50 throughout the year (Figure 4b). Population growth rates calculated for a representative point in Bay Jimmy were much lower than those calculated for a scenario without oil effects in the summer months following the Deepwater Horizon spill (June – August 2010) and during warmer months in subsequent years (Figure 4b).

Population projections from the four SEPM scenarios (“no oil”, “SCAT oil”, “oil avoidance”, and “homogenous oil”) had variable dynamics when using the discrete tPAH categories to represent SCAT classifications (Figure 5a). Although differences between spatially explicit oiled and non-oiled population growth rates were minimal during the winter months, the impacts of reduced population growth rates in warmer months were more apparent (Figure 5a). The “homogeneous oil” scenario resulted in reduced sheephead abundance immediately following the spill when compared to the model that included site-specific oiling categorization (“SCAT oil”) but recovered quickly (Figure 5a). The “oil avoidance” scenario was virtually indistinguishable from the “SCAT oil” scenario with abundance varying on average by $< 1\%$. These same four simulation scenarios that used oil concentrations from resampled empirical tPAH values from sediment samples did not capture the same variability in population growth rate between scenarios as our discrete categorical simulations were able to distinguish (Figure

5b). Slight differences immediately following initial severe coastal oiling were detected; however, sheepshead abundance was similar for the remaining duration of the simulations in all four scenarios.

Risk quotient for acute and chronic oil effects were 113.26 and 65.09, respectively. Both acute and chronic RQs indicate that estuarine fish are at a high risk of adverse impacts from exposure to the maximum environmental concentrations observed throughout Barataria Bay. These values far exceed the levels of concern for both acute and chronic effects to listed and non-listed species ($RQ = 1.0$).

Discussion

Sheepshead minnow model development

In this population-level ecological risk assessment of potential Deepwater Horizon impacts, we use a common toxicological test species and empirical, stage-specific effect data in spatially and temporally explicit models of an estuarine fish population, exposed to oiled sediment within its natural habitat. The lessons learned from this unique confluence of toxicological tests and ecological modeling offer perspective on the potential utility of this approach, as well as more basic approaches, given the substantial data demands. Spatially explicit population models can include situation-specific, ecologically relevant details about habitat restrictions, contaminant effects, and demographic rates for populations expected to be sensitive to changes in these parameters (e.g., limited species distribution, spatial distinctions in exposure risk, or known impacts at a sensitive life stage). Less complex matrix models offer perspective on a range of possible measures (e.g., abundance or population growth) when detailed habitat and movement data are lacking for more complex approaches. The models

developed for evaluation in this study suggest that the capabilities of the spatially explicit approach are not always warranted by the spatial resolution and quality of the available data.

Some qualitative information from SCAT oiling categories has been linked to effects (Brunner et al. 2013) and was suggestive of general tPAH differences in our study, although concentrations overlapped substantially and confounded a spatial representation of heterogeneous exposure risk within the bay (Table 3). In general, SCAT observations were temporally and spatially inconsistent, and oiling was heterogeneous and patchy, such that SCAT categories did not correlate well with measured tPAH concentrations (Turner et al. 2014a, Michel et al. 2013), some of which degraded quickly within 18 months (Mahmoudi et al. 2013). Although our models demonstrate a reduction in population abundance in response to oil exposure with our discrete SCAT categorization of tPAH, temporal variation in oiling within Barataria Bay was not always reflected in the SCAT observations (Turner et al. 2014b), and SCAT categories were not indicative of a distinction in tPAH exposure risk. These more cost-effective data collection methods offer some indication of severely impacted ecosystems but might fail to capture long-term chronic effects on recovering populations. Subjective classifications collected by many observers might also contribute to misleading interpretations, and patchy oil distribution could complicate the use of SCAT categories as representative contaminant data. The spatial and temporal heterogeneity in sampling effort could have failed to capture some reoiling or patchily distributed coastal oiling, thereby underestimating the oiling in some areas. Inclusion of contaminant distribution data would be more effective for contaminants that are persistent or distributed in an established gradient or pattern (e.g., terrestrial and/or point source contamination).

