1 **A Multi-taxonomic Framework for Assessing Relative Petrochemical Vulnerability of Marine**
2 **Biodiversity in the Gulf of Mexico.**
3

4 Beth Polidoro[a*], Cole W. Matson[b], Mary Ann Ottinger[c], D. Abigail Renegar[d], Isabel C. Romero[e], Daniel
5 Schlenk[f], John Pierce Wise, Sr.[g], Jesús Beltrán González[h], Peter Bruns[b], Kent Carpenter[i], Dorka Cobián
6 Rojas[j], Tracy K. Collier[k], Thomas F. Duda, Jr.[l], Patricia González-Díaz[m], Richard Di Giulio[n], R. Dean
7 Grubbs[o], J. Christopher Haney[p], John P. Incardona[q], Guillermo Horta-Puga[r], Christi Linardich[i], Jon A.
8 Moore[s], Daniel Pech[t], Susana Perera Valderrama[u], Gina M. Ralph[i], Kyle Strongin[a], Amy H. Ringwood[v],
9 Bernd Würsig[w]
10
11 *Corresponding author
12
13 **Affiliations**
14 [a] School of Mathematics and Natural Sciences, Arizona State University, 4701 W. Thunderbird Rd,
15 Glendale, Arizona 85306, USA.
16 [b] Department of Environmental Science, Baylor University, One Bear Place #97266, Waco, TX 76798,
17 United States
18 [c] Department of Biology and Biochemistry, 3455 Cullen Boulevard, #221E, University of Houston,
19 Houston, TX 77204-5001
20 [d] Halmos College of Arts and Sciences, Nova Southeastern University, 8000 North Ocean Drive, Dania, FL
21 33004, USA
22 [e] University of South Florida, College of Marine Science, 140 7th Ave S, St Petersburg, FL, 33701, USA
23 [f] Department of Environmental Sciences, University of California Riverside, 900 University Blvd.
24 Riverside, CA 92054
25 [g] Wise Laboratory of Environmental and Genetic Toxicology, 500 S. Preston St., 55A Department of
26 Pharmacology and Toxicology, University of Louisville, Louisville, KY 40292
27 [h] Centro de Investigación y Manejo Ambiental del Transporte (Cimab), Ctra. del Cristo esq. Tiscornia,
28 Casablanca, Habana, Cuba.
29 [i] International Union for Conservation of Nature Marine Biodiversity Unit, Department of Biological
30 Sciences, Old Dominion University, 5115 Hampton Blvd., Norfolk, Virginia 23529, USA
31 [j] Parque Nacional Guanahacabibes, Centro de Investigaciones y Servicios Ambientales (ECOVIDA),
32 Ministerio de Ciencia, Tecnología y Medio Ambiente (CITMA), La Bajada, 22100, Sandino, Pinar Del Río,
33 Cuba
34 [k] Huxley College of the Environment, Western Washington University, 516 High Street, Bellingham,
35 WA 98225-9079
36 [l] Museum of Zoology & Department of Ecology of Evolutionary Biology, University of Michigan, 1105 N.
37 University, Ann Arbor, MI 48109-1085 USA
38 [m] Centro de Investigaciones Marinas. Universidad de La Habana. Calle 16, No. 114 entre 1ra y 3ra,
39 Municipio Playa. La Habana, Cuba. CP: 11300
40 [n] Nicholas School of the Environment, Duke University, Research Drive, Durham, NC 27708, USA
41 [o] Florida State University Coastal and Marine Laboratory, 3618 Highway 98, St. Teresa, Florida 32358
42 [p] Terra Mar Applied Sciences, 1370 Tewkesbury Place NW, Washington, DC 20012, USA
43 [q] Ecotoxicology Program, Environmental Conservation Division, Northwest Fisheries Science
44 Center, National Oceanic and Atmospheric Administration, Seattle, WA 98112
45 [r] Lab. Biogeoquímica, UBIPRO, FES Iztacala, Universidad Nacional Autónoma de México. Av. de los
46 Barrios 1, Los Reyes Iztacala, Tlalnepantla, México, 54090, Mexico.
47 [s] Wilkes Honors College, Florida Atlantic University, 5353 Parkside Dr., Jupiter, FL 33458 USA and Harbor
48 Branch Oceanographic Institute, 5600 US 1, Ft. Pierce, FL 34964 USA

49 [t] Laboratorio de Biodiversidad Marina y Cambio Climático (BIOMARCCA), El Colegio de la Frontera Sur,
50 Lerma, 24500, Campeche, México
51 [u] National Commission for the Knowledge and Use of Biodiversity (CONABIO). Liga Periférico -
52 Insurgentes Sur 4903, Parques del Pedregal, Tlalpan, 14010, Mexico City, Mexico.
53 [v] Dept of Biology, 9201 University City Blvd, University of North Carolina Charlotte, Charlotte, NC 28223
54 [w] Department of Marine Biology, Texas A&M University at Galveston, 200 Seawolf Pkwy, Galveston, TX
55 77553, USA.
56
57

58 **Abstract**

59 A fundamental understanding of the impact of petrochemicals and other stressors on marine

60 biodiversity is critical for effective management, restoration, recovery, and mitigation initiatives. As

61 species-specific information on levels of petrochemical exposure and toxicological response are lacking

62 for the majority of marine species, a trait-based assessment to rank species vulnerabilities to

63 petrochemical activities in the Gulf of Mexico can provide a more comprehensive and effective means to

64 prioritize species, habitats, and ecosystems for improved management, restoration and recovery. To

65 initiate and standardize this process, we developed a trait-based framework, applicable to a wide range

66 of vertebrate and invertebrate species, that can be used to rank relative population vulnerabilities of

67 species to petrochemical activities in the Gulf of Mexico. Through expert consultation, 18 traits related

68 to likelihood of exposure, individual sensitivity, and population resilience were identified and defined.

69 The resulting multi-taxonomic petrochemical vulnerability framework can be adapted and applied to a

70 wide variety of species groups and geographic regions. Additional recommendations and guidance on

71 the application of the framework to rank species vulnerabilities under specific petrochemical exposure

72 scenarios, management needs or data limitations are also discussed.

73

74 **Introduction**

75 Globally, a multitude of activities including overfishing; pollution from sewage, erosion and sediment,

76 excess nutrients and oil spills; increased shipping and boat traffic; coastal development, dredging; and

2

77   intensive aquaculture (Karnauskas et al. 2013, Schirripa et al. 2013, Campagna et al. 2011) can

78   negatively impact populations of marine species and their habitats. Effective management, restoration,

79   and mitigation efforts for living marine resources requires comprehensive and extensive knowledge of

80   the status of complete clades of marine species and ecosystems, including their vulnerability to

81   combined or specific stressors, such as petrochemical exposure (Campagna et al. 2011). Resource

82   managers have long recognized the need for improved comprehensive species information to more

83   effectively select and prioritize species, habitats, and geographic areas for improved management,

84   restoration and recovery (Ottinger et al. 2019, Skyler et al. 2017, Campagna et al. 2011, Chakrabarty et

85   al. 2010). Similarly, oil and gas industries have recognized the need to maintain sustainable business

86   practices by better quantifying and reducing their impacts on living marine resources, while also

87   protecting their return on investment and managing business risk (Cordes et al. 2016).

