A Comprehensive Petrochemical Vulnerability Index for Marine Fishes in the Gulf of Mexico

by

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ABSTRACT

The Gulf of Mexico (or “Gulf”) is of critical significance to the oil and gas industries’ offshore production, but the potential for accidental petrochemical influx into the Gulf due to such processes is high; two of the largest marine oil spills in history, Pemex's *Ixtoc I* spill (1979) and British Petroleum's (BP) *Deepwater Horizon* (2010), have occurred in the region. However, the Gulf is also of critical significance to thousands of unique species, many of which may be irreparably harmed by accidental petrochemical exposure. To better manage the conservation and recovery of marine species in the Gulf ecosystem, a Petrochemical Vulnerability Index was developed to determine the potential impact of a petrochemical influx on Gulf marine fishes, therein providing an objective framework with which to determine the best immediate and long-term management strategies for resource managers and decision-makers. The resulting Petrochemical Vulnerability Index (PVI) was developed and applied to all bony fishes and shark/ray species in the Gulf of Mexico (1,670 spp), based on a theoretical petrochemical vulnerability framework developed by peer review. The PVI for fishes embodies three key facets of species vulnerability: likelihood of exposure, individual sensitivity, and population resilience, and comprised of 11 total metrics (Distribution, Longevity, Mobility, Habitat, Pre-Adult Stage Length, Pre-Adult Exposure; Increased Adult Sensitivity Due to UV Light, Increased Pre-Adult Sensitivity Due to UV Light; and Abundance, Reproductive Turnover Rate, Diet/Habitat Specialization). The resulting PVI can be used to guide attention to the species potentially most in need of immediate attention in the event of an oil spill or other petrochemical influx, as well as those species that may require intensive long-term recovery. The scored relative vulnerability rankings

can also provide information on species that ought to be the focus of future toxicological research, by indicating which species lack toxicological data, and may potentially experience significant impacts.

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CHAPTER 1

INTRODUCTION

The Gulf of Mexico is about 1.6 million km^2, of which about half is deep sea, and is an ecosystem critical to thousands of marine species (Fisher et al. 2016). However, the Gulf of Mexico is also the site of several global petroleum and natural gas industries (Buskey et al. 2016). It provides about 23% of U.S. crude oil (Hine et al. 2013). As a result of the petroleum industries' interest in the Gulf of Mexico, two of the largest marine oil spills in history, Pemex's *Ixtoc I.* spill (1979) and British Petroleum's (BP) *Deepwater Horizon* (2010), have occurred in the region since the first offshore oil and gas platform was installed (1947) (Macdonald 1998; Buskey et al. 2016). During the *Deepwater Horizon* spill, about 4.9 million barrels, or 779 million liters, of oil entered the Gulf at 1,500 m depth (Daly et al. 2016; Bagby et al. 2016; Wilson et al. 2017). The spill covered about 180,000 km^2 of ocean and impacted 37% of the Gulf coastline (Daly et al. 2016; Wilson et al. 2017). The spills have drastically upset the ecosystem, with significant impact on Gulf species. Any species can be harmed by exposure to a petrochemical influx like crude oil. Documented effects of exposure to PAHs, of which crude oil is comprised, include reduction in daily function (e.g. swimming performance), limited function in the embryonic stage, damage to the immune system, reduced cognition, edema, cataracts, lesions, tumors, narcosis, a damaged cellular metabolism, cardiac dysfunction, and death (Logan 2007; Buskey et al. 2016). However, despite such observed effects, efforts to sufficiently recover Gulf species post-spill have been difficult (Corn & Copeland 2010). Following the *Deepwater Horizon* spill, a submitted

Congressional Research Service (CRS) Report for Congress entitled "The Deepwater Horizon Oil Spill: Coastal Wetland and Wildlife Impacts and Response" stated the following on efforts to recover impacted Gulf of Mexico species.

> "Decisions about cleanup of wildlife are no easier. Cleanup of individual animals is labor intensive, and some scientists argue that the survival of an animal that has been cleaned is so uncertain as to call into question whether treatment is, in fact, humane. Rescue groups are dedicated to salvaging those that can still be saved. The effects on a species as a whole vary markedly from one species to another, depending on that species' abundance and ecological needs; appropriate responses at the species level are unclear." (Corn & Copeland 2010)

The CRS report suggests that attempts to recover Gulf species affected by an oil spill are stymied by the lack of an efficient mechanism for which to quantify species' vulnerability to petrochemical exposure. Therefore, methods to determine impacted species, and to what degree, are critical to prioritize immediate and long-term recovery efforts in the case of ecotoxicological disaster, while also improving current management/conservation initiatives in the Gulf of Mexico. This paper presents a new methodology, a Petrochemical Vulnerability Index (PVI) for fishes, with which to evaluate 1,660 Gulf bony fishes and shark/ray species' relative vulnerability to a petrochemical influx. This is the first comprehensive PVI of all species of Gulf bony fishes and sharks/rays. The 1,660 fish species are an apt choice of such study; fishes are recognized as being the most "visible" members of aquatic communities (Logan 2007). This is because fishes have commercial/recreational importance, are a mid-trophic member of countless food-webs, e.g. fish, human, mammal, bird, etc., but can also be exposed to petrochemicals at the surface, water column, through demersal layers, etc. (Logan 2007).

CHAPTER 2

BACKGROUND

Crude Oil in the Gulf of Mexico

The Gulf of Mexico contains a significant portion of the Earth's available crude oil. Crude oil is comprised of Polycyclic Aromatic Hydrocarbons (PAHs) (Logan 2007). PAHs vary in physical/chemical composition, i.e. size, structure, and toxicological effect (Logan 2007). PAH mixtures, like crude oil, are classified by environmental source: pyrogenic, from combustion of organic material; petrogenic, like petroleum; diagenic, from biogenic material, e.g. anaerobic; and biogenic, directly formed by animals, plants, fungi, and bacterial (Logan 2007). The PAHs at hand, here, are petrogenic PAHs, and were formed during the geological formation of the Gulf of Mexico. The buried crude oil and gas, i.e. hydrocarbons, in the Gulf resulted from layers of thick, compacted sediment with organic material, i.e. plants, expired organisms, etc. (Foote 1984; Grace 2007; Hine et al. 2013). The compacted carbonate banks were saturated with water, and over time petroleum rose throughout the permeable, buried sediment until "trapped" in under an impermeable layer, forming an oil reservoir, which oil rigs like *Ixtoc I* and *Deepwater Horizon* mined prior to the spill (Foote 1984; Macdonald 1998; Grace 2007; Hine et al. 2013). The Gulf of Mexico's basin is perfect for hydrocarbon deposition, given its irregular basin floor from folding, slumping, salt diapirism, etc. which act as pocket-like traps (Foote 1984; MacDonald 1998; Grace 2007). While the crude oil is relatively harmless buried, if too much crude oil permeates Gulf water, there is significant danger of ecotoxicological disaster. Crude oil exits the Earth's crust either via natural seepage or via drilling, e.g. *Ixtoc I* and *Deepwater Horizon.*

Natural oil seepage is noted throughout centuries of historical record (MacDonald 1998). Geothermal energy has continued to bake the Gulf's hydrocarbon deposition, and bubbles of oil escape from the Gulf of Mexico seafloor through faulted sediment (MacDonald 1998). Salt tectonism also results in faults through which oil can travel from the seafloor to the surface (MacDonald 1998; Fisher et al. 2016). The source of natural oil seepage is typically fixed, with surface oil found within a few kilometers from the source, covering a relatively small surface area (MacDonald 1998). The oil slick spreads thinner and thinner until it disappears altogether, either evaporating into the atmosphere or mixing with the Gulf and dispersing (MacDonald 1998). About 40 million liters of oil flow naturally into the Gulf per decade (MacDonald 1998). About 914 areas in the Gulf where natural oil slick can be observed on the sea-surface have been identified (Fisher et al. 2016). This natural seepage is even a boon to some species of marine life, providing chemical energy like that found at hydrothermal vents, nourishing species that wouldn't typically thrive at such depth (MacDonald 1998).