Movements associated with avoidance behavior were not as effective as anticipated in mitigating oil effects, however given the broad coastal impacts and variable distribution, dispersal distances might not have been representative of movement strategies to avoid oiled sediment. Finer resolution of contaminant data are required to adequately capture variance in oil conditions and movement response. The spatially explicit population models also did not include seasonal distinctions in stage-specific movement, whereby adults move modest distances in the spring and young-of-year fish migrate in the fall (Chitty and Able 2004). However, minimal sample sizes and lack of quantitative dispersal estimates prevent improvements on these assumptions currently. Although we did not include hypothesized movements into deeper, more thermally stable habitat during winter months, we nonetheless observed fluctuations in populations consistent with summer peaks in abundance reported elsewhere, supporting the possibility that with observed limited seasonal migration, marsh habitat provides suitable wintering habitat (Chitty and Able 2004). Such year-round dependence on marsh habitat would reduce the likelihood of estuarine species' ability to avoid catastrophic events and increases the value of maintaining uncontaminated marshland for population viability. Habitat quality was a relative measure based on conditions during the period of our field study. It was not a dynamic variable within our temporal simulations, and therefore did not include fluctuations in salinity and dissolved oxygen, or subsequent changes in movement, as a result of freshwater diversions from Davis Pond. We anticipate variable salinity to have relatively less impact on the habits of this euryhaline species within the bay, compared to the oil exposure during the same period of time (cf. Rose et al. 2014). Validation of the habitat suitability model using Pensacola Bay data to predict Choctawhatchee Bay habitat suggested that inter-estuarine variability, even within

local geographic regions, bears further consideration before habitat models are used to predict species distribution in a region where occupancy data was not collected empirically.

Our model did not explore potential interactions of temperature and oil or ultraviolet light and oil and assumed that tPAH had relatively proportional effect regardless of season or phototoxicity (Incardona et al. 2013). Exposure assessment, i.e., distribution, fate, and transport of the contaminant, is a critical component of any risk assessment and is often performed via models that account for physico-chemical properties of the contaminant and hydrological/landscape features of the impacted area. For oil-contaminated systems, exposure modeling is a complex integration of oil distribution on water surface, along shorelines, in the water column and sediments and accounts for spreading, evaporation, weathering, transport, dispersion, emulsification, entrainment, dissolution, volatilization, partitioning sedimentation, and degradation (French-McCay 2004). While oil slicks were being tracked through a number of modeling and remote sensing efforts (e.g., Klemas 2010), the use of dispersants across a wide expanse between the well head and Barataria Bay made incorporation of fate and transport models less reliable than observed and measured oil within the study site. In estimates of vital rates, contaminant concentrations, and habitat suitability, data sources that are appropriate in scale and representative of meaningful distinctions in contaminant effects are prerequisite to ecological model development, ensuring that biological and chemical details are sufficiently represented to warrant additional model complexity.

Implications of complex population model use in ecological risk assessment

The various modeling scenarios demonstrate population-level effects of oil-contaminated sediment on a resident estuarine fish. These simulations are intended to compare exposure and

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response scenarios and evaluate information requirements with respect to model output, rather than provide a definitive evaluation of oil effects on Gulf of Mexico fish populations. We compared risk-based approaches that range from the simple RQ, as commonly used in standard risk assessment practices (USEPA 1997), to spatially-explicit population models that included seasonal temperature fluctuations, spatially and temporally varying oil concentrations, and fish movement and contaminant avoidance behavior. Along this spectrum we included a total of four spatially explicit scenarios (“no oil”, “SCAT oil”, “oil avoidance”, “homogenous oil”) and two non-spatial perspectives (seasonal matrix model, simple matrix model). We demonstrate that spatial approaches need not include high resolution contaminant distribution or detailed behavioral functions to demonstrate a decline in heavily impacted portions of the population. In situations where differential exposure is expected within the distribution of the species, spatial simulations of relative distinctions in exposure effects could identify compensatory or source-sink dynamics meaningful to risk assessment. Likewise, periodic matrix models offer a means of evaluating duration of impact or time to population recovery, and simple matrix models contribute a valuable method of comparative population-level assessment of risk over RQs where habitat data and species distribution are lacking.