88

89   In the Gulf of Mexico, which encompasses exclusive economic zones of Cuba, Mexico and the United

90   States, oil and gas operations are an important component of the economy, yet can have significant

91   impacts on living marine resources during all stages of operations (Holdway 2002, Ko and Day 2004,

92   Mendelssohn et al. 2012, among others). In United States and Mexican waters, the majority of

93   petrochemical activities, including permitting, environmental assessments and conservation or

94   restoration efforts, are focused on reducing impacts to critical habitats and species protected under the

95   U.S. Endangered Species Act or Mexico Norma 059 (Strongin et al. 2020, Wallace et al. 2017). However,

96   impacts to the majority of non-threatened or non-commercial marine species across the Gulf of Mexico

97   are generally ignored, due to the lack of information, regulatory preferences, or both. This presents an

98   extensive gap in critical, species-level information needed by resource managers to effectively prioritize

99   species, habitats, and ecosystems impacted by petrochemical activities for conservation, management,

100   restoration or recovery (Campagna et al. 2011).

101

102 During routine oil and gas activities, or in the event of a large oil spill, it is clear that a wide range of

103 marine species can be exposed to petrochemicals (Pulster et al. 2020, Sutton et al. 2020). Additionally,

104 the Gulf of Mexico is known to have extensive natural petrochemical seeps (Song et al. 2008, Kennicutt

105 et al. 1988, MacDonald et al. 2015) However, the biological and ecological impacts to marine species

106 ranging from relatively low, chronic exposures to severely, high, acute exposures are largely unknown

107 (Murawski et al. 2016, Pulster et al. 2020, Sutton et al. 2020). A major impediment is that acute or

108 chronic toxicity data for petrochemical exposures, regardless of individual biological response, are not

109 available for the majority of marine species. Single species toxicological testing is costly, can be

110 logistically impossible for animals that do not rear well in laboratory or mesocosm studies, and is

111 generally inefficient and time-consuming to conduct experimentally for all marine species (Romero et al.

112 2018, Romero et al. 2020). Furthermore, comparisons across different toxicological studies, even for the

113 same species, can be complex due to wide variation in environmentally-relevant exposures, chemical

114 mixtures, impacts on different life stages, and response parameters.

115

116 Regardless, available toxicity data derived from laboratory species or model organisms, are still often

117 considered representative of broader taxonomic groups. This approach is very useful in comparing

118 impacts from exposure across different chemicals and doses, but cannot generally account for the wide

119 variety of physiological and life history differences among species, which make some species more

120 vulnerable to adverse impacts. Moreover, while the importance of linking data from these experimental

121 approaches to population or ecosystem level impacts is widely recognized (Maltby et al. 2001, Moore et

122 al. 2006), it can be challenging due to the diversity of species-specific ecological and functional roles.

123

124   To guide conservation, restoration or recovery initiatives, population-level effects from cumulative

125   exposures to stressors may be more informative than data on the sensitivity of individual species to

126   stressors (Forbes et al. 2011, Spromberg and Birge 2005). Commonly, population-level assessments of

127   the impact of stressors are based on comparing relative abundance or other indicators in a threatened

128   "impacted site" with that of a "non-impacted site." However, this approach cannot always account for

129   natural differences in species abundance, synergistic effects, or other ecological factors that can

130   influence population sizes and function (Pacifici et al. 2015, Culp et al. 2011). Furthermore, observation

131   of direct impacts of threats are especially difficult to measure for the vast majority of marine species,

132   particularly those that are highly migratory, deep sea, or cryptic (Haney et al. 2017). For these reasons,

133   analysis of species-specific biological and ecological traits has been proposed as an improved approach

134   to comprehensively estimate relative species vulnerabilities to different stressors (Baird et al. 2008,

135   Rubach et al. 2011). Trait-based assessments, which use phenotypic or ecological characters of a species

136   to explain or predict variation and vulnerabilities in and across species, populations or ecological

137   systems, represent a new frontier in ecological risk assessment and biomonitoring of aquatic ecosystems

138   (De Lange et al. 2009, Van den Brink 2007, Poff et al. 2006, Usseglio Polatera et al. 2000).

139

140   Increasingly, trait-based frameworks are being developed to predict the vulnerability of individual

141   species, populations, and ecosystems to a number of past, current or future stressors (De Lange et al.

142   2009, Ottinger et al. 2019, King and McFarlane 2003) by identifying key traits that may increase the

143   relative tolerance or sensitivity of species or populations to a given threat (Rosenberger et al. 2017, Hare

144   et al. 2016, Chin et al. 2010) or combination of threats. The strengths of trait-based vulnerability

145   assessments are that species traits can be transferable to different geographic regions for similar

146   assessments of vulnerability to stressors, have both mechanistic and diagnostic components, generally

147   require no new field sampling, and serve to supplement taxonomic-based abundance analyses (Van den

148   Brink et al. 2011, Culp et al. 2011). Weaknesses include the generally low availability of marine species

149   trait data, low historic database quality, and the lack of standardization across species data and trait

150   information (Van den Brink et al. 2011). However, the methodology and species-specific information

151   generated by the IUCN Red List assessment process can address each of these weaknesses by involving

152   hundreds of regional scientists in data collection, peer-review and data synthesis processes, and by

153   providing a time-tested standardized process of species assessment, ranking of threats, and database

154   publication (Hoffmann et al. 2008, De Grammont and Cuarón 2006, Rodrigues et al. 2006).

155

156   Our objective was to develop a peer-reviewed, multi-taxonomic framework for estimating relative

157   marine species vulnerabilities to potential adverse impacts from petrochemical activities across the Gulf

158   of Mexico. The benefits of a unified vulnerability framework that can encompass multiple taxonomic

159   groups (e.g. all vertebrates and invertebrates) are that it allows for transparent reproducibility for

160   application in other regions, as well as direct comparisons of species and population-level vulnerabilities

161   to petrochemical impacts across disparate taxonomic groups. Application of the resulting framework

162   can serve as a valuable tool for coastal and marine managers, decision-makers and for coordination of

163   public policy.

164

165   **A Novel Multi-Taxonomic Framework for Ranking Population-level Petrochemical Vulnerability**

166   To develop the multi-taxonomic petrochemical vulnerability index (PVI) framework for marine

167   vertebrates and select groups of invertebrates in the Gulf of Mexico, 28 scientists representing a

168   breadth of taxonomic expertise in molecular or species sensitivities to petrochemicals, marine ecology,

169   pharmacokinetic modeling, and petrochemical environmental chemistry attended a PVI framework

170   development workshop, held in Guanahacabibes National Park, Cuba in June 2019. Workshop

171   participants worked collaboratively in three groups (fishes, invertebrates, and tetrapods) to discuss and

172   identify key species traits that influence the relative severity of petrochemical exposure, individual

173   sensitivity or response, and population resilience. In plenary each of the three groups presented their

174   results and worked collaboratively to synthesize their discussions into a single, cohesive framework. The

175   resulting framework was designed to be relevant for multiple taxonomic groups, but flexible in

176   application for a user to employ selective weighting of traits, customized ranking of questions, and

177   different scoring schemes depending upon the taxonomic group to be assessed and specific

178   characteristics of a petrochemical threat scenario. Given the resulting framework's flexibility in

179   application across different taxa and petrochemical threat scenarios, an important part of the

180   framework is an explicit assumption that states how each selected trait was perceived to operate in

181   terms of increasing vulnerability (Figure 1).