Oil spills from drilling are catastrophic. Total quantities of various accidental oil spills can be roughly equivocated to the 40 million liters of natural seepage per decade described; however, the respective rate of exposure is completely different (MacDonald 1998). Most spilled oil floats on the water's surface, given its density (Wilson et al. 2017). Like with natural seepage, the oil is spread via current, wind, waves, and typically evaporates into the atmosphere or disperses (Wilson et al. 2017). However, the slick is much thicker than a natural slick, resulting in a longer-lasting, further spreading slick. During the *Deepwater Horizon*, elevated levels of oil were found at water depths greater than 3,280 feet, as far as eight miles from the wellhead, and additional water samples containing oil droplets were found as far as 96 miles from the wellhead (Wilson et al. 2017). Sub-surface oil, that which was either dispersed via surface breakage or never reached the surface at all, remain undissolved, are naturally dispersed, or settle on the seafloor (Imanian et al. 2011; Passow et al. 2014; Daly et al. 2016).

Oil is naturally dispersed by dissolution or biodegradation, in which hydrocarbon organic matter is broken-down by microbial organisms (Imanian et al. 2011). However, as sub-surface droplets sink, there is a decline in microbial response, due to insufficient oxygen or nutrients to maintain the microbial metabolism, so the oil remains undispersed, settling on the seafloor through sedimentation (Passow et al. 2014; Daly et al. 2016; Bagby et al. 2016). For example, Marine Oil Snow Sedimentation and Flocculent Accumulation (MOSSFA), a novel development observed during the *Deepwater Horizon* oil spill the 4-5 months during and after the spill, saw microbes release high molecular weight exudates in the presence of oil, and the resulting "microbial mucus" biofilm functioned as marine snow, leading to crude oil sedimentation of the Gulf of Mexico (Passow et al. 2014). The estimated percentage of the *Deepwater Horizon* spill that was deposited on the seafloor ranges from 0.5% to 25% (Daly et al. 2016). The outflow of rivers, e.g. sediment from the Mississippi River outflow, shallow waters, drilling mud, and burnt oil byproduct can result in additional sedimentation, i.e. sinking oil-mineral aggregations (OMAs) (Passow et al. 2014; Daly et al. 2016; Wilson et al. 2017). Both the deep current and marine species on the seafloor bury, move, and redistribute oil along the seafloor (Wilson et al. 2017). OMAs are small compared to MOFFSA, but OMAs sink fast (Daly et al. 2016). MOFFSA is likely to have affected the food web; zooplankton feed on marine snow, resulting in compounding effects across trophic levels (Daly et al. 2016). Benthic species were affected, with the golden tilefish, which burrows into sediment, observed with higher PAH metabolites by Snyder et al. (2015) (Daly et al. 2016).

The Development of Vulnerability Indices

The development of vulnerability indices stems from the need for simple methodologies to effectively translate environments' biological responses to stressors, e.g. petrochemical influx, for impact assessments (King & Sanger 1979). Such indices provide an objective means with which to determine the best allocation of often limited resources (Millsap et al. 1990). Methodologies differ in subject, location, purpose, and choice of component(s), but most are species-based (Millsap et al. 1990). Indices to determine species' petrochemical vulnerabilities are essential, as it is nearly impossible to test all individual species' responses to potential oil, gas and chemical exposures. This study alone comprises almost 1,700 species. As such, a relative vulnerability index of species may be the most efficient way to score/rank and prioritize species relative responses, in the absence of comprehensive laboratory toxicity testing.

Included are five example vulnerability indices, components of which are representative of the approach used to develop this paper's Petrochemical Vulnerability Index (PVI) methodology (Table 1). Each index differs in the species chosen, variable(s) selected, and of what each variable is indicative. King and Sanger's (1987) Oil Vulnerability Index (OVI) is an early, simple iteration of an oil pollution-based vulnerability index for marine birds; the index is scored by birds' biological traits importance to Northeast Pacific Oil Development. Each subsequent index has improved upon this early iteration, whether with "action" data to develop long-term site-specific strategies, consideration of exposure vs. sensitivity, data representative of species' population-level resilience, e.g. "rebound potential," etc. (Millsap et al. 1990; Golden & Rattner 2003; Chin et al. 2010; Rosenberger et al. 2017). The studies acknowledge that some human judgement, i.e. in taxa selection, subjective assessment, will always be present in vulnerability indices; there are extensive data gaps, e.g. species' sensitivity to oil, functional role of species in an ecosystem, etc. (Millsap et al. 1990; Golden & Rattner 2003; Chin et al. 2010; Rosenberger et al. 2017). Expert opinion can differ on occasion, and Golden and Rattner established that under each index's metric, species might be considered vulnerable due to specific biological traits, e.g. tendency to accumulate and retain mercury, or considered potentially vulnerable due to inadequate data, despite no evidence reported "in nature," (Millsap et al. 1990; Golden & Rattner 2003). However, despite data gaps and subjectivity, a systematized methodology like a vulnerability index is both efficient and objective as-a-whole.

Table 1. Vulnerability Indices Used in Development of the PVI

Source	Species	Location	Goal	Index Component(s)
King and Sanger 1979	Birds w/ Marine Habitat (176)	Washington, U.S.A.; Alaska, U.S.A.; British Columbia (BC), Canada	Rank avifauna species' risk to environmental hazards to improve management/prioritization.	Range (Breeding, Migration, Winter, Marine Orientation) Population (Size, Productivity) Habits (Roosting, Foraging, Escape, Flocking, Nesting Density, Specialization) Mortality (Hunted by Man, Animal Depredations, Non-oil Pollution, History of Oiling) Exposure (Spring, Summer, Fall, Winter).
Millsap et al. 1990	Vertebrate Native to Florida (668)	Florida, U.S.A.	Develop system to prioritize vertebrate management efforts in Florida.	Biological (Population Size, Population Trend, Range Size, Distribution Trend, Population Concentration, Reproductive Potential for Recovery [i.e. Avg. Young, Age at First Reproduction], Ecological Specialization [i.e. Diet/Reproductive]) Action (Knowledge of Distribution in Florida, Knowledge of Population Trend in Florida, Knowledge of Florida Population Limitations, Ongoing management Activities in Florida) Supplemental Variables (Systematic Significance of the Taxon, Percent of Taxon's Total Range that Occurs in Florida, Trend in Taxon's Florida Population, Period of Occurrence in Florida, harvest of the Taxon in Florida)
Golden and Rattner 2003	Terrestrial Vertebrae Common to Estuarine Habitat (25)	Atlantic Estuarine Habitat, U.S.A.	Identify a sentinel species of contaminant exposure and evaluate species' vulnerability to contaminant effects.	Utility Index (Identify a Sentinel Species) • Exposure Potential (Dietary preference, Habitat Preference, Longevity, Foraging Technique, etc.) • Geographic Occurrence (Range, Residency) • Ease of Collection (Social Structure, Accessibility, Ease of Capture, Abundance, and Management Status) • Quantity of Existing Exposure and Effects Data Vulnerability Index (Evaluate Species' Vulnerability) • Exposure Potential (Dietary preference, Habitat Preference, Longevity, Foraging Technique, etc.) • Sensitivity • Resilience of a Population (Based on Abundance Within and Outside the Study Area, Reproductive Potential, and Age of Individuals at First Breeding)
Chin et al. 2010	Sharks and Rays (133)	Australia's Great Barrier Reef (GBR)	Assess the vulnerability of sharks/rays of GBR to climate change.	Exposure (Extent of Overlap of Species' Geographic and Bathymetric Range and Habitat Use w/ Redacted Footprint of Climate Change) Sensitivity (Rarity, Habitat Specificity) Adaptive Capacity/Rigidity (Trophic Specificity, Immobility, Physical or Chemical Intolerance, Latitudinal Range)
Rosenberger et al. 2017	Marine Mammals (21)	Coastal British Columbia (BC), Canada	Evaluate the impacts of potential oil exposure at species and population level for risk-based oil predictions.	Individual Likelihood of Oil Exposure (Contact, Adhesion, Inhalation, Direct Ingestion, Ingestion Through Contaminated Prey) Population-Level Likelihood of Oil Exposure (Population, Distribution, Group Size, Habitat, Reproduction, Life History, Diversity of Diet, Prey Susceptibility to Decline)