Due to its minimal data requirements, the risk quotient is the most widely applied metric of chemical risk; however, simple matrix models that translate toxicity test data into changes in λ have been used in many case studies (e.g., Munns et al. 1997, Miller and Ankley 2004, Spromberg and Meador 2005, Raimondo et al. 2009) and are rooted by well-established methodology (Caswell 2001, Morris and Doak 2003). The evaluation provided from the RQs of the present study confirmed resident fish were at high risk of negative effects, without quantification or description of risk beyond that categorization. The matrix model demonstrated

a decline in λ at heavily oiled sites at any temperature and the temperature-dependent difference between population growth vs. decline at less oiled sites. While matrix models contain considerably more insight into how a wildlife population will respond to a contaminant over an RQ, they are nonetheless criticized for lacking the ecological realism of population connectivity and environmental stochasticity, with toxicity data still limited to species commonly used in laboratory toxicity tests.

The seasonal fluctuation in demographic rates is an important factor of survival, growth, and development (Raimondo 2012), and seasonal patterns of mortality have been noted as a critical part of evaluating long-term impacts of chemical exposure (Nacci et al. 2002). Projecting the matrix model approach to include changing oil exposure and seasonal fluctuations in vital rates demonstrated a very clear decline in λ during the months following the oil spill and showed a possible recovery over the five years of the simulation. The seasonal fluctuations modeled in the present study were derived from empirically-based temperature-dependent growth functions calibrated to field survival estimates for the sheepshead minnow and represent a data-intensive approach to modeling seasonality (Raimondo 2012). This level of information is not likely to be available even for well-studied wildlife species; however, the significant contribution of seasonal fluctuations in demographic rates to projections of λ demonstrated here emphasizes the importance of including known fluctuations in vital rates via differential equations or periodic matrix models. The time to recovery provided by time-varying models provides a valuable assessment of long-term impacts, especially in the case of independent catastrophic events, that is not provided by the RQ or a single matrix model. The interaction of seasonality and chemical impacts has not been explored extensively for fish, but is demonstrated here to be an important first step to adding ecological relevance to population modeling for ecological risk assessment.

Spatially-explicit population models offer the flexibility to include variables that provide more realistic scenarios and yield more informative assessment perspectives (e.g., percent population decline, source-sink connectivity) but at the price of greater information costs. We demonstrate here that model complexity that includes behavioral chemical avoidance and contaminant distribution require more attention to relevant spatial extent and resolution. While spatially explicit contaminant data did provide greater detail for contaminant distribution, simulating the effects with data from a single location produced estimates that were not vastly different than the SCAT oil model after the initial post-oiling months. Representing the entire bay with this particular single data source from the heavily oiled Bay Jimmy area simulates a potential worst case scenario. The homogenous oil scenario, therefore represents an appropriate projection for other retrospective assessments, in which monitoring data are limited to the most impacted areas. Our evaluation suggests that using a single site data source where minimal data are available and high resolution contaminant information is lacking can be an adequate cost-effective strategy of modeling population effects. Similarly, for prospective risk assessment where exposure heterogeneity is unknown, this approach could be used without intensive monitoring and sample analysis. Additional spatial resolution on contaminant distribution would be most informative in situations where contaminant exposure is expected to vary (e.g., different pesticides used in different areas as a result of crop rotation or sporadically applied chemicals). The increasing level of information included in the SEPMs includes added uncertainty associated with each layer. The SEPMs described here contained estimates for habitat suitability, chemical concentration, and migration as well as vital rates. Empirical data was collected in this study and used to determine the value added by increased specificity. In most practical applications,

however, risk assessors will need to evaluate the trade-off of adding model complexity where information is lacking relative to the exposure scenario and desired endpoints.

Effects of oiled sediment exposure on embryo survival and larval and juvenile growth, at levels representative of the most heavily oiled sites in Barataria Bay, were sufficient to cause population level declines in sheepshead minnows, according to vital rates measured in laboratory experiments. These declines have the greatest relative impact during warmer months when sheepshead minnow populations are most abundant and population growth rates are normally increasing. After catastrophic impacts of an oil spill, simulations in this study suggest that population recovery over time is possible, and results using single-site data as a representative worst case scenario provide similar results to a spatially explicit simulation incorporating categorical coastal oiling classifications but without the broad-scale, labor-intensive observations. For species with known distribution, considering the available habitat and seasonal fluctuations for a particular site offers additional detail that could be vital to anticipating population recovery rates and contaminant effects on population dynamics, especially in circumstances of variable or episodic exposure risk. Although toxicity data for species of concern are frequently lacking, the simulation-oriented approach presented here provides a framework for evaluating potential impacts and determining areas to prioritize for mitigation or seasons and life stages during which exposure might have relatively greater population-level impacts, facilitating proactive and adaptive management strategies.

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Table 1. Levels of model complexity including spatial and temporal information on fish population dynamics and coastal oiling for each of the model constructs explored (NA = not applicable)

Model Construct	Fish Dynamics				Oiled Site Categorization		Oil Dynamics	
	Fish population	Migration	Seasonal Fluctuations	Behavioral Response	SCAT discrete	SCAT resampled	Temporal	Spatial
SEPM no oil	X	X	X		NA	NA	NA	NA
SEPM SCAT oil	X	X	X		X	X	X	X
SEPM oil avoidance	X	X	X	X	X	X	X	X
SEPM homogenous oil	X	X	X		X	X	X	
Seasonal matrix model	X		X		X		X	
Simple matrix model	X				X			
Risk quotient								

Table 2. Candidate modelset using variables available as spatial data layers for Barataria Bay.

model	log likelihood	Δ AICc	AICc weights
SALINITY + DO + DEPTH	-59.8184	0.0000	0.4230
SALINITY + DO	-62.5715	1.1653	0.2362
SALINITY + DEPTH	-62.1684	1.8716	0.1659
DO + DEPTH	-62.7470	2.9473	0.0969
SALINITY	-66.2311	4.7798	0.0388
DO	-66.4831	5.5965	0.0258
DEPTH	-62.8139	6.8875	0.0135

Table 3. Concentrations of tPAH (mg/kg) in sediment at sites sampled within one year following the Deepwater Horizon spill in Barataria Bay and coastal Louisiana. Results are summarized according to maximum SCAT categorization during that year for the coastline closest to sample location (NOO = no oil observed).

Category	Min	1st qu.	Median	3rd qu.	Max
NOO	0	0.07	0.20	0.49	45.98
Very Light	0	0.02	0.19	0.50	29.50
Light	0	0.05	0.28	4.31	484.20
Moderate	0	0.01	0.14	0.76	5663.00
Heavy	0	0.29	1.32	11.38	3607.00

Figures

Figure 1. Predicted sheepshead minnow habitat in Barataria Bay in red, using parameters from a generalized linear model developed from Pensacola Bay and Choctawhatchee Bay data for salinity, dissolved oxygen, and depth. Habitat suitability is presented on a continuous scale from low (blue) to high (red).

Figure 2. Barataria Bay maximum SCAT categorizations following the oil spill are indicated by lines (red = heavy, orange = moderate, yellow = light, light green = very light, dark green = no oil observed), and starred locations represent SCAT categorization at time of sediment sampling from low (green stars) to high (red stars) with the measured tPAH ranges (mg/kg) of samples indicated parenthetically.

Figure 3. Effects of oiled sediment exposure on (a) embryo survival, (b) proportional increase in larval stage duration, and (c) proportional increase in juvenile stage duration.

Figure 4. (a) Population growth rate at various temperatures, modified with reduced embryo survival and lengthened larval and juvenile stage duration according to tPAH concentration, divided evenly into five discrete categories within the range of observed sediment tPAH in Barataria Bay and (b) seasonal fluctuations in population growth rate over the period of the study (October 2009 – September 2014) without oil effects (green) and based on the discrete SCAT categorization of oil effects and approximated tPAH exposure at one site in Bay Jimmy (blue).

Figure 5. Simulated abundance of sheepshead minnow in Barataria Bay over the study period with no oil effects (green), oil effects and same movement patterns (red), oil effects with oil avoidance included in movement patterns (orange), and no spatial distinction in oil effects (based on single site information; blue). Spatial population dynamics were simulated using (a) hypothesized discrete tPAH ranges for SCAT categories of oil exposure and (b) resampled empirical tPAH values from sediment samples within each SCAT categorizations.

