182

183   **Likelihood of Exposure:** Nine ecological and/or biological traits or factors were identified that may

184   increase the likelihood of a species encountering higher than baseline concentrations of petrochemicals

185   in the Gulf: Distribution, Water Column Position, Mobility, Longevity, Body Surface, Respiration Mode,

186   Feeding Behavior, Longevity of Most Sensitive Pre-Adult Stage, and Distribution and/or Mobility of Most

187   Sensitive Pre-Adult Stage.

188

189   One of the most important factors that directly increases likelihood of exposure is whether or not the

190   species occurs in areas with high probability of encountering petrochemicals. Although more direct

191   measurements of exposure should be made by mapping species distributions across specific scenarios of

192   known or modeled petrochemical concentrations, indirect estimations can be calculated based on the

193   proportion of a species range that overlaps areas of high petrochemical activity (e.g. areas with a higher

194   number of platforms, density of shipping routes, proximity of refineries, current or historic locations of

195   common or catastrophic oil spills, etc.). Water Column Position is also very scenario specific, in that

196 increased exposure could occur at the surface, in the event of a surface spill, or much lower in the water

197 column or near the sea floor in the event of a deep-water blow-out, as occurred during the *Deepwater*

198 *Horizon* blow-out in 2010, or through settling and sedimentation (Romero et al. 2017, Passow 2016, Daly

199 et al. 2016). In this sense, species that are benthic, benthopelagic, epipelagic, or spend a lot of time on

200 the surface (e.g. marine mammals, sea turtles and seabirds), may have increased exposures compared

201 to meso or bathypelagic species.

202

203 The likelihood of a species being exposed to petrochemicals within its distribution also increases if that

204 species is sessile, and/or not able or likely to move out of the area of exposure, which can also result in

205 prolonged exposures and/or multiple exposures over time (McKinley and Johnston 2010). In spill

206 scenarios, such as Deepwater Horizon, where oil dispersants are applied on a large-scale, the exposure

207 to additional chemicals has been shown to amplify the impact on sessile species, such as corals (DeLeo

208 et al. 2016). Similarly, longer-lived species may experience increased, multiple exposures over time.

209 Although placed here within the Exposure component, Longevity is also an important trait in terms of

210 Population Resilience, as species with longer-life spans tend to be slower to recover from disturbance,

211 as they can experience increased annual adult mortality rates (measured as percentage of loss per year)

212 compared to shorter-lived species over more years (Mace et al. 2008, Ottinger 2010).

213

214 In traditional toxicology, primary routes of exposure are considered to be dermal, oral or respiratory

215 (Golden and Rattner 2003, Tormoehlen et al. 2014). For these reasons, Body Surface Type, Respiratory

216 Mode and Feeding or Other Behaviors should be included as important exposure pathways in marine

217 species. Although additional studies are likely needed on the relative degree of exposure differences

218 among species with different body surface coverings, diets and respiratory modes, the assumptions are

219 that certain body covering types (e.g. skin, feathers, scales), respiratory modes (e.g. lungs, gills, skin,

220   diffusion) and feeding/grooming behaviors (e.g. surface feeders, deposit feeders, filter feeders,

221   preening) will result in differential uptake or absorption of petrochemicals. Interestingly, some studies

222   have shown that petrochemically-derived polycyclic aromatic hydrocarbons (PAHs) may undergo trophic

223   dilution in marine food webs, potentially due to low assimilation efficiencies and more efficient

224   metabolic transformations in species occupying higher trophic levels (Wan et al. 2007).

225

226   For species that reproduce sexually, the most vulnerable life stage in terms of both likelihood of

227   exposure and/or sensitivity, may be during pre-adult stages, such in the embryonic, larval or juvenile

228   stages (Carls and Meador 2009, Adams et al. 2014a, West et al. 2014, Sørhus et al. 2016, Heintz et al.

229   1999, Heintz et al. 2000, Sørhus et al. 2017). This stage is especially important for those species that

230   reproduce only once in a year, or for a short period of time in a year (e.g, hermatypic corals, sponges,

231   etc.). By contrast, species that reproduce asexually, may be more resilient to contaminant impacts

232   (Archambault et al. 2010, Richmond et al. 2018). To account for exposure differences among species

233   with more sensitive pre-adult stages, the likelihood of exposure for the most sensitive pre-adult stage

234   should be estimated based on known or modelled overlap of the pre-adult stage distribution with

235   petrochemical concentrations and/or activities, especially if the distributions of pre-adults, such as

236   planktonic larval stages, are different than that of adults. Similarly, the longevity of the most sensitive

237   pre-adult stage, which can range from a few days or weeks (e.g. coral and oyster larvae, some fish

238   larvae) to months (e.g. shark eggs, sea turtle eggs, sea bird eggs) or years (e.g. embryonic or juvenile

239   marine mammals) for both sexually and asexually reproducing species, is important to capture the

240   increasing likelihood of multiple or prolonged exposures during the critical stages of development and

241   recruitment of pre-adults.

242

243 **Species Sensitivity:** Five ecological and/or biological traits were identified that may be related to

244 increased adverse responses or outcomes of species already exposed to petrochemicals in the Gulf:

245 Toxicokinetics, Body Surface Function, Exposure to UV Light, Most Sensitive Pre-Adult Stage Form, and

246 Presence of Other Chemical or Environmental Stressors.

247

248 Although the number of studies on the toxicokinetics of PAHs and other components of petrochemicals

249 in marine organisms is widely growing, there is still very little known on uptake, maternal transfer,

250 metabolism and elimination of these compounds (or combination of compounds) for the majority of

251 marine species or their sensitive life stages (Grech et al. 2017). Regardless, species-specific differences in

252 uptake, metabolism, and biomarker response from exposure to PAHs have been well-documented (Jung

253 et al. 2015, Sørensen et al .2017, Grech et al. 2019), such that measured body burdens of PAHs in

254 different species without complementary biomarker or other toxicological studies cannot reliably

255 predict differences in species' exposures or toxicological responses (Hueter 2012). Uptake rates of

256 individual PAH's can vary by compound, species respiration rate, gill structure and exposure duration

257 (Jonsson et al. 2004). Similarly, uptake, metabolism and elimination may also be influenced by life stage

258 as embryonic stages may be more or less sensitive due to limited toxicokinetic capabilities.

259

260 Body surface covering can be considered a component of toxicokinetic models, as physiological and

261 biochemical differences among skin membranes, feathers and scales may differentially facilitate the

262 uptake of PAHs from the aquatic environment. However, surface coverings can also influence different

263 exposure routes and physiological function, such as ingestion of oil by preening birds and/or significant

264 changes in mobility, water repellency and insulation due to oiled feathers (Leighton 1993). Further,

265 ingested contaminants often transfer to eggs, thereby exposing the embryo throughout development

266 (Lin et al, 2004; Ottinger et al, 2005).

267

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 (Butt et al. in prep, Carrier et al. 2018).

279

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-

Martinez 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,

291 population reductions caused by exposures to petrochemicals (Lewis et al. 2020, Harley and Rogers-

292 Bennett 2004).

293

294 **Population Resilience:** Four ecological and/or biological traits were identified that are related to

295 increases or decreases in population resilience, regardless of stressor type. These include Abundance,

296 Population Connectivity, Reproductive Turnover, and Feeding or Habitat Specialization.

297

298 In general, species extinctions and/or local extirpations occur when the mortalities or emigration rates

299 are greater than births or immigration rates (Mace et al. 2008). As such, the likelihood of significant

300 population reduction leading to extinction or local extirpation is higher when population sizes are small

301 or abundance is low. Very small populations also have increased susceptibility to demographic

302 stochasticity, where even random variations in birth or death rates can lead to population declines

303 (Richter-Dyn and Goel 1972, Goodman 1987). Similarly, populations that are highly fragmented or

304 poorly connected cannot benefit from any rescue effects due to low rates of immigration of new

305 individuals to the impacted population (Mace et al. 2008). This connectivity concept is critically

306 important for many marine species where the movement or dispersal capabilities of larval propagules is

307 essential for metapopulation maintenance, and can be significantly greater in distance than those of

308 more sedentary or less mobile adult stages (Grantham et al. 2003, Hanski and Ovaskainen 2003).

309

310 Reproductive turnover refers to the rate at which cohorts of new breeding individuals are added to the

311 population, and can be measured in a variety of ways including generation time (Mace et al. 2008) or

312 population turnover (Salguero-Gomez et al. 2016). It has been well-documented that later-maturing,

313 slower-growing and longer-lived species, even with higher fecundities, can be at greater risk from

314 increased annual mortality rates and experience longer population recovery times compared to earlier-

12

315 maturing, faster-growing, and shorter-lived species (Mace et al. 2008, Winemiller 2005, Bell et al. 2014,

316 Murua et al. 2017, Oliver et al. 2015). Further, the attenuation of lifespan due to environmental

317 challenges in combination with reduced productivity/offspring survival can have profound population

318 level impacts over time.

319

320 Species with narrowly-defined niches are more likely to be feeding or habitat specialists, with a lower

321 capacity to respond to stressors that drive changes in habitat or feeding conditions (Slatyer et al. 2013).

322 Species with broader habitat ranges experience a wider range of conditions and environments and are

323 expected to have greater ecological versatility and therefore lower vulnerability (Wilson et al. 2008,

324 Munday 2004, among others). Similarly, species with smaller breadth of diet, and/or with reliance on

325 interspecific interactions, may be more vulnerable to changes in ecosystems, habitats and

326 environmental conditions (González-Suárez et al. 2013, Bender et al. 2013, Sunday et al. 2015).

327

328 **Considerations for Application**

329 In order to apply the framework and derive species-specific petrochemical vulnerability rankings for a

330 given petrochemical threat scenario, measurable and/or well-defined indicators of each trait that can

331 account for differences among species need to be identified. Based on the indicators selected, relevant

332 ranking questions are developed ideally within a custom petrochemical threat scenario, along with a

333 logical scoring scheme. As an example, Golden and Rattner (2003) developed a similar type of scoring

334 scheme specifically to rank bird species' vulnerabilities to petroleum crude oil. Other examples of

335 application of ranking questions and scoring schemes to estimate relative species vulnerabilities to

336 climate change have been developed for fishes (Hare et al. 2016), corals (Foden et al. 2013), and sharks

337 (Chin et al. 2010).

338   In some cases, depending upon the threat scenario and/or taxonomic groups to be ranked,

339   weighting of critical traits may be desired. For example, in the event of an oil spill that occurs primarily

340   as a surface slick, traits that estimate exposure and sensitivity of pre-adult fishes may need to be

341   weighted or have higher scoring schemes to account for the increased vulnerability of fish species with

342   buoyant eggs or more sensitive larval stages that spend extended time at the surface. A deep-water

343   subsurface spill, in contrast, has the potential to impact species throughout the water column

344   depending upon the response option employed. The scoring scheme should therefore account for the

345   additional risk to vulnerable mesopelagic and deep-water benthic species.

346

347   A key benefit of this framework lies in the potential for active application in pre-spill planning exercises

348   to increase spill response preparedness, such as Net Environmental Benefit Analysis (NEBA). NEBA is a

349   structured management tool that informs the relative advantages and disadvantages of response

350   options for oil spills, and prioritizes environmental outcomes. The NEBA process can be significantly

351   limited, however, by knowledge gaps and uncertainties regarding relative species vulnerabilities. By

352   using all available data to fill these data gaps, the framework can substantially contribute to improving

353   oil spill response.

354

355   To account for data gaps in life history and other traits, a number of different methods can be

356   employed, such as assigning a middle or neutral score for unknown values, conducting random forest

357   analyses or other machine learning techniques to impute missing trait values among similar species

358   (Comeros-Raynal et al. 2016), or assigning an uncertainty or error value to final rankings based on

359   relative amount of data gaps underlying each species' final ranking.

360

361   The strength or validity of final species rankings should be tested through sensitivity analyses, such as

362   those that explore differences in results when selected traits are removed or perhaps weighted

363   differently. Furthermore, final ranking results can also be tested or validated by comparing the final

364   relative species vulnerability rankings with published toxicological endpoints related to acute or chronic

365   impacts. However, given the large variation in laboratory methods, species uptake rates, physiological

366   responses, oil/contaminant type, and both field or laboratory doses, extreme care needs to be taken in

367   correlating disparate toxicological response studies or field-derived PAH body burdens with final species

368   rankings.

369

370   Lastly, as knowledge of toxicological responses, distributions, and life history traits of species are

371   expanded, the PVI framework can be adapted and adjusted by incorporating new data inputs, improved

372   ranking and scoring schemes, and refinement of trait weighting scenarios. In this sense, this PVI should

373   be treated as a living framework that can be adapted to a number of different threat scenarios,

374   taxonomic groups, and refinements in ecological and toxicological information over time.

375

383
384   **Tables and Figures**

Figure 1: Traits, assumptions and example indicators for a multispecies Petrochemical Vulnerability

Index framework based on likelihood of exposure, sensitivity and population resilience.

References

Adams, J., Bornstein, J.M., Munno, K., Hollebone, B., King, T., Brown, R.S., Hodson, P.V. 2014a. Identification of compounds in heavy fuel oil that are chronically toxic to rainbow trout embryos by effects-driven chemical fractionation. *Environmental Toxicology and Chemistry* 33 (4): 825–835.

Adams, J., Sweezey, M., Hodson, P.V. 2014b. Oil and oil dispersant do not cause synergistic toxicity to fish embryos. *Environmental Toxicology and Chemistry* 33: 107-114.

Almeda, R., Harvey, T.E., Connelly, T.L., Baca, S., Buskey, E.J., 2016. Influence of UVB radiation on the lethal and sublethal toxicity of dispersed crude oil to planktonic copepod nauplii. *Chemosphere* 152: 446-458.

Archaimbault, V., Usseglio-Polatera, P., Garric, J., Wasson, J.G., Babut, M. 2010. Assessing pollution of toxic sediment in streams using bio-ecological traits of benthic macroinvertebrates. *Freshwater Biology* 55(7): 1430-1446.

Baird, D.J., Rubach, M.N., Van den Brinkt, P.J. 2008. Trait-based ecological risk assessment (TERA): The new frontier? *Integrated Environmental Assessment and Management* 4(1): 2-3.

Barron, M.G., Carls, M.G., Short, J.W., Rice, S.D. 2003. Photoenhanced toxicity of aqueous phase and chemically dispersed weathered Alaska North Slope crude oil to Pacific herring eggs and larvae. *Environmental Toxicology and Chemistry: An International Journal* 22(3): 650-660.

Bell, J.J., Smith, D., Hannan, D., Haris, A., Jompa, J., Thomas, L. 2014. Resilience to disturbance despite limited dispersal and self-recruitment in tropical barrel sponges: implications for conservation and management. *PLoS One* 9(3): e91635.

Bender, M.G., Floeter, S.R., Mayer, F.P., Vila-Nova, D.A, Longo, G.O., Hanazaki, N., Carvalho-Filho, A., Ferreira, C.E.L. 2013. Biological attributes and major threats as predictors of the vulnerability of species: a case study with Brazilian reef fishes. *Oryx* 47: 259-265.

Buskey, E.J., White, H.K., Esbaugh, A.J., 2016. Impact of oil spills on marine life in the Gulf of Mexico: effects on plankton, nekton, and deep-sea benthos. *Oceanography* 29(3): 174-181.

430 Campagna, C., Short, F.T., Polidoro, B.A., McManus, R., Collette, B.B., Pilcher, N.J., Sadovy de Mitcheson,
431 Y., Stuart, S.N., Carpenter, K.E., 2011. Gulf of Mexico oil blowout increases risks to globally threatened
432 species. *BioScience* 61(5): 393-397.

434 Carls, M. G., Meador, J.P. 2009. A perspective on the toxicity of petrogenic PAHs to developing fish
435 embryos related to environmental chemistry. *Human and Ecological Risk Assessment* 15: 1084–1098.

437 Carrier, T.J., Reitzel, A.M., Heyland, A. eds., 2018. *Evolutionary ecology of marine invertebrate larvae.*
438 Oxford University Press.

440 Chakrabarty, P., Lam, C., Hardman, J., Aaronson, J., House, P.H., Janies, D.A. 2012. Species Map: a web-
441 based application for visualizing the overlap of distributions and pollution events, with a list of fishes put
442 at risk by the 2010 Gulf of Mexico oil spill. *Biodiversity and Conservation* 21(7): 1865-1876.

444 Chin, A., Kyne, P.M., Walker, T.I., Mcauley, R.B. 2010. An integrated risk assessment for climate change:
445 analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. *Global Change
446 Biology* 16(7): 1936-1953.

448 Comeros-Raynal, M., Polidoro, B.A.**,** Broatch, J., Mann, B.Q., Gorman, C., Buxton, C.D., Goodpaster, A.M.,
449 Iwatsuki, Y., McDonald, T.C., Pollard, D., Russell, B., Carpenter, K.E. 2016. Key predictors of extinction
450 risk in sea breams and porgies (Family: Sparidae). *Biological Conservation* 202: 88-98.

452 Cordes, E.E., Jones, D.O., Schlacher, T.A., Amon, D.J., Bernardino, A.F., Brooke, S., Carney, R., DeLeo,
453 D.M., Dunlop, K.M., Escobar-Briones, E.G., Gates, A.R. 2016. Environmental impacts of the deep-water
454 oil and gas industry: a review to guide management strategies. *Frontiers in Environmental Science* 4: 58.

456 Culp, J.M., Armanini, D.G., Dunbar, M.J., Orlofske, J.M., Poff, N.L., Pollard, A.I., Yates, A.G., Hose, G.C.
457 2011. Incorporating traits in aquatic biomonitoring to enhance causal diagnosis and
458 prediction. *Integrated Environmental Assessment and Management 7*(2): 187-197.

460 Daly, K.L., Passow, U., Chanton, J., Hollander, D. 2016. Assessing the impacts of oil-associated marine
461 snow formation and sedimentation during and after the Deepwater Horizon oil spill. *Anthropocene 13*:
462 18-33.

464 Dasgupta, S., Huang, I.J., McElroy, A.E. 2015. Hypoxia enhances the toxicity of Corexit EC9500A and
465 chemically dispersed Southern Louisiana Sweet Crude Oil (MC-242) to sheepshead minnow (*Cyprinodon
466 variegatus)* larvae. *PloS one* 10(6): e0128939.

468 de Grammont, P.C., Cuarón, A.D. 2006. An evaluation of threatened species categorization systems used
469 on the American continent. *Conservation Biology* 20: 14-27.

471 De Lange, H.J., Lahr, J., Van der Pol, J.J., Wessels, Y., Faber, J.H. 2009. Ecological vulnerability in wildlife:
472 an expert judgment and multicriteria analysis tool using ecological traits to assess relative impact of
473 pollutants. *Environmental Toxicology and Chemistry: An International Journal* 28(10): 2233-2240.

475 De Leo, D.M., Ruiz-Ramos, D.V., Baums, I.B., Cordes, E.E. 2016. Response of deep-water corals to oil and
476 chemical dispersant exposure. *Deep Sea Research Part II: Topical Studies in Oceanography* 129: 137-147.
477

478 Dussauze, M., Pichavant-Rafini, K., Le Floch, S., Lemaire, P., Theron, M. 2015. Acute toxicity of chemically
479 and mechanically dispersed crude oil to juvenile sea bass (*Dicentrarchus labrax*): Absence of synergistic
480 effects between oil and dispersants. *Environmental Toxicology and Chemistry* 34(7): 1543-1551.
481
482 Foden, W.B., Butchart, S.H., Stuart, S.N., Vié, J.C., Akçakaya, H.R., Angulo, A., DeVantier, L.M.,
483 Gutsche, A., Turak, E., Cao, L. Donner, S.D. 2013. Identifying the world's most climate change vulnerable
484 species: a systematic trait-based assessment of all birds, amphibians and corals. *PloS one 8*: e65427.
485
486 Forbes, V.E., Calow, P., Grimm, V., Hayashi, T.I., Jager, T., Katholm, A., Palmqvist, A., Pastorok, R., Salvito,
487 D., Sibly, R., Spromberg, J. 2011. Adding value to ecological risk assessment with population
488 modeling. *Human and Ecological Risk Assessment* 17(2): 287-299.
489
490 Golden, N.H., Rattner, B.A. 2003. Ranking terrestrial vertebrate species for utility in biomonitoring and
491 vulnerability to environmental contaminants. Pages 67-136 in *Reviews of Environmental Contamination
492 and Toxicology*, Springer, New York, NY.
493
494 González-Suárez M, Gómez A, Revilla E. 2013 Which intrinsic traits predict vulnerability to extinction
495 depends on the actual threatening processes. *Ecosphere* 4: 1-16.
496
497 Goodman, D. 1987. The demography of chance extinction. Pages 11–34 in M.E. Soulé (Ed). *Viable
498 Populations for Conservation*. Cambridge University Press, Cambridge, United Kingdom.
499
500 Grantham, B.A., Eckert, G.L., Shanks, A.L. 2003. Dispersal potential of marine invertebrates in diverse
501 habitats: Ecological Archives A013-001-A1. *Ecological Applications 13*: 108-116.
502
503 Grech, A., Brochot, C., Dorne, J.L., Quignot, N., Bois, F.Y., Beaudouin, R. 2017. Toxicokinetic models and
504 related tools in environmental risk assessment of chemicals. *Science of The Total Environment* 578: 1-15.
505
506 Grech, A., Tebby, C., Brochot, C., Bois, F.Y., Bado-Nilles, A., Dorne, J.L., Quignot, N., Beaudouin, R. 2019.
507 Generic physiologically-based toxicokinetic modelling for fish: Integration of environmental factors and
508 species variability. *Science of the Total Environment* 651: 516-531.
509
510 Hanski, I., Ovaskainen, O. 2003. Metapopulation theory for fragmented landscapes. *Theoretical
511 Population Biology* 64(1): 119-127.
512
513 Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, E.J., Griffis, R.B., Alexander, M.A.,
514 Scott, J.D., Alade, L., Bell, R.J., Chute, A.S. 2016. A vulnerability assessment of fish and invertebrates to
515 climate change on the Northeast US Continental Shelf. *PloS one 11*(2): e0146756.
516
517 Haney, J.C., Jodice, P.G., Montevecchi, W.A., Evers, D.C. 2017. Challenges to oil spill assessment for
518 seabirds in the deep ocean. *Archives of Environmental Contamination and Toxicology 73*(1): 33-39.
519
520 Harley, C.D., Rogers-Bennett, L. 2004. The potential synergistic effects of climate change and fishing
521 pressure on exploited invertebrates on rocky intertidal shores. *California Cooperative Oceanic Fisheries
522 Investigations Report 45:* 98.
523

524   Heintz, R.A., Short, J.W., Rice, S.D. 1999. Sensitivity of fish embryos to weathered crude oil: Part 2.
525   Increased mortality of pink salmon (*Oncorhynchus gorbuscha*) embryos incubating down- stream from
526   weathered Exxon Valdez Crude Oil. *Environmental Toxicology and Chemistry* 18(3): 494–503.

528   Heintz, R.A., Rice, S.D., Wertheimer, A.C., Bradshaw, R.F., Thrower, F.P., Joyce, J.E., Short, J.W., 2000.
529   Delayed effects on growth and marine survival of pink salmon *Oncorhynchus gorbuscha* after exposure
530   to crude oil during embryonic development. *Marine Ecology Progress Series* 208: 205-216.

532   Hoffmann, M., Brooks, T.M., da Fonseca, G.A., Gascon, C., Hawkins, A.F.A., James, R.E., Langhammer, P.,
533   Mittermeier, R.A., Pilgrim, J.D., Rodrigues, A.S.L., Silva, J.M.C. 2008. Conservation planning and the IUCN
534   Red List. *Endangered Species Research* 6: 113-125.

536   Holdway, D.A. 2002. The acute and chronic effects of wastes associated with offshore oil and gas
537   production on temperate and tropical marine ecological processes. *Marine Pollution Bulletin* 44: 185-
538   203.

540   Hueter, R.E. 2012. Mote Marine Laboratory: Effects of the Deepwater Horizon Oil Spill on epipelagic and
541   large coastal sharks and teleosts of the Gulf of Mexico. *FIO Block Grants-Final Report*.

543   Jonsson, G., Bechmann, R.K., Bamber, S.D., Baussant, T. 2004. Bioconcentration, biotransformation, and
544   elimination of polycyclic aromatic hydrocarbons in sheepshead minnows (*Cyprinodon variegatus*)
545   exposed to contaminated seawater. *Environmental Toxicology and Chemistry: An International Journal*
546   *23*(6): 1538-1548.

548   Jung, J.H., Kim, M., Yim, U.H., Ha, S.Y., Shim, W.J., Chae, Y.S., Kim, H., Incardona, J.P., Linbo, T.L., Kwon,
549   J.H. 2015. Differential toxicokinetics determines the sensitivity of two marine embryonic fish exposed to
550   Iranian Heavy Crude Oil. *Environmental Science and Technology 49*(22): 13639-13648.

552   Karnauskas, M., Schirripa, M.J., Kelble, C.R., Cook, G.S., Craig, J.K. 2013. Ecosystem status report for the
553   Gulf of Mexico. *NOAA Technical Memorandum NMFS-SEFSC 653*: 52.

555   Kennicutt, M.C. II, Brooks, J.M., Atlas, E.L., Giam, C.S. 1988. Organic compounds of environmental
556   concern in the Gulf of Mexico: a review. *Aquatic Toxicology* 11: 191–212.

558   King, J.R., McFarlane, G.A. 2003. Marine fish life history strategies: applications to fishery
559   management. *Fisheries Management and Ecology 10*(4): 249-264.

561   Ko, J.Y., Day, J.W. 2004. A review of ecological impacts of oil and gas development on coastal
562   ecosystems in the Mississippi Delta. *Ocean & Coastal Management 47*: 597-623.

564   Leighton, F.A. 1993. The toxicity of petroleum oils to birds. *Environmental Reviews 1*(2): 92-103.

566   Lewis, J.P., Tarnecki, J.H., Garner, S.B., Chagaris, D.D., Patterson, W.F. 2020. changes in reef fish
567   community structure following the Deepwater Horizon oil spill. *Scientific Reports 10*(1): 1-13.

569   Lin, F., Wu, J., Abdelnabi, M.A., Ottinger, M.A., Giusti, M.M. 2004. Effects of dose and glycosylation on
570   the transfer of genistein into the eggs of the Japanese quail (*Coturnix japonica*). *Journal of Agricultural*
571   *and Food Chemistry 52*(8): 2397-2403.

572

573 Logan, D.T. 2007. Perspective on ecotoxicology of PAHs to fish. *Human and Ecological Risk*
574 *Assessment 13*(2): 302-316.

575

576 MacDonald, I.R., Garcia-Pineda, O., Beet, A., Daneshgar Asl, S., Feng, L., Graettinger, G., French-McCay,
577 D., Holmes, J., Hu, C., Huffer, F., Leifer, I. 2015. Natural and unnatural oil slicks in the Gulf of
578 Mexico. *Journal of Geophysical Research: Oceans 120*(12): 8364-8380.

579

580 Mace, G.M., Collar, N.J., Gaston, K.J., Hilton-Taylor, C., Akçakaya, H.R., Leader-Williams, N., Milner-
581 Gulland, E.J., Stuart, S.N. 2008. Quantification of extinction risk: IUCN's system for classifying threatened
582 species. *Conservation Biology 22*(6): 1424-1442.

583

584 Maltby, L, T.J. Kedwards, V.E. Forbes, K. Grasman, J.E. Kammenga, W.R. Munns, Jr., A.H. Ringwood, J.S.
585 Weis, S.N. Wood. 2001. Linking individual-level responses and population-level consequences. Pages 27-
586 82 in D.J. Baird & G.A. Burton, Jr. (Eds) *Ecological Complexity: New Directions for Assessing Responses to*
587 *Stress*, SETAC Special Publication Series.

588

589 McKinley, A., Johnston, E.L. 2010. Impacts of contaminant sources on marine fish abundance and species
590 richness: a review and meta-analysis of evidence from the field. *Marine Ecology Progress Series 420*:
591 175-191.

592

593 Mendelssohn, I.A., Andersen, G.L., Baltz, D.M., Caffey, R.H., Carman, K.R., Fleeger, J.W., Joye, S.B., Lin,
594 Q., Maltby, E., Overton, E.B., Rozas, L.P. 2012. Oil impacts on coastal wetlands: implications for the
595 Mississippi River Delta ecosystem after the Deepwater Horizon oil spill. *BioScience 62*(6): 562-574.

596

597 Moore, M.N., J. I. Allen, A. McVeigh. 2006. Environmental prognostics: an integrated model supporting
598 lysosomal stress responses as predictive biomarkers of animal health status. *Marine Environmental*
599 *Research* 61: 278-304.

600

601 Munday, P.L. 2004. Habitat loss, resource specialization, and extinction on coral reefs. *Global Change*
602 *Biology 10*(10): 1642-1647.

603

604 Murawski, S.A., Fleeger, J.W., Patterson, III W.F., Hu, C., Daly, K., Romero, I.C., Toro-Farmer, G.A. 2016.
605 How did the Deepwater Horizon oil spill affect coastal and continental shelf ecosystems of the Gulf of
606 Mexico? *Oceanography* 29:160–173.

607

608 Murua, H., Rodriguez-Marin, E., Neilson, J.D., Farley, J.H., Juan-Jordá, M.J., 2017. Fast versus slow
609 growing tuna species: age, growth, and implications for population dynamics and fisheries
610 management. *Reviews in Fish Biology and Fisheries 27*(4): 733-773.

611

612 Newsted, J.L., Giesy, J.P. 1987. Predictive models for pho-toinduced acute toxicity of polycyclic aromatic
613 hydrocarbons to *Daphnia magna*, Strauss (Cladocera, Crustacea). *Environmental Toxicology and*
614 *Chemistry* 6: 445–461.

615 Oliver, T.H., Heard, M.S., Isaac, N.J., Roy, D.B., Procter, D., Eigenbrod, F., Freckleton, R., Hector, A.,
616 Orme, C.D.L., Petchey, O.L., Proença, V. 2015. Biodiversity and resilience of ecosystem functions. *Trends*
617 *in Ecology & Evolution 30*(11): 673-684.

618

619 Ottinger, M.A. 2010. Mechanisms of reproductive aging: conserved mechanisms and environmental
620 factors. *Annals of the New York Academy of Sciences 1204*: 73.

622 Ottinger, M.A., Wu, J.M., Hazelton, J.L., Abdelnabi, M.A., Thompson, N., Quinn Jr, M.L., Donoghue, D.,
623 Schenck, F., Ruscio, M., Beavers, J., Jaber, M. 2005. Assessing the consequences of the pesticide
624 methoxychlor: neuroendocrine and behavioral measures as indicators of biological impact of an
625 estrogenic environmental chemical. *Brain Research Bulletin 65*(3):199-209.

627 Ottinger, M.A., Manness, T., Grace, J.K., Wilson, R.R., Jodice, P.G.R. 2019. Avian health assessments. In
628 Gulf of Mexico Avian Monitoring Network Strategic Avian Monitoring Plan. Eds: Wilson, RR., Fournier
629 AMV., Gleason JS., Lyons JE., Woodrey. Mississippi State University Research Bulletin 1228.

631 Pacifici, M., Foden, W.B., Visconti, P., Watson, J.E., Butchart, S.H., Kovacs, K.M., Scheffers, B.R., Hole,
632 D.G., Martin, T.G., Akçakaya, H.R., Corlett, R.T. 2015. Assessing species vulnerability to climate
633 change. *Nature Climate Change 5*(3): 215-224.

635 Passow, U. 2016. Formation of rapidly-sinking, oil-associated marine snow. *Deep Sea Research Part II:
636 Topical Studies in Oceanography 129*: 232-240.

638 Pelletier, M.C., Burgess, R.M., Ho, K.T., Kuhn, A., McKinney, R.A., Ryba, S.A. 1997. Phototoxicity of
639 individual polycyclic aromatic hydrocarbons and petroleum to marine invertebrate larvae and
640 juveniles. *Environmental Toxicology and Chemistry: An International Journal 16*(10): 2190-2199.

642 Poff, N.L., Olden, J.D., Vieira, N.K., Finn, D.S., Simmons, M.P., Kondratieff, B.C. 2006. Functional trait
643 niches of North American lotic insects: traits-based ecological applications in light of phylogenetic
644 relationships. *Journal of the North American Benthological Society 25*(4): 730-755.

646 Pulster, E.L., Gracia, A., Armenteros, M., Toro-Farmer, G., Snyder, S.M., Carr, B.E., Schwaab, M.R.,
647 Nicholson, T.J., Mrowicki, J., Murawski, S.A. 2020. A first comprehensive baseline of hydrocarbon
648 pollution in Gulf of Mexico fishes. *Scientific Reports 10*(1): 1-14.

650 Qian, J., Ding, Q., Guo, A., Zhang, D., Wang, K. 2017. Alteration in successional trajectories of
651 bacterioplankton communities in response to co-exposure of cadmium and phenanthrene in coastal
652 water microcosms. *Environmental Pollution 221*: 480-490.

654 Richmond, R.H., Tisthammer, K.H., Spies, N.P. 2018. The effects of anthropogenic stressors on
655 reproduction and recruitment of corals and reef organisms. *Frontiers in Marine Science 5*: 226.

657 Richter-Dyn, N., Goel, N.S. 1972. On the extinction of a colonizing species. *Theoretical Population Biology*
658 3**:** 406–433.

660 Rico-Martínez, R., Snell, T.W., Shearer, T.L. 2013. Synergistic toxicity of Macondo crude oil and
661 dispersant Corexit 9500A® to the *Brachionus plicatilis* species complex (Rotifera). *Environmental
662 Pollution 173*: 5-10.

664 Rodrigues, A.S., Pilgrim, J.D., Lamoreux, J.F., Hoffmann, M., Brooks, T.M. 2006. The value of the IUCN
665 Red List for conservation. *Trends in Ecology & Evolution* 21**:** 71-76.

667 Romero, I.C., Toro-farmer, G., Diercks, A., Schwing, P., Muller-Karger, F., Murawski, S., Hollander, D.J.
668 2017. Large-scale deposition of weathered oil in the Gulf of Mexico following a deep-water oil spill.
669 *Environmental Pollution* 228: 179–189.

671 Romero, I.C., Sutton, T., Carr, B., Quintana-Rizzo, E., Ross, S.W., Hollande,r D.J., Torres, J.J. 2018. A
672 decadal assessment of polycyclic aromatic hydrocarbons in mesopelagic fishes from the Gulf of Mexico
673 reveals exposure to oil-derived sources. *Environmental Science and Technology* 52(19): 10985-10996

675 Romero, I.C., Judkins, H., Vecchione, M. 2020. Temporal variability of polycyclic aromatic hydrocarbons
676 in deep-sea cephalopods of the northern Gulf of Mexico. *Frontiers in Marine Science 7*: 54.

678 Rosenberger, A.L.J., MacDuffee, M., Rosenberger, A.G. and Ross, P.S., 2017. Oil spills and marine
679 mammals in British Columbia, Canada: Development and application of a risk-based conceptual
680 framework. *Archives of Environmental Contamination and Toxicology 73*(1): 131-153.

682 Rubach, M.N., Ashauer, R., Buchwalter, D.B., De Lange, H.J., Hamer, M., Preuss, T.G., Töpke, K., Maund,
683 S.J. 2011. Framework for traits-based assessment in ecotoxicology. *Integrated Environmental
684 Assessment and Management 7*(2): 172-186.

686 Salguero-Gómez, R., Jones, O.R., Jongejans, E., Blomberg, S.P., Hodgson, D.J., Mbeau-Ache, C., Zuidema,
687 P.A., de Kroon, H., Buckley, Y.M. 2016. Fast–slow continuum and reproductive strategies structure plant
688 life-history variation worldwide. *Proceedings of the National Academy of Sciences 113*(1): 230-235.

690 Suchanek, T.H. 1993. Oil impacts on marine invertebrate populations and communities. *American
691 Zoologist 33*(6): 510-523.

693 Slatyer, R.A., Hirst, M., Sexton, J.P. 2013. Niche breadth predicts geographical range size: a general
694 ecological pattern. *Ecology Letters 16*(8): 1104-1114.

696 Schirripa, M.J., Allee, B., Cross, S., Kelble, C., Parsons, A.R. 2013. Progress towards an integrated
697 ecosystem assessment for the Gulf of Mexico. *Collective Volume of Scientific Papers ICCAT 69*(4): 1867-
698 1875.

700 Sagarese, S.R., Lauretta, M.V., Walter III, J.F. 2017. Progress towards a next-generation fisheries
701 ecosystem model for the northern Gulf of Mexico. *Ecological Modelling 345*: 75-98.

703 Song, Z., Wang, L., Liu, J., Wang, C., Chen, D. 2008. Characterizing organic matter in marine sediments
704 associated with gas hydrate and oil seepage from the Gulf of Mexico. *Geofluid*s 8: 293–300.

706 Sørensen, L., Sørhus, E., Nordtug, T., Incardona, J.P., Linbo, T.L., Giovanetti, L., Karlsen, Ø., Meier, S.
707 2017. Oil droplet fouling and differential toxicokinetics of polycyclic aromatic hydrocarbons in embryos
708 of Atlantic haddock and cod. *PloS one 12*(7): e0180048

710 Sørhus, E., Incardona, J.P., Karlsen, Ø., Linbo, T., Sørensen, L., Nordtug, T., van der Meeren, T., Thorsen,
711 A., Thorbjørnsen, M., Jentoft, S. 2016. Crude oil exposures reveal roles for intracellular calcium cycling in
712 haddock craniofacial and cardiac development. *Science Reports* 6: 1–21.
713

714   Sørhus, E., Incardona, J.P., Furmanek, T., Goetz, G.W., Scholz, N.L., Meier, S., Edvardsen, R.B., Jentoft, S.
715   2017. Novel adverse outcome pathways revealed by chemical genetics in a developing marine fish. *Elife*
716   6: e20707.

718   Spromberg, J.A., Birge, W.J. 2005. Modeling the effects of chronic toxicity on fish populations: The
719   influence of life-history strategies. *Environmental Toxicology and Chemistry: An International*
720   *Journal 24*(6): 1532-1540.

722   Strongin, K., Polidoro, B., Linardich, C., Ralph, G., Saul, S., Carpenter, K. 2020. Translating globally
723   threatened marine species information into regional guidance for the Gulf of Mexico. *Global Ecology*
724   *and Conservation*: e01010.

726   Sunday, J.M., Pecl, G.T., Frusher, S., Hobday, A.J., Hill, N., Holbrook, N.J., Edgar, G.J., Stuart-Smith, R.,
727   Barrett, N., Wernberg, T., Watson, R.A. 2015. Species traits and climate velocity explain geographic
728   range shifts in an ocean-warming hotspot. *Ecology Letters 18*(9): 944-953.

730   Sutton, T.T., Frank, T., Judkins, H. and Romero, I.C., 2020. As gulf oil extraction goes deeper, who is at
731   risk? community structure, distribution, and connectivity of the deep-pelagic fauna. In pages 403-418
732   *Scenarios and Responses to Future Deep Oil Spills* Springer, Cham.

734   Tormoehlen, L.M., Tekulve, K.J., Nañagas, K.A. 2014. Hydrocarbon toxicity: a review. *Clinical*
735   *Toxicology 52*(5): 479-489.

737   Usseglio-Polatera, P., Bournaud, M., Richoux, P., Tachet, H. 2000. Biological and ecological traits of
738   benthic freshwater macroinvertebrates: relationships and definition of groups with similar
739   traits. *Freshwater Biology 43*(2):175-205.

741   Van den Brink, P.J., Baveco, J.M., Verboom, J., Heimbach, F. 2007. An individual-based approach to
742   model spatial population dynamics of invertebrates in aquatic ecosystems after pesticide
743   contamination. *Environmental Toxicology and Chemistry: An International Journal 26*(10): 2226-2236.

745   Van den Brink, P.J., Rubach, M.N., Culp, J.M., Pascoe, T., Maund, S.J., Baird, D.J. 2011. Traits-based
746   ecological risk assessment (TERA): Realizing the potential of ecoinformatics approaches in
747   ecotoxicology. *Integrated Environmental Assessment and Management 7*(2): 169-171.

749   Vieira, L.R., Guilhermino, L. 2012. Multiple stress effects on marine planktonic organisms: influence of
750   temperature on the toxicity of polycyclic aromatic hydrocarbons to *Tetraselmis chuii*. *Journal of Sea*
751   *Research 72*: 94-98.

753   Wallace, B.P., Brosnan, T., McLamb, D., Rowles, T., Ruder, E., Schroeder, B., Schwacke, L., Stacy, B.,
754   Sullivan, L., Takeshita, R., Wehner, D. 2017. Effects of the Deepwater Horizon oil spill on protected
755   marine species. *Endangered Species Research 33*: 1-7.

757   Wan, Y., Jin, X., Hu, J., Jin, F. 2007. Trophic dilution of polycyclic aromatic hydrocarbons (PAHs) in a
758   marine food web from Bohai Bay, North China. *Environmental Science & Technology 41*(9): 3109-3114.

760   West, J.E., O'Neill, S.M., Ylitalo, G.M., Incardona, J.P., Doty, D.C., Dutch, M.E. 2014. An evaluation of
761   background levels and sources of polycyclic aromatic hydrocarbons in naturally spawned embryos of

762 Pacific herring (Clupea pallasii) from Puget Sound, Washington, USA. *Science of the Total Environment*
763 *499*: 114-124.
764
765 Wilson, S.K., Burgess, S.C., Cheal, A.J., Emslie, M., Fisher, R., Miller, I., Polunin, N.V., Sweatman, H.P.
766 2008. Habitat utilization by coral reef fish: implications for specialists vs. generalists in a changing
767 environment. *Journal of Animal Ecology 77*(2): 220-228.
768
769 Winemiller, K.O. 2005. Life history strategies, population regulation, and implications for fisheries
770 management. *Canadian Journal of Fisheries and Aquatic Sciences 62*(4): 872-885.
771
772 Woltering, D.M. 1984. The growth response in fish chronic and early life stage toxicity tests: a critical
773 review. *Aquatic Toxicology 5*(1): 1-2.

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