CHAPTER 3

METHODS

The scoring methodology for the Petrochemical Vulnerability Index (PVI) was derived from an overarching, theoretical multi-species framework developed in consultation with 25 different species experts in a workshop setting in Guanahacabibes National Park, Cuba, and adapted for fishes. The theoretical framework consisted of three major sections: likelihood of exposure (Distribution, Longevity, Body Type, Respiration Mode, Diet/Oral [Feeding Behavior], Mobility, Habitat, Pre-Adult Stage Longevity, Pre-Adult Stage Exposure); individual sensitivity (Toxicodynamics, Body Type, Pre-Adult Sensitivity/Reproductive Mode, Increased Adult Sensitivity Due to UV Light, Increased Pre-Adult Sensitivity Due to UV Light, Presence of Synergistic, Multiple Stressors); and population resilience (Abundance, Population Connectivity [Rescue Effect], Reproductive Turnover Rate, Diet/Habitat Specialization) (Polidoro et al. in prep). This multi-species framework was modified for these fish-specific metrics, and aspects present in the multi-species framework described were altered/not present, either due to being unchanged amongst fishes (e.g. Body Type, Respiration Mode etc.) or lack of available data (e.g. Toxicodynamics, Population Connectivity, etc.). Included is summarized Petrochemical Vulnerability Index for fishes (Table 2). The final fishes index therefore consists of 11 components scored from 1 to 5, with the species' overall Petrochemical Vulnerability score ranging from a minimum score 11 to a maximum score 55. Each component was scored from 1 to 5, to prevent inadvertent weighting to any single metric. Where trait information was Unknown, an "average" score of 3 was assigned.

The dataset includes all taxonomically valid Gulf fish species. Each of the 1,660 species is described by Phylum, Class, Order, Family, Genus species, common group, and common name. Data was collected from the IUCN's Species Information Service (SIS), plus available scholarship. The dataset was initially composed of free-text, and additional columns were added to tabulate the data for ease-of-analysis. Of the 1,660 Gulf fish species, 1,577 are bony fishes, all belonging to Phylum Chordata and Class Actinopterygii. The most specious Orders include Perciformes (608), Stomiiformes (138), Anguilliformes (118), Lophiiformes (71), and Myctophiformes (70), of 32 total Orders. The most specious Families include Gobiidae (69), Myctophidae (67), Stomiidae (67), Serranidae (59), and Ophidiidae (46), of 201 total Families. Approximately 91% of species were assessed as Least Concern (LC) by the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species, with six% Data Deficient (DD), around two% Vulnerable (VU), and less than one% each Near Threatened (NT), Endangered (EN), and Critically Endangered (CR). The remaining 83 species are sharks/rays, all belonging to Phylum Chordata and Class Chondrichthyes. The most specious Orders include Rajiformes (35), Carcharhiniformes (24), and Squaliformes (10), of eight total Orders. The most specious Families include Rajidae (13), Carcharhinidae (12), and Scyliorhinidae (7), of 32 total Families. Approximately 42% of Chondrichthyans were assessed as Data Deficient (DD) by the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species, with 27% Least Concern (LC), around 16% Near Threatened (NT), 11% Vulnerable (VU), and 2% each Critically Endangered (CR) and Endangered (EN).

Table 2. Summarized PVI

	Likelihood of Exposure (for Individual Encounters)						Toxicological Sensitivity		Population Resilience		
LABEL	Distribution	Longevity	Mobility	Habitat	Pre-Adult Stage Longevity	Pre-Adult Stage Exposure	Increased Adult Sensitivity Due to UV Light	Increased Pre-Adult Sensitivity Due to UV Light	Abundance	Reproductive Turnover Rate	Diet/Habitat Specialization
General Assumption	Gulf species with habitat with a smaller depth interval (m)/horizontal range (km^2) will have a higher likelihood of exposure over time.	Gulf species with longer lifespan will have protracted and/or repeated, exposure(s) over time.	Gulf species with limited mobility will have prolonged and/or repeated exposures over time.	Gulf species' adult individuals that spend time in habitat w/ extended retention of petrochemicals will have protracted and/or repeated, exposure(s) over time.	Gulf species with a longer, critical pre-adult stage will have protracted and/or repeated, exposure(s) over time.	Gulf species' pre-adult individuals that spend time in habitat w/ extended retention of petrochemicals will have protracted and/or repeated, exposure(s) over time.	Gulf species' adult individuals that spend time in habitat where UV light can lower toxicological thresholds may be more sensitive.	Gulf species' pre-adult individuals that spend time in habitat where UV light can lower toxicological thresholds may be more sensitive.	Gulf species populations that are less abundant in individuals will be less resilient to petrochemical activity.	Gul species populations with lower reproductive turnover rates will recover more slowly from disturbance by petrochemical activity.	Gulf species populations with high specialization in diet/habitat will be less adaptable to petrochemical activity.
Potential Indicators	Limited depth interval (m)/horizontal range (km^2)	Lifespan	Full Migrant, Spawning Migration, Not a Migrant, Site Fidelity, etc.	Migratory/Movement Pattern (diel); Habitat	Pre-Adult Stage Length	Migratory/Movement Pattern (Diel); Habitat; Dispersal Capacity	Migratory/Movement Pattern (Diel at Night); Habitat	Migratory/Movement Pattern (Diel at Night); Habitat; Dispersal Capacity	Abundant, Common, Uncommon, etc.	Generation Length, Population Doubling Time	Invertebrate(s), Fish, Other, At Least Two Habitats, etc.
Definition	Average of Depth Interval (m) and Horizontal Range (km^2) Score	Lifespan	The migratory/movement pattern of the species.	Do the adult individuals of a species spend time in habitat that retains petrochemical exposure?	Longevity (Pre-Adult)	Do the pre-adult individuals of a species spend time in habitat that retains petrochemical exposure?	Do adult individuals of the species experience increased UV sensitivity?	Do pre-adult individuals of the species experience increased UV sensitivity?	Abundance of species in the Gulf of Mexico.	Estimated reproductive turnover rate.	Diet/Habitat Specialization.
Score	1 = Quintile 1 2 = Quintile 2 3= Quintile 3 4= Quintile 4 5= Quintile 5	1 = < 1y 2 = [1-5)y 3= [5-10)y 4= [10-20)y 5= > 20y	1 = Highly Mobile 2= Moderately Mobile/Diel/Unknown 3= Not Mobile	0 = No 3 = Unknown 5 = Yes	1 = < 1d 2= [1d, 1w) 3 = [1w, 1m) 4 = [1m, 1y) 5 = > 1y	0 = No 3 = Unknown 5 = Yes	0 = No 3 = Unknown 5 = Yes	0 = No 3 = Unknown 5 = Yes	1 = Abundant 2= Common 3= Uncommon/Unknown 4= Occasional 5 = Rare	1 = < 1y 2 = [1-5)y 3= [5-10)y 4= [10-20)y 5= > 20y	1 = No Specialization 2 = Very Adaptable 3 = Moderately Adaptable 4 = Somewhat Specialized 5 = Highly Specialized

Likelihood of Exposure

The following metrics are designed to model fish species' likelihood of exposure to a petrochemical influx, which contributes to the species' petrochemical vulnerability score. Certain metrics present in the original theoretical framework, such as Body Type, Respiration Mode, etc. were generally unchanged between fish species and/or unavailable, and thus not included in this fish-specific index. A higher score, here, is indicative of increased likelihood of exposure. If the data was not specified as either adult/pre-adult, the data was assumed to represent both adult/pre-adult individuals of the species.

1) Distribution. The first likelihood of exposure metric is a combination of species' depth interval (m) and horizontal range (km^2). If possible, this metric would measure the proportion of the species' range exposed to petrochemical activity, i.e. overlap with existing drill sites, production refineries, etc.; however, current data on petrochemical activity in the southern Gulf is incomplete. As a result, the metric was adjusted. The species' depth interval and range were each scored from 1 to 5, larger depth intervals/ranges considered the least vulnerable at score 1. Gulf species with a smaller depth interval and smaller range will have a higher likelihood of exposure. Each iteration of score was based on quintiles of available species' depth interval/range. The scores were then averaged.
2) Longevity. The second likelihood of exposure metric is the species' lifespan (years). Gulf species with longer lifespan will have protracted and/or repeated

exposure(s) over time. The species' lifespan is determined from the maximum available lifespan, regardless of year cited, location, etc., but averaged by sex. The longevity score is 1, 2, 3, 4, or 5. Score 1 species, the least likely exposed and least vulnerable due to lifespan, have a lifespan of less than one year. Score 2 species, at least one year, but less than five years. Score 3 species, at least five years, but less than 10 years. Score 4 species, at least 10 years, but less than 20 years. Score 5 species, at least 20 years.

3) Mobility. The third likelihood of exposure metric is the species' adult migratory and/or diel movement pattern. Gulf species with limited mobility will have prolonged and/or repeated exposure(s) over time. The mobility score is 1, 3, or 5. Score 1 species, the least likely exposed and least vulnerable due to mobility, are highly migratory with either/or far-reaching, repeated movement per given year. For example, a species' feeding migration from the Gulf to the Arctic Circle is a score 1, highly migratory, species. This includes species classified as “Full Migrant.” Score 3 species are semi-migratory, with some migration, diel movement, and/or an undefined range of movement. For example, a species that takes part in spawning migration(s), but without known range, is score 3. A species with diel migration is score 3. A species with unknown adult migratory and/or diel movement pattern is score 3. Score 5 species are either/or immobile, with observed high site-fidelity, or classified “Not a Migrant.” If the data was not specified as either adult/pre-adult, the data was assumed to represent both adult/pre-adult individuals of the species.

4) Habitat. The fourth likelihood of exposure metric is the species' adult exposure through permanent habitat and/or movement between habitat(s) at any given time. Gulf species' adult individuals that spend time in habitat with extended retention of petrochemicals, i.e. surface, sediment, etc., will have protracted and/or repeated, exposure(s) over time. Habitat includes Marine Deep Benthic, Marine Neritic -- Rocky to Muddy, Marine Neritic -- Estuaries, Mangroves, Inland Wetlands, Oceanic -- Epipelagic, and/or diel migration into Oceanic -- Epipelagic (+ 200m). The exposed habitat score is 1, 3, or 5. Score 1 species, the least likely exposed and least vulnerable due to habitat, did not inhabit nor move into saturated habitat. Score 5 species inhabited and/or moved into saturated habitat. Score 3 species' habitat/movement was unknown. If the data was not specified as either adult/pre-adult, the data was assumed to represent both adult/pre-adult individuals of the species.
5) Pre-Adult Stage Length. The fifth likelihood of exposure metric is the species' pre-adult stage length. Gulf species with a longer pre-adult stage will have protracted and/or repeated, exposure(s) -- of a particularly vulnerable stage of species' development -- over time. The species' pre-adult stage length is determined from the average of maximum/minimum available pre-adult stage length, regardless of year cited, location, etc., but averaged by sex. The pre-adult stage length score is 1, 2, 3, 4, or 5. Score 1 species, the least likely exposed and least vulnerable due to pre-adult stage length, have a pre-adult stage length of less than one day. Score 2 species, at least one day, but less

than one week. Score 3 species, at least one week, but less than one month. Score 4 species, at least one month, but less than one year. Score 5, the most likely exposed, have a pre-adult stage length of at least one year.

6) Pre-Adult Stage Exposure. The sixth likelihood of exposure metric is the species' pre-adult exposure through dispersal, permanent habitat, and/or movement between habitat(s) at any given time. Gulf species' pre-adult individuals that spend time in habitat with extended retention of petrochemicals, i.e. surface, sediment, etc., will have protracted and/or repeated, exposure(s) over time. Habitat includes Marine Deep Benthic, Marine Neritic -- Rocky to Muddy, Marine Neritic -- Estuaries, Mangroves, Inland Wetlands, Oceanic -- Epipelagic, and/or diel migration into Oceanic -- Epipelagic (+ 200m). The pre-adult metric also includes dispersal capacities of Buoyant Egg(s), Epipelagic Egg(s), Epipelagic Larvae/Juvenile(s), Benthic/Demersal Egg(s), Benthic/Demersal Larvae/Juvenile(s), Egg(s) Laid/Attached to Substrate, Larvae/Juveniles Associated w/ Substrate, Estuarine Egg(s)/Larvae/Juvenile(s), Mangrove Egg(s)/Larvae/Juvenile(s). The exposed habitat score is 1, 3, or 5. Score 1 species, the least likely exposed and least vulnerable due to habitat, did not inhabit nor move into saturated habitat. Score 5 species pre-adult individuals inhabited and/or moved into saturated habitat. Score 3 species' habitat/movement for pre-adult individuals was unknown. If the data was not specified as either adult/pre-

adult, the data was assumed to represent both adult/pre-adult individuals of the species.

Individual Sensitivity

The following metrics are designed to model fish individuals' toxicological sensitivity to a petrochemical influx, which contributes to the species' overall petrochemical vulnerability score. Certain metrics present in the original theoretical framework, such as toxicodynamics, body type, etc. were generally unavailable for the majority of species (e.g. metabolic pathways and Toxicodynamics) or would be unchanged between fish species (e.g. Body Type), and thus left out of this fish-specific model. A higher score, here, is indicative of increased individual sensitivity. Both sensitivity metrics are based on research that UV irradiation of PAHs in crude oil enhances PAH toxicity (Logan 2007; Buskey et al. 2016). This occurs at the sea surface photic zone/microlayer, where the toxicant interacts with UV light (Logan 2007). The pre-adult stage is heavily affected by UV irradiation, with reduced survival upon ultraviolet light exposure, including during spawning, i.e. buoyant egg(s) and shallow spawning habitat (Buskey et al. 2016). Note that phototoxicity of PAHs depends on the PAHs' chemical composition (Buskey et al. 2016). If the data was not specified as either adult/pre-adult, the data was assumed to represent both adult/pre-adult individuals of the species.

1) Increased Sensitivity Due to UV Light. The first individual sensitivity metric is the species' adult Sensitivity Due to UV Light. Gulf species' adult individuals permanent, and/or semi-permanent residence within habitat at the

sea surface where UV light can lower toxicological thresholds may be more sensitive. Habitat includes Oceanic -- Epipelagic, and/or diel migration into Oceanic -- Epipelagic (+ 200m) during the day when UV is present; diel migration at night did not qualify as UV-affected. The increased sensitivity due to UV light score is 1, 3, or 5. Score 1 species, the least sensitive and least vulnerable due to UV light, did not inhabit UV-exposed habitat, nor move into UV-exposed habitat. Score 5 species inhabited and/or moved into UV-exposed habitat. Unknown species' habitat and movement was scored 3.

2) Increased Pre-Adult Sensitivity Due to UV Light. The second individual sensitivity metric is the species' pre-adult Sensitivity Due to UV Light. Gulf species' pre-adult individuals with dispersal within, permanent, and/or semi-permanent residence within habitat at the sea surface where UV light can lower toxicological thresholds may be more sensitive when exposed to petrochemical influx. UV-exposed dispersal includes Buoyant Egg(s), Epipelagic Egg(s), Epipelagic Larvae; and UV-exposed habitat includes Oceanic -- Epipelagic, and/or diel migration into Oceanic -- Epipelagic (+ 200m) during the day when UV is present. The increased sensitivity due to UV light score is 1, 3, or 5. Score 1 species, the least sensitive and least vulnerable due to UV light, were not dispersed as pre-adults as described, did not inhabit UV-exposed habitat, nor move into UV-exposed habitat. Score 5 species dispersed as pre-adults as described, inhabited UV-exposed habitat,

and/or moved into UV-exposed habitat. Unknown species' habitat and movement was scored 3.

Population Resilience

The following metrics are designed to model fish species' population resilience to a petrochemical influx, which contributes to the species' overall petrochemical vulnerability score. Certain metrics present in the original theoretical framework, such as Population Connectivity were generally unchanged between fish species and/or unavailable, and thus not included in this fish-specific model. A higher score, here, is indicative of *decreased* population resilience.

1) Abundance. The first population resilience metric is the abundance of adult individuals of the species in the Gulf of Mexico. Gulf species' populations that are less abundant in adult individuals will be less resilient. Score 1 species, the most resilient and least vulnerable due to abundance, were abundant in the Gulf of Mexico. Score 2, common, not uncommon, etc. Score 3, uncommon, not common, etc. Score 3 also included species with unknown abundance, either in the Gulf of Mexico or overall, plus species considered rare due to sampling difficulty. Score 4 species were occasional in the Gulf. Score 5, rare. If a species was marked abundant/common, or a similar split, the species' abundance was assumed the larger, i.e. assumed abundant if abundant/common, assumed common if common/uncommon, etc. Gulf data was prioritized; if Gulf abundance was unknown, the species scored 3, but if no location was specified, the data was assumed to equally represent the

species' range and include the Gulf of Mexico population. Museum collection data, given the sampling area was unknown, also scored 3. Data were assumed adult unless specifically designated larval/pre-adult.

2) Reproductive Turnover Rate. The second population resilience metric is the species' reproductive turnover rate, a combination of generation length (years) and population doubling time (years). Gulf species' populations with lower reproductive turnover rates will recover slowly, and therefore be less resilient. The species were scored by both generation length and population doubling time with both scores averaged for a final reproductive turnover rate score. The species' generation length was determined from the average of maximum/minimum available generation length, regardless of year cited, location, etc., but averaged by sex. The reproductive turnover rate score is 1, 2, 3, 4, or 5. Score 1 species, the most resilient and least vulnerable due to reproductive turnover rate, have a reproductive turnover rate of less than one year. Score 2 species, at least one year, but less than five years. Score 3 species, at least five years, but less than 10 years. Score 4 species, at least 10 years, but less than 20 years. Score 5 species, at least 20 years.

3) Feeding/Habitat Specialization. The third population resilience metric is the species' diet/habitat specialization. Gulf species' populations with high specialization in diet/habitat will be less adaptable, and therefore less resilient. Score 1 species have no specialization, a generalist diet/habitat, with a diet of multiple invertebrates, fish, and at least two habitats. Score 2 species are

highly adaptable in diet/habitat, with a diet of multiple types of either invertebrates, fishes, or an "other" diet in plus a single invertebrate/fish, plus at least two habitats. Score 3 species are moderately adaptable in diet/habitat, including a diet of only one type of either invertebrates, fish, or "other," plus at least two habitats. Score 4 species are somewhat specialized in diet/habitat, including a diet of multiple types of invertebrates, fish, and/or "other," but only one habitat. Score 5 species are highly specialized in diet/habitat, including a diet of one invertebrate, fish, or "other," plus one habitat. General descriptions of diet such as "invertebrates" or "small fishes" were considered representative of multiple types of invertebrates or fish, indicative of a less specialized diet. If either diet/habitat data were unknown, the species was scored 3; if both were unknown, the species scored 4.

Additional Information

Additional information included in the dataset, although not attributed to a specific metric, includes species' trophic position, age at first maturity (Y), maximum body size (cm.), reproductive strategy, breeding season, and threats. Age at first maturity was determined from the maximum available age at first maturity available, regardless of year cited, location, etc., but averaged by sex. Maximum body size was specified as either tail length (TL), standard length (SL), fork length (FL), and disk width (DW). If the maximum body size was not specified in-source as TL, SL, etc., the data was assumed to be TL. Maximum body size maturity was determined from the maximum available body size, regardless of year cited, location, etc., and not averaged by sex to prevent skew from parasitic males. Although reproductive strategy was considered a potential metric in the original, theoretical framework, the best method of utilization in the context of petrochemical vulnerability was unclear, given a current dearth of research into how fishes' reproductive strategy translates to petrochemical vulnerability.

CHAPTER 4

RESULTS

Bony Fishes

This section summarizes key results of the Petrochemical Vulnerability Index (PVI) (Table 3). Each species' global Red List (RL) status is also included. The top 17 bony fishes, corresponding to the highest, uppermost five overall PVI scores, including multiple tie-scores, are listed, followed by the bottommost 12 bony fishes, the smallest three total PVI scores, including multiple tie-scores. Based on the logic of the PVI, the top 17 species are the most vulnerable to petrochemical influx, while the bottom 12 species are the least vulnerable to petrochemical influx. Also included in this section is a histogram of all bony fish species' PVI scores, with cumulative frequency (Figure 1). There are two major peaks within, at 25 and 32.5, with surrounding scores clustered around. A bimodal histogram can suggest mixed processes in the data, i.e. potentially two different sets of metrics contributing differently to the scores, which will be explored in later sections.

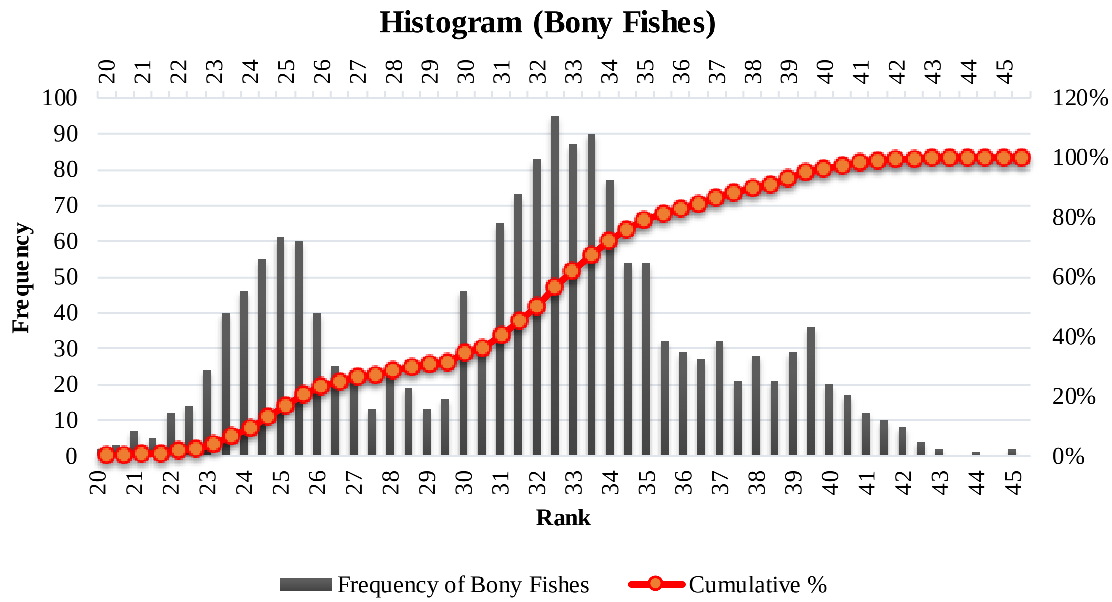
Table 3. Highest and Lowest Scoring Bony Fishes

Genus Species	Global RL	Score
Cheilopogon exsiliens	LC	45.0
Mycteroperca bonaci	NT	45.0
Eustomias furcifer	LC	44.0
Gigantactis herwigi	LC	43.0
Canthidermis sufflamen	LC	43.0
Coryphaenoides rudis	LC	42.5
Gigantactis gracilicauda	DD	42.5
Luvarus imperialis	LC	42.5
Scomber colias	LC	42.5
Cheilopogon furcatus	LC	42.0
Snyderidia canina	LC	42.0
Phtheirichthys lineatus	LC	42.0
Remora osteochir	LC	42.0
Cubiceps gracilis	LC	42.0
Lonchopisthus lemur	LC	42.0
Diodon eydouxii	LC	42.0
Mola mola	VU	42.0

[. . .]

Alepocephalus productus	LC	21.0
Asquamiceps caeruleus	LC	21.0
Talismania homoptera	LC	21.0
Kuronezumia bubonic	LC	21.0
Dysalotus alcocki	LC	21.0
Cyclothone pseudopallida	LC	21.0
Aristostomias tittmanni	LC	21.0
Stylephorus chordates	LC	20.5
Gobionellus oceanicus	LC	20.5
Bathophilus longipinnis	LC	20.5
Squalogadus modificatus	LC	20.0
Scopelogadus beanie	DD	20.0

Figure 1. A Histogram of PVI Scores for Bony Fishes



A Principle Component Analysis (PCA) was also conducted on the bony fishes (1,577 spp). The results of total variance explained by each Principle Component (PC) are shown (Table 4). The threshold of the PCs selected was Eigenvalue 1, based on the Kaiser Criterion. This threshold is validated by the Scree plot (Figure 2). The Component Matrix of the PCA is shown as well (Table 5). The four PCs explain about 62% of the variance in the sharks/rays' dataset. The cutoff of the absolute value of the coefficient (see Coefficient Matrix, Table 5), i.e. the importance, was 0.5. PC1 is positively associated with Increased Pre-Adult Sensitivity Due to UV Light, Increased Adult Sensitivity Due to UV Light, Habitat, and Pre-Adult Exposure. PC2 is positively associated with Pre-Adult Exposure, Habitat, and Distribution. PC3 is positively associated with Longevity and Reproductive Turnover Rate. PC4 is positively associated with Mobility and negatively associated with Diet/Habitat Specialization. Together, PC1 and PC2 explain 40% of the variance in the bony fishes' dataset. A scatterplot of PC1 against PC2 exhibits how the two split bony fishes' PVI scores amongst Low, Moderate, and High Vulnerability (Figure 3).

Table 4. Total Variance Explained of Bony Fishes (PCA)

Total Variance Explained						
	Initial Eigenvalues			Extraction Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.632	23.924	23.924	2.632	23.924	23.924
2	1.707	15.522	39.447	1.707	15.522	39.447
3	1.387	12.607	52.054	1.387	12.607	52.054
4	1.084	9.855	61.909	1.084	9.855	61.909
5	0.994	9.035	70.944			
6	0.907	8.241	79.185			
7	0.817	7.429	86.614			
8	0.676	6.147	92.761			
9	0.525	4.777	97.538			
10	0.187	1.702	99.240			
11	0.084	0.760	100.000			

Figure 2. Scree Plot of Bony Fishes (PCA)

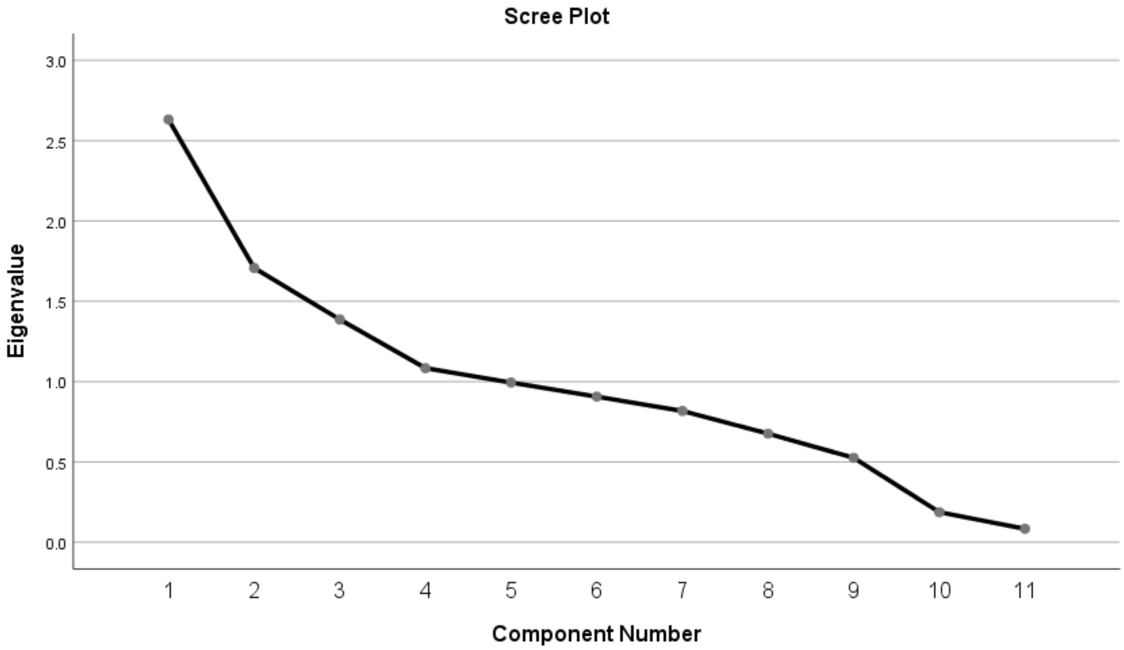
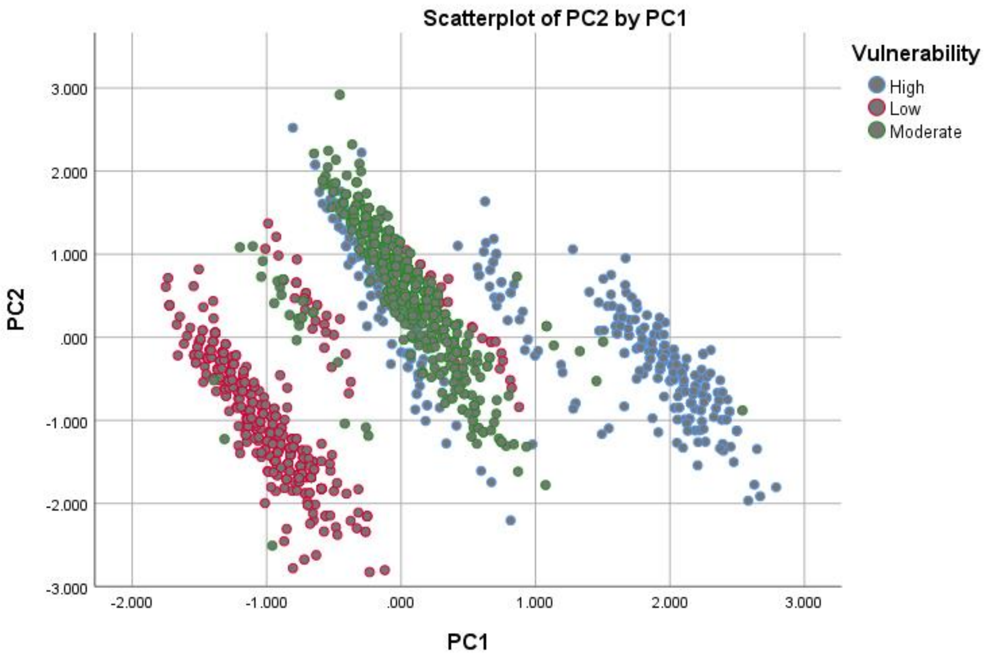


Table 5. Component Matrix of Bony Fishes (PCA)

Component Matrix

	Component			
	1	2	3	4
Increased Pre-Adult Sensitivity Due to UV Light	0.822	-0.189	-0.251	-0.220
Increased Adult Sensitivity Due to UV Light	0.819	-0.196	-0.251	-0.225
Habitat	0.645	0.636	0.272	0.133
Pre-Adult Exposure	0.644	0.651	0.266	0.116
Distribution	-0.478	0.547	-0.028	-0.053
Pre-Adult Stage Length	-0.047	0.132	0.023	-0.043
Longevity	-0.004	-0.208	0.778	-0.150
Reproductive Turnover Rate	0.136	-0.436	0.697	0.117
Mobility	-0.172	0.175	-0.088	0.662
Diet/Habitat Specialization	-0.395	0.250	0.116	-0.539
Abundance	0.145	-0.403	-0.055	0.428

Figure 3. Scatterplot of PC2 by PC1 for Bony Fishes (PCA)



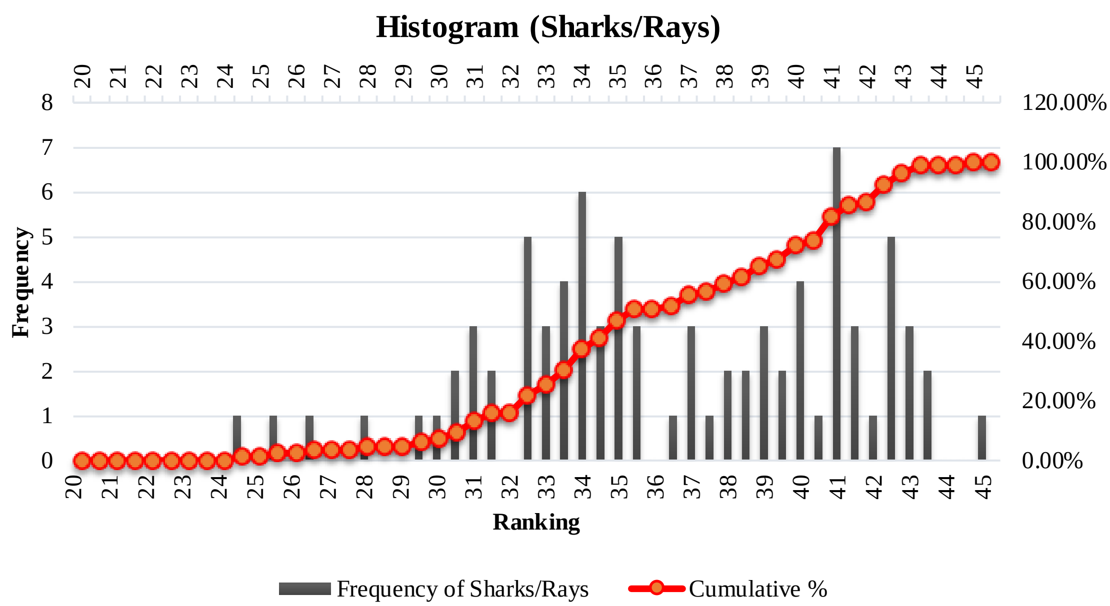
Sharks and Rays

This section summarizes key results of the final PVI for sharks/rays (Table 6). Each species' global Red List (RL) status is also included. The top 12 sharks/rays, corresponding to the highest five total PVI scores, including multiple tie-scores, are listed, followed by the bottommost three sharks/rays, the smallest three total PVI scores. Based on the logic of the PVI, the top 12 species are the most vulnerable to petrochemical influx, while the bottom three species are the least vulnerable to petrochemical influx. Also included is a histogram of all bony fish species' PVI scores, with cumulative frequency (Figure 4). The peak is at about 41, with smaller peaks at 32.5, 34, and 35. The histogram appears left skewed, with the greatest concentration at higher PVI scores.

Table 6. Highest and Lowest Scoring Sharks/Rays

Genus Species	Global Rl	Score
Scyliorhinus meadi	DD	45.0
Oxynotus caribbaeus	DD	43.5
Apristurus parvipinnis	DD	43.5
Mobula hypostoma	DD	43.0
Etmopterus bigelowi	LC	43.0
Galeocerdo cuvier	NT	43.0
Mustelus norrisi	DD	42.5
Mustelus sinusmexicanus	DD	42.5
Centroscymnus owstonii	LC	42.5
Etmopterus gracilispinis	LC	42.5
Isurus oxyrinchus	VU	42.5
Rhinochimaera atlantica	LC	42.0
[. . .]		
Raja ackleyi	DD	26.5
Myliobatis goodei	DD	25.5
Rajella fuliginea	LC	24.5

Figure 4. A Histogram of PVI Scores for Sharks/Rays



A Principle Component Analysis (PCA) was also conducted on the sharks/rays (83 spp). The results of total variance explained by each Principle Component (PC) are shown (Table 7). The threshold of the PCs selected was Eigenvalue 1, based on the Kaiser Criterion. This threshold is validated by the Scree plot. The Component Matrix of the PCA is shown as well (Table 8). The four PCs explain about 73% of the variance in the sharks/rays' dataset. The cutoff of the absolute value of the coefficient (see Coefficient Matrix, Table 8), i.e. the importance, was 0.5. PC1 is positively associated with Longevity, Pre-Adult Stage Length, Increased Pre-Adult Sensitivity Due to UV Light, and Increased Adult Sensitivity Due to UV Light, but negatively associated with Abundance and Distribution. PC2 is positively associated with Pre-Adult Exposure, Habitat, Increased Pre-Adult Sensitivity Due to UV Light, and Increased Adult Sensitivity Due to UV Light, but negatively associated with Longevity. PC3 is positively associated with Pre-Adult Exposure and Habitat, but negatively associated with Increased Pre-Adult Sensitivity Due to UV Light, and Increased Adult Sensitivity Due to UV Light. PC4 is negatively associated with Reproductive Turnover Rate. Together, PC1 and PC2 explain 48% of the variance in the sharks/rays' dataset. A scatterplot of PC1 against PC2 exhibits how both split sharks/rays amongst Low, Moderate, and High Vulnerability.

Table 7. Total Variance Explained of Sharks/Rays (PCA)

Total Variance Explained						
	Initial Eigenvalues			Extraction Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.220	29.276	29.276	3.220	29.276	29.276
2	2.107	19.151	48.427	2.107	19.151	48.427
3	1.502	13.653	62.080	1.502	13.653	62.080
4	1.202	10.930	73.010	1.202	10.930	73.010
5	0.946	8.601	81.611			
6	0.634	5.762	87.373			
7	0.584	5.309	92.682			
8	0.441	4.009	96.690			
9	0.236	2.150	98.840			
10	0.108	0.978	99.819			
11	0.020	0.181	100.000			

Figure 5. Scree Plot of Sharks/Rays (PCA)

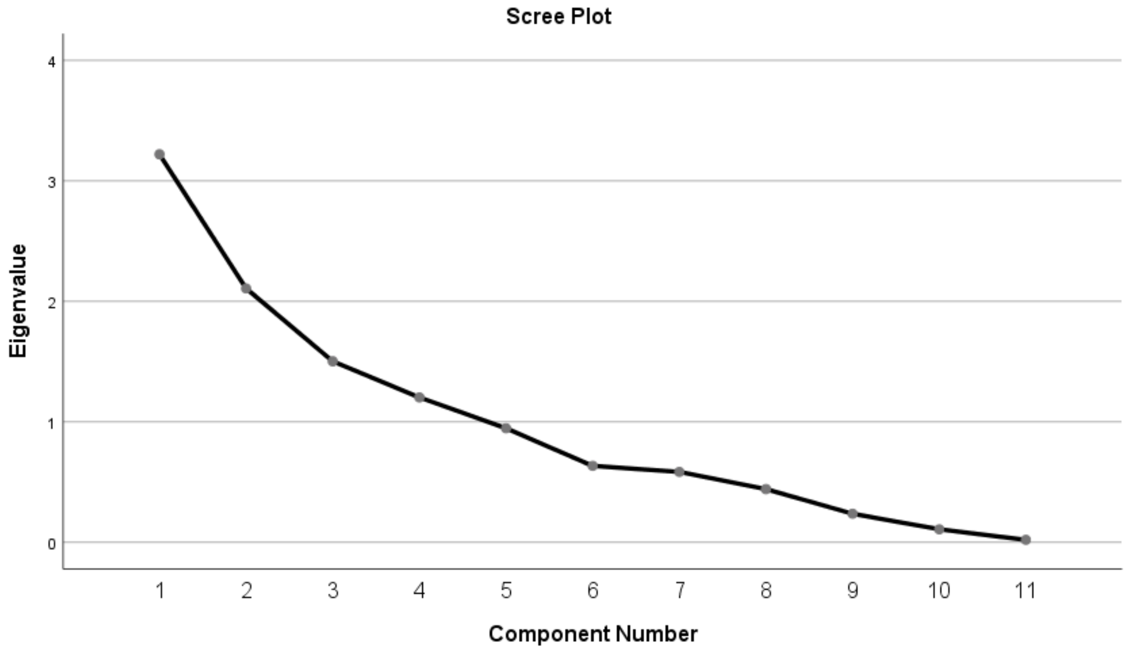
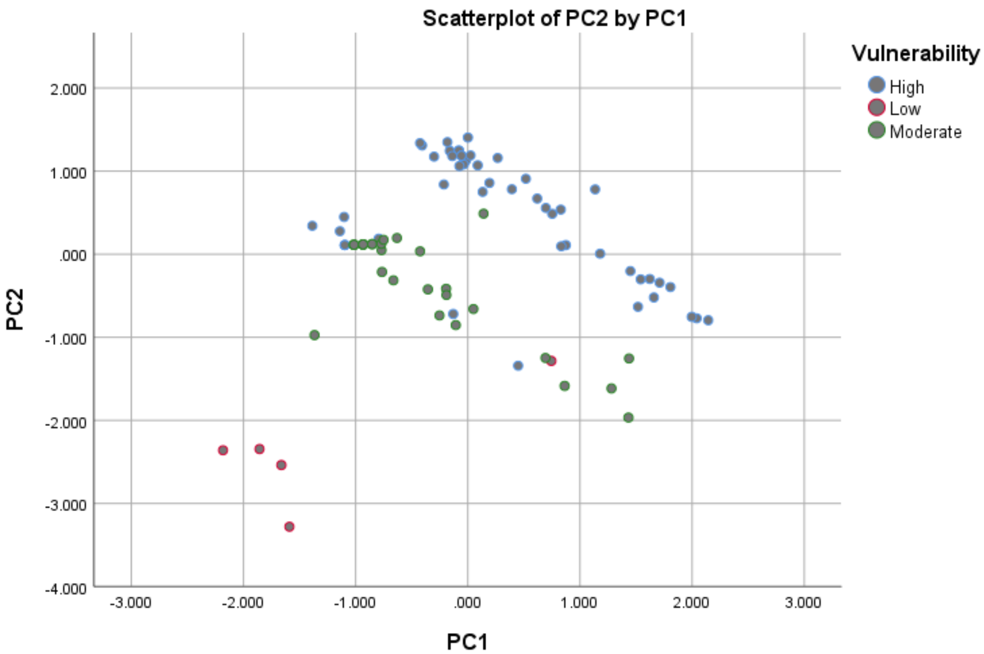


Table 8. Component Matrix of Sharks/Rays (PCA)

Component Matrix				
	Component			
	1	2	3	4
Longevity	0.717	-0.506	0.067	0.020
Pre-Adult Stage Length	0.653	-0.473	0.109	0.296
Abundance	-0.585	0.306	-0.095	0.070
Increased Pre-Adult Sensitivity Due to UV Light	0.580	0.568	-0.509	0.257
Increased Adult Sensitivity Due to UV Light	0.577	0.556	-0.504	0.281
Distribution	-0.509	-0.016	0.237	0.387
Mobility	-0.468	0.096	0.138	0.331
Habitat	0.441	0.586	0.636	-0.046
Pre-Adult Exposure	0.413	0.596	0.636	-0.119
Reproