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A multi-taxonomic framework for assessing relative petrochemical vulnerability of marine biodiversity in the Gulf of Mexico

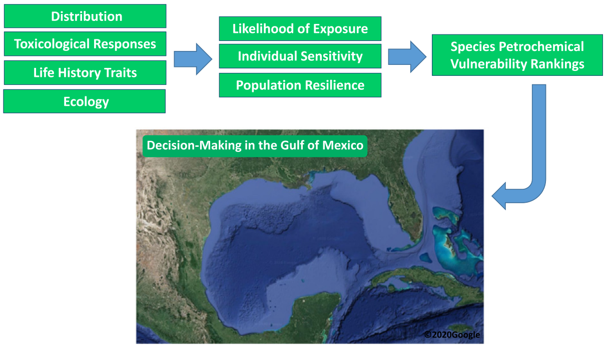
Beth Polidoro [a,*], Cole W. Matson [b], Mary Ann Ottinger [c], D. Abigail Renegar [d], Isabel C. Romero [e], Daniel Schlenk [f], John Pierce Wise Sr. [g], Jesús Beltrán González [h], Peter Bruns [b], Kent Carpenter [i], Dorka Cobián Rojas [j], Tracy K. Collier [k], Thomas F. Duda Jr. [l], Patricia González-Díaz [m], Richard Di Giulio [n], R. Dean Grubbs [o], J. Christopher Haney [p], John P. Incardona [q], Guillermo Horta-Puga [r], Christi Linardich [i], Jon A. Moore [s,x], Daniel Pech [t], Susana Perera Valderrama [u], Gina M. Ralph [i], Kyle Strongin [a], Amy H. Ringwood [v], Bernd Würsig [w]

[a] *School of Mathematics and Natural Sciences, Arizona State University, 4701 W. Thunderbird Rd, Glendale, AZ 85306, USA*
[b] *Department of Environmental Science, Baylor University, One Bear Place #97266, Waco, TX 76798, USA*
[c] *Department of Biology and Biochemistry, 3455 Cullen Boulevard, #221E, University of Houston, Houston, TX 77204-5001, USA*
[d] *Halmos College of Arts and Sciences, Nova Southeastern University, 8000 North Ocean Drive, Dania, FL 33004, USA*
[e] *University of South Florida, College of Marine Science, 140 7th Ave S, St Petersburg, FL 33701, USA*
[f] *Department of Environmental Sciences, University of California Riverside, 900 University Blvd., Riverside, CA 92054, USA*
[g] *Wise Laboratory of Environmental and Genetic Toxicology, 500 S. Preston St., 55A Department of Pharmacology and Toxicology, University of Louisville, Louisville, KY 40292, USA*
[h] *Centro de Investigación y Manejo Ambiental del Transporte (Cimab), Ctra. del Cristo esq. Tiscornia, Casablanca, Habana, Cuba*
[i] *International Union for Conservation of Nature Marine Biodiversity Unit, Department of Biological Sciences, Old Dominion University, 5115 Hampton Blvd., Norfolk, VA 23529, USA*
[j] *Parque Nacional Guanahacabibes, Centro de Investigaciones y Servicios Ambientales (ECOVIDA), Ministerio de Ciencia, Tecnología y Medio Ambiente (CITMA), La Bajada, 22100 Sandino, Pinar Del Río, Cuba*
[k] *Huxley College of the Environment, Western Washington University, 516 High Street, Bellingham, WA 98225-9079, USA*
[l] *Museum of Zoology & Department of Ecology of Evolutionary Biology, University of Michigan, 1105 N. University, Ann Arbor, MI 48109-1085, USA*
[m] *Centro de Investigaciones Marinas, Universidad de La Habana, Calle 16, No. 114 entre 1ra y 3ra, Municipio Playa, La Habana CP: 11300, Cuba*
[n] *Nicholas School of the Environment, Duke University, Research Drive, Durham, NC 27708, USA*
[o] *Florida State University Coastal and Marine Laboratory, 3618 Highway 98, St. Teresa, FL 32358, USA*
[p] *Terra Mar Applied Sciences, 1370 Tewkesbury Place NW, Washington, DC 20012, USA*
[q] *Ecotoxicology Program, Environmental Conservation Division, Northwest Fisheries Science Center, National Oceanic and Atmospheric Administration, Seattle, WA 98112, USA*
[r] *Lab. Biogeoquímica, UBIPRO, FES Iztacala, Universidad Nacional Autónoma de México, Av. de los Barrios 1, Los Reyes Iztacala, Tlalnepantla, México 54090, Mexico*
[s] *Wilkes Honors College, Florida Atlantic University, 5353 Parkside Dr., Jupiter, FL 33458, USA*
[t] *Laboratorio de Biodiversidad Marina y Cambio Climático (BIOMARCCA), El Colegio de la Frontera Sur, Lerma, 24500 Campeche, Mexico*
[u] *National Commission for the Knowledge and Use of Biodiversity (CONABIO), Liga Periférico - Insurgentes Sur 4903, Parques del Pedregal, Tlalpan, 14010 Mexico City, Mexico*
[v] *Dept of Biology, 9201 University City Blvd, University of North Carolina Charlotte, Charlotte, NC 28223, USA*
[w] *Department of Marine Biology, Texas A&M University at Galveston, 200 Seawolf Pkwy, Galveston, TX 77553, USA*
[x] *Harbor Branch Oceanographic Institute, 5600 US 1, Ft. Pierce, FL 34964, USA*

HIGHLIGHTS

- Ecological and life-history traits can inform species' relative vulnerabilities to threats.
- Eighteen traits were identified to estimate petrochemical exposure, individual sensitivities and population resilience.
- The resulting framework is applicable to multiple marine taxa and petrochemical exposure scenarios.

GRAPHICAL ABSTRACT



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* Corresponding author.
E-mail address: beth.polidoro@asu.edu (B. Polidoro).

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ABSTRACT

A fundamental understanding of the impact of petrochemicals and other stressors on marine biodiversity is critical for effective management, restoration, recovery, and mitigation initiatives. As species-specific information on levels of petrochemical exposure and toxicological response are lacking for the majority of marine species, a trait-based assessment to rank species vulnerabilities to petrochemical activities in the Gulf of Mexico can provide a more comprehensive and effective means to prioritize species, habitats, and ecosystems for improved management, restoration and recovery. To initiate and standardize this process, we developed a trait-based framework, applicable to a wide range of vertebrate and invertebrate species, that can be used to rank relative population vulnerabilities of species to petrochemical activities in the Gulf of Mexico. Through expert consultation, 18 traits related to likelihood of exposure, individual sensitivity, and population resilience were identified and defined. The resulting multi-taxonomic petrochemical vulnerability framework can be adapted and applied to a wide variety of species groups and geographic regions. Additional recommendations and guidance on the application of the framework to rank species vulnerabilities under specific petrochemical exposure scenarios, management needs or data limitations are also discussed.

1. Introductions

Globally, a multitude of activities including overfishing; pollution from sewage, erosion and sediment, excess nutrients and oil spills; increased shipping and boat traffic; coastal development, dredging; and intensive aquaculture (Karnauskas et al., 2013; Schirripa et al., 2013; Campagna et al., 2011) can negatively impact populations of marine species and their habitats. Effective management, restoration, and mitigation efforts for living marine resources requires comprehensive and extensive knowledge of the status of complete clades of marine species and ecosystems, including their vulnerability to combined or specific stressors, such as petrochemical exposure (Campagna et al., 2011). Resource managers have long recognized the need for improved comprehensive species information to more effectively select and prioritize species, habitats, and geographic areas for improved management, restoration and recovery (Ottinger et al., 2019; Sagarese et al., 2017; Campagna et al., 2011; Chakrabarty et al., 2012). Similarly, oil and gas industries have recognized the need to maintain sustainable business practices by better quantifying and reducing their impacts on living marine resources, while also protecting their return on investment and managing business risk (Cordes et al., 2016).

In the Gulf of Mexico, which encompasses exclusive economic zones of Cuba, Mexico and the United States, oil and gas operations are an important component of the economy, yet can have significant impacts on living marine resources during all stages of operations (Holdway, 2002; Ko and Day, 2004; Mendelssohn et al., 2012, among others). In United States and Mexican waters, the majority of petrochemical activities, including permitting, environmental assessments and conservation or restoration efforts, are focused on reducing impacts to critical habitats and species protected under the U.S. Endangered Species Act or Mexico Norma 059 (Strongin et al., 2020; Wallace et al., 2017). However, impacts to the majority of non-threatened or non-commercial marine species across the Gulf of Mexico are generally ignored, due to the lack of information, regulatory preferences, or both. This presents an extensive gap in critical, species-level information needed by resource managers to effectively prioritize species, habitats, and ecosystems impacted by petrochemical activities for conservation, management, restoration or recovery (Campagna et al., 2011).

During routine oil and gas activities, or in the event of a large oil spill, it is clear that a wide range of marine species can be exposed to petrochemicals (Pulster et al., 2020; Sutton et al., 2020). Additionally, the Gulf of Mexico is known to have extensive natural petrochemical seeps (Song et al., 2008; Kennicutt et al., 1988; MacDonald et al., 2015) However, the biological and ecological impacts to marine species ranging from relatively low, chronic exposures to severely, high, acute exposures are largely unknown (Murawski et al., 2016; Pulster et al., 2020; Sutton et al., 2020). A major impediment is that acute or chronic toxicity data for petrochemical exposures, regardless of individual biological response, are not available for the majority of marine species. Single species toxicological testing is costly, can be logistically impossible for animals that do not rear well in laboratory or mesocosm studies, and is generally inefficient and time-consuming to conduct experimentally for all marine species (Romero et al., 2018; Romero et al., 2020). Furthermore, comparisons across different toxicological studies, even for the same species, can be complex due to wide variation in environmentally-relevant exposures, chemical mixtures, impacts on different life stages, and response parameters.

Regardless, available toxicity data derived from laboratory species or model organisms, are still often considered representative of broader taxonomic groups. This approach is very useful in comparing impacts from exposure across different chemicals and doses, but cannot generally account for the wide variety of physiological and life history differences among species, which make some species more vulnerable to adverse impacts. Moreover, while the importance of linking data from these experimental approaches to population or ecosystem level impacts is widely recognized (Maltby et al., 2001; Moore et al., 2006), it can be challenging due to the diversity of species-specific ecological and functional roles.

To guide conservation, restoration or recovery initiatives, population-level effects from cumulative exposures to stressors may be more informative than data on the sensitivity of individual species to stressors (Forbes et al., 2011; Spromberg and Birge, 2005). Commonly, population-level assessments of the impact of stressors are based on comparing relative abundance or other indicators in a threatened “impacted site” with that of a “non-impacted site.” However, this approach cannot always account for natural differences in species abundance, synergistic effects, or other ecological factors that can influence population sizes and function (Pacifici et al., 2015; Culp et al., 2011). Furthermore, observation of direct impacts of threats is especially difficult to measure for the vast majority of marine species, particularly those that are highly migratory, deep sea, or cryptic (Haney et al., 2017). For these reasons, analysis of species-specific biological and ecological traits has been proposed as an improved approach to comprehensively estimate relative species vulnerabilities to different stressors (Baird et al., 2008; Rubach et al., 2011). Trait-based assessments, which use phenotypic or ecological characters of a species to explain or predict variation and vulnerabilities in and across species, populations or ecological systems, represent a new frontier in ecological risk assessment and biomonitoring of aquatic ecosystems (De Lange et al., 2009; Van den Brink et al., 2007; Poff et al., 2006; Usseglio-Polatera et al., 2000).

Increasingly, trait-based frameworks are being developed to predict the vulnerability of individual species, populations, and ecosystems to a number of past, current or future stressors (De Lange et al., 2009;

Ottinger et al., 2019; King and McFarlane, 2003) by identifying key traits that may increase the relative tolerance or sensitivity of species or populations to a given threat (Rosenberger et al., 2017; Hare et al., 2016; Chin et al., 2010) or combination of threats. The strengths of trait-based vulnerability assessments are that species traits can be transferable to different geographic regions for similar assessments of vulnerability to stressors, have both mechanistic and diagnostic components, generally require no new field sampling, and serve to supplement taxonomic-based abundance analyses (Van den Brink et al., 2011; Culp et al., 2011). Weaknesses include the generally low availability of marine species trait data, low historic database quality, and the lack of standardization across species data and trait information (Van den Brink et al., 2011). However, the methodology and species-specific information generated by the IUCN Red List assessment process can address each of these weaknesses by involving hundreds of regional scientists in data collection, peer-review and data synthesis processes, and by providing a time-tested standardized process of species assessment, ranking of threats, and database publication (Hoffmann et al., 2008; de Grammont and Cuarón, 2006; Rodrigues et al., 2006).

Our objective was to develop a peer-reviewed, multi-taxonomic framework for estimating relative marine species vulnerabilities to potential adverse impacts from petrochemical activities across the Gulf of Mexico. The benefits of a unified vulnerability framework that can encompass multiple taxonomic groups (e.g. all vertebrates and invertebrates) are that it allows for transparent reproducibility for application in other regions, as well as direct comparisons of species and population-level vulnerabilities to petrochemical impacts across disparate taxonomic groups. Application of the resulting framework can serve as a valuable tool for coastal and marine managers, decision-makers and for coordination of public policy.

2. A novel multi-taxonomic framework for ranking population-level petrochemical vulnerability

To develop the multi-taxonomic petrochemical vulnerability index (PVI) framework for marine vertebrates and select groups of invertebrates in the Gulf of Mexico, 28 scientists representing a breadth of taxonomic expertise in molecular or species sensitivities to petrochemicals, marine ecology, pharmacokinetic modeling, and petrochemical environmental chemistry attended a PVI framework development workshop, held in Guanahacabibes National Park, Cuba in June 2019. Workshop participants worked collaboratively in three groups (fishes, invertebrates, and tetrapods) to discuss and identify key species traits that influence the relative severity of petrochemical exposure, individual sensitivity or response, and population resilience. In plenary each of the three groups presented their results and worked collaboratively to synthesize their discussions into a single, cohesive framework. The resulting framework was designed to be relevant for multiple taxonomic groups, but flexible in application for a user to employ selective weighting of traits, customized ranking of questions, and different scoring schemes depending upon the taxonomic group to be assessed and specific characteristics of a petrochemical threat scenario. Given the resulting framework's flexibility in application across different taxa and petrochemical threat scenarios, an important part of the framework is an explicit assumption that states how each selected trait was perceived to operate in terms of increasing vulnerability (Fig. 1).

3. Likelihood of exposure

Nine ecological and/or biological traits or factors were identified that may increase the likelihood of a species encountering higher than baseline concentrations of petrochemicals in the Gulf: Distribution, Water Column Position, Mobility, Longevity, Body Surface, Respiration Mode, Feeding Behavior, Longevity of Most Sensitive Pre-Adult Stage, and Distribution and/or Mobility of Most Sensitive Pre-Adult Stage.

One of the most important factors that directly increases likelihood of exposure is whether or not the species occurs in areas with high probability of encountering petrochemicals. Although more direct measurements of exposure should be made by mapping species distributions across specific scenarios of known or modeled petrochemical concentrations, indirect estimations can be calculated based on the proportion of a species range that overlaps areas of high petrochemical activity (e.g. areas with a higher number of platforms, density of shipping routes, proximity of refineries, current or historic locations of common or catastrophic oil spills, etc.). Water Column Position is also very scenario specific, in that increased exposure could occur at the surface, in the event of a surface spill, or much lower in the water column or near the sea floor in the event of a deep-water blow-out, as occurred during the *Deepwater Horizon* blow-out in 2010, or through settling and sedimentation (Romero et al., 2017; Passow, 2016; Daly et al., 2016). In this sense, species that are benthic, benthopelagic, epipelagic, or spend a lot of time on the surface (e.g. marine mammals, sea turtles and seabirds), may have increased exposures compared to meso or bathypelagic species.

The likelihood of a species being exposed to petrochemicals within its distribution also increases if that species is sessile, and/or not able or likely to move out of the area of exposure, which can also result in prolonged exposures and/or multiple exposures over time (McKinley and Johnston, 2010). In spill scenarios, such as Deepwater Horizon, where oil dispersants are applied on a large-scale, the exposure to additional chemicals has been shown to amplify the impact on sessile species, such as corals (De Leo et al., 2016). Similarly, longer-lived species may experience increased, multiple exposures over time. Although placed here within the Exposure component, Longevity is also an important trait in terms of Population Resilience, as species with longer-life spans tend to be slower to recover from disturbance, as they can experience increased annual adult mortality rates (measured as percentage of loss per year) compared to shorter-lived species over more years (Mace et al., 2008; Ottinger, 2010).

In traditional toxicology, primary routes of exposure are considered to be dermal, oral or respiratory (Golden and Rattner, 2003; Tormoehlen et al., 2014). For these reasons, Body Surface Type, Respiratory Mode and Feeding or Other Behaviors should be included as important exposure pathways in marine species. Although additional studies are likely needed on the relative degree of exposure differences among species with different body surface coverings, diets and respiratory modes, the assumptions are that certain body covering types (e.g. skin, feathers, scales), respiratory modes (e.g. lungs, gills, skin, diffusion) and feeding/grooming behaviors (e.g. surface feeders, deposit feeders, filter feeders, preening) will result in differential uptake or absorption of petrochemicals. Interestingly, some studies have shown that petrochemically-derived polycyclic aromatic hydrocarbons (PAHs) may undergo trophic dilution in marine food webs, potentially due to low assimilation efficiencies and more efficient metabolic transformations in species occupying higher trophic levels (Wan et al., 2007).

For species that reproduce sexually, the most vulnerable life stage in terms of both likelihood of exposure and/or sensitivity, may be during pre-adult stages, such in the embryonic, larval or juvenile stages (Carls and Meador, 2009; Adams et al., 2014a; West et al., 2014; Sørhus et al., 2016; Heintz et al., 1999; Heintz et al., 2000; Sørhus et al., 2017). This stage is especially important for those species that reproduce only once in a year, or for a short period of time in a year (e.g., hermatypic corals, sponges, etc.). By contrast, species that reproduce asexually, may be more resilient to contaminant impacts (Archaimbault et al., 2010, Richmond et al., 2018). To account for exposure differences among species with more sensitive pre-adult stages, the likelihood of exposure for the most sensitive pre-adult stage should be estimated based on known or modeled overlap of the pre-adult stage distribution with petrochemical concentrations and/or activities, especially if the distributions of pre-adults, such as planktonic larval stages, are different than that of adults. Similarly, the longevity of the most

	Likelihood of Exposure								
Trait	**Distribution**	**Water Column Position**	**Mobility**	**Longevity**	**Body Surface Type (Dermal)**	**Respiration Mode (Inhalation)**	**Feeding or Other Behaviors (Oral)**	**Longevity of most sensitive pre-adult stage**	**Distribution of most sensitve pre-adult stage**
Assumption	Species with a larger proportion of their range in areas with petrochemical activities will have a higher likelihood of exposure over time	Species that spend longer amounts of time on the surface or on sediments will have higher exposures	Sessile species or small-ranging species may have more prolonged or repeated exposures over time	Longer-lived adults will have more repeated exposures overtime	Certain outer layers are more susceptible to dermal exposure	Certain repiratory modes are more susceptible to inhalation exposures	Certain feeding behaviors may increase oral exposure	Likelihood of exposure for the most-sensitive pre-adult stage (e.g. eggs, larvae, neonate, asexual budding, etc.) increases with longer pre-adult stages.	Likelihood of exposure for the most sensitive pre-adult stage is increased due to pre-adult stage distribution, and/or mobility.
Example Indicators	• Area of overlap with petrochemical activities in the Gulf	• Benthic or sediment dwellers • Time spent at the surface	• Sessile • Site fidelity • Speed or mobility	• Lifespan • Generation length • Growth rate	• Outer layer type (feathers, scales, skin, shell, etc.) • Surface area • Surface to body ratio	• Presence or absence of lungs or gills • Surface area for gas exchange	• Sessile prey • Location of prey in sediment or on surface • Deposit feeders • Trophic level • Preening • Filter or suspension feeders	• Length of time in most sensitive pre-adult stage	• Distribution and/or frequency of occurance of pre-adults in high petrochemical activity areas • Pre-adults occur at surface or in sediments •Pre-adults are sessile or small ranging

	Species Sensitivity					Population Resilience			
Trait	**Toxicokinetics**	**Body Surface Function**	**Exposure to UV light**	**Most Sensitive Pre-Adult Stage Form**	**Presence of Multiple Stressors**	**Abundance**	**Population Connectivity**	**Reproductive Turnover Rate**	**Feeding or Habitat Specialization**
Assumption	Some species have more robust compensatory mechanisms (e.g. improved metabolism and clearing of hydrocarbons, greater antioxidant capacities).	Certain outer layers (e.g. feathers vs. fur vs. scales, etc.) will be more impacted in terms of **function** by oiling.	Species that occur at the surface where UV light lowers toxcological thresholds, may be more sensitive.	Certain pre-adult stages are more sensitive than others when exposed.	Species that are simultaneously impacted by other stressors (e.g. low oxygen, high temperatures, loss of prey, other chemicals etc) will have increased sensitivity.	Populations that are less abundant in number of individuals will be less resilient.	Populations with little or no connectivity to populations outside of petrochemical activity areas will be less resilient.	Species with lower reproductive turnover rates will recover more slowly from disturbances.	Species with high specialization in habitat and/or dietary choices, are less resilient.
Example Indicators	• Detoxification mechanisms • Antioxidant capacity • Immuno-response • Bio-accumulation • Lipid metabolism	• Outer cover type and morphology	• Daylight time spent at the surface • Transparency or absence of UV protecting pigments	• Live birth • Eggs • Larvae • Asexual reproduction	• Proportion of range with seasonal hypoxia, or seasonal high temperatures, or high fishing activity • Proximity to urbanized areas	• Population size • Rare vs. common vs. abundant • Colonial vs. solitary vs. aggregating	• Proportion of range outside of petrochemical areas • Connectivity with populations within or outside of petrochemical activity area	• Number of offspring/year • Age at first breeding • R vs. K species • Generation length • Fecundity • Recruitment rate	• Number of habitat preferences • Number of food preferences • Symbiont dependency

Fig. 1. Traits, assumptions and example indicators for a multispecies Petrochemical Vulnerability Index framework based on likelihood of exposure, sensitivity and population resilience.

sensitive pre-adult stage, which can range from a few days or weeks (e.g. coral and oyster larvae, some fish larvae) to months (e.g. shark eggs, sea turtle eggs, sea bird eggs) or years (e.g. embryonic or juvenile marine mammals) for both sexually and asexually reproducing species, is important to capture the increasing likelihood of multiple or prolonged exposures during the critical stages of development and recruitment of pre-adults.

4. Species sensitivity

Five ecological and/or biological traits were identified that may be related to increased adverse responses or outcomes of species already exposed to petrochemicals in the Gulf: Toxicokinetics, Body Surface Function, Exposure to UV Light, Most Sensitive Pre-Adult Stage Form, and Presence of Other Chemical or Environmental Stressors.

Although the number of studies on the toxicokinetics of PAHs and other components of petrochemicals in marine organisms is widely growing, there is still very little known on uptake, maternal transfer, metabolism and elimination of these compounds (or combination of compounds) for the majority of marine species or their sensitive life stages (Grech et al., 2017). Regardless, species-specific differences in uptake, metabolism, and biomarker response from exposure to PAHs have been well-documented (Jung et al., 2015; Sørensen et al., 2017; Grech et al., 2019), such that measured body burdens of PAHs in different species without complementary biomarker or other toxicological studies cannot reliably predict differences in species' exposures or toxicological responses (Hueter, 2012). Uptake rates of individual PAH's can vary by compound, species respiration rate, gill structure and exposure duration (Jonsson et al., 2004). Similarly, uptake, metabolism and elimination may also be influenced by life stage as embryonic stages may be more or less sensitive due to limited toxicokinetic capabilities.

Body surface covering can be considered a component of toxicokinetic models, as physiological and biochemical differences among skin membranes, feathers and scales may differentially facilitate the uptake of PAHs from the aquatic environment. However, surface coverings can also influence different exposure routes and physiological function, such as ingestion of oil by preening birds and/or significant changes in mobility, water repellency and insulation due to oiled feathers (Leighton, 1993). Further, ingested contaminants often transfer to eggs, thereby exposing the embryo throughout development (Lin et al., 2004; Ottinger et al., 2005).

Several studies have documented the increased toxicity of PAHs to marine organisms in the presence of UV light (Pelletier et al., 1997; Almeda et al., 2016; Buskey et al., 2016; Barron et al., 2003). Increased phototoxicity occurs when UV radiation is absorbed by the conjugated PAH molecule bonds, exciting them to a triplet state (Newsted and Giesy, 1987). This phenomenon primarily occurs at the sea surface photic zone/microlayer (Logan, 2007), where larvae, buoyant eggs and plankton can be heavily affected by UV irradiation, resulting in reduced survival (Buskey et al., 2016). For the majority of species, the most sensitive life stage to adverse impacts from contaminant exposure are in the embryonic, larval or pre-adult forms, when growth and developmental responses can be most significantly altered (Woltering, 1984). However, there may be differences in the severity of impact and/or mortality rates among different pre-adult stage forms, e.g. feeding vs non-feeding larvae, buoyant or attached eggs with or without protective coverings, live-births (Carrier et al., 2018).

The presence of additional stressors can cause both synergistic and additive impacts to individuals and populations (Harley and Rogers-Bennett, 2004). For example, synergistic effects that exacerbate physiological impacts can manifest when changes in environmental conditions, such as hypoxia, increased temperatures, or sedimentation, occur simultaneously with exposure to petrochemicals (Suchanek, 1993; Dasgupta et al., 2015; Vieira and Guilhermino, 2012). Co-exposures to metals and other chemical pollutants in the Gulf also have synergistic or additive impacts (Qian et al., 2017). Synergistic toxicities of exposure to oil and oil dispersants are variable depending upon the species and dose (Rico-Martínez et al., 2013; Adams et al., 2014b; Dussauze et al., 2015). Regardless, if individual fitness decreases in the presence of other stressors or threats, increased sensitivity to impacts from petrochemical exposures can occur. Additive impacts to populations can also occur when stressors such as overfishing, habitat loss or disease cause population reductions independent of, but in addition to, population reductions caused by exposures to petrochemicals (Lewis et al., 2020; Harley and Rogers-Bennett, 2004).

5. Population resilience

Four ecological and/or biological traits were identified that are related to increases or decreases in population resilience, regardless of stressor type. These include Abundance, Population Connectivity, Reproductive Turnover, and Feeding or Habitat Specialization.

In general, species extinctions and/or local extirpations occur when the mortalities or emigration rates are greater than births or immigration rates (Mace et al., 2008). As such, the likelihood of significant population reduction leading to extinction or local extirpation is higher when population sizes are small or abundance is low. Very small populations also have increased susceptibility to demographic stochasticity, where even random variations in birth or death rates can lead to population declines (Richter-Dyn and Goel, 1972; Goodman, 1987). Similarly, populations that are highly fragmented or poorly connected cannot benefit from any rescue effects due to low rates of immigration of new individuals to the impacted population (Mace et al., 2008). This connectivity concept is critically important for many marine species where the movement or dispersal capabilities of larval propagules is essential for metapopulation maintenance, and can be significantly greater in distance than those of more sedentary or less mobile adult stages (Grantham et al., 2003; Hanski and Ovaskainen, 2003).

Reproductive turnover refers to the rate at which cohorts of new breeding individuals are added to the population, and can be measured in a variety of ways including generation time (Mace et al., 2008) or population turnover (Salguero-Gómez et al., 2016). It has been well-documented that later-maturing, slower-growing and longer-lived species, even with higher fecundities, can be at greater risk from increased annual mortality rates and experience longer population recovery times compared to earlier-maturing, faster-growing, and shorter-lived species (Mace et al., 2008; Winemiller, 2005; Bell et al., 2014; Murua et al., 2017; Oliver et al., 2015). Further, the attenuation of lifespan due to environmental challenges in combination with reduced productivity/offspring survival can have profound population level impacts over time.

Species with narrowly-defined niches are more likely to be feeding or habitat specialists, with a lower capacity to respond to stressors that drive changes in habitat or feeding conditions (Slatyer et al., 2013). Species with broader habitat ranges experience a wider range of conditions and environments and are expected to have greater ecological versatility and therefore lower vulnerability (Wilson et al., 2008; Munday, 2004, among others). Similarly, species with smaller breadth of diet, and/or with reliance on interspecific interactions, may be more vulnerable to changes in ecosystems, habitats and environmental conditions (González-Suárez et al., 2013; Bender et al., 2013; Sunday et al., 2015).

6. Considerations for application

In order to apply the framework and derive species-specific petrochemical vulnerability rankings for a given petrochemical threat scenario, measurable and/or well-defined indicators of each trait that can account for differences among species need to be identified. Based on the indicators selected, relevant ranking questions are developed ideally within a custom petrochemical threat scenario, along with a logical scoring scheme. As an example, Golden and Rattner (2003) developed a similar type of scoring scheme specifically to rank bird species' vulnerabilities to petroleum crude oil. Other examples of application of ranking questions and scoring schemes to estimate relative species vulnerabilities to climate change have been developed for fishes (Hare et al., 2016), corals (Foden et al., 2013), and sharks (Chin et al., 2010).

In some cases, depending upon the threat scenario and/or taxonomic groups to be ranked, weighting of critical traits may be desired. For example, in the event of an oil spill that occurs primarily as a surface slick, traits that estimate exposure and sensitivity of pre-adult fishes may need to be weighted or have higher scoring schemes to account for the increased vulnerability of fish species with buoyant eggs or more sensitive larval stages that spend extended time at the surface. A deep-water subsurface spill, in contrast, has the potential to impact species throughout the water column depending upon the response option employed. The scoring scheme should therefore account for the additional risk to vulnerable mesopelagic and deep-water benthic species.

A key benefit of this framework lies in the potential for active application in pre-spill planning exercises to increase spill response preparedness, such as Net Environmental Benefit Analysis (NEBA). NEBA is a structured management tool that informs the relative advantages and disadvantages of response options for oil spills, and prioritizes environmental outcomes. The NEBA process can be significantly limited, however, by knowledge gaps and uncertainties regarding relative species vulnerabilities. By using all available data to fill these data gaps, the framework can substantially contribute to improving oil spill response.

To account for data gaps in life history and other traits, a number of different methods can be employed, such as assigning a middle or neutral score for unknown values, conducting random forest analyses or other machine learning techniques to impute missing trait values among similar species (Comeros-Raynal et al., 2016), or assigning an uncertainty or error value to final rankings based on relative amount of data gaps underlying each species' final ranking.

The strength or validity of final species rankings should be tested through sensitivity analyses, such as those that explore differences in results when selected traits are removed or perhaps weighted differently. Furthermore, final ranking results can also be tested or validated by comparing the final relative species vulnerability rankings with published toxicological endpoints related to acute or chronic impacts.

However, given the large variation in laboratory methods, species uptake rates, physiological responses, oil/contaminant type, and both field or laboratory doses, extreme care needs to be taken in correlating disparate toxicological response studies or field-derived PAH body burdens with final species rankings.

Lastly, as knowledge of toxicological responses, distributions, and life history traits of species are expanded, the PVI framework can be adapted and adjusted by incorporating new data inputs, improved ranking and scoring schemes, and refinement of trait weighting scenarios. In this sense, this PVI should be treated as a living framework that can be adapted to a number of different threat scenarios, taxonomic groups, and refinements in ecological and toxicological information over time.

CRediT authorship contribution statement

Beth Polidoro: Funding acquisition, project administration, Writing-original draft, conceptualization, methodology. **Cole W. Matson:** Funding acquisition, conceptualization, methodology, writing-review and editing. **Mary Ann Ottinger:** Conceptualization, methodology, resources, writing-review and editing. **D. Abigail Renegar:** Conceptualization, methodology, resources, writing-review and editing. **Isabel C. Romero:** Conceptualization, methodology, resources, writing-review and editing. **Daniel Schlenk:** Conceptualization, methodology, resources, writing-review and editing. **John Pierce Wise, Sr.:** Conceptualization, methodology, resources, writing-review and editing. **Jesús Beltrán González:** Investigation, resources, writing-review and editing. **Peter Bruns:** Data curation (workshop data collection and facilitation). **Kent Carpenter:** Investigation, resources, writing-review and editing. **Dorka Cobián Rojas:** Investigation, resources, writing-review and editing. **Tracy K. Collier:** Investigation, resources, writing-review and editing. **Thomas F. Duda, Jr.:** Investigation, resources, writing-review and editing. **Patricia González-Díaz:** Investigation, resources, writing-review and editing. **Richard Di Giulio:** Investigation, resources, writing-review and editing. **R. Dean Grubbs:** Investigation, resources, writing-review and editing. **J. Christopher Haney:** Investigation, resources, writing-review and editing. **John P. Incardona:** Investigation, resources, writing-review and editing. **Guillermo Horta-Puga:** Investigation, resources, writing-review and editing. **Christi Linardich:** Data curation (workshop data collection and facilitation). **Jon A. Moore:** Investigation, resources, writing-review and editing. **Daniel Pech:** Investigation, resources, writing-review and editing. **Susana Perera Valderrama:** Investigation, resources, writing-review and editing. **Gina M. Ralph:** Data curation (workshop data collection and facilitation). **Kyle Strongin:** Data curation (workshop data collection and facilitation). **Amy H. Ringwood:** Investigation, resources, writing-review and editing. **Bernd Würsig:** Investigation, resources, writing-review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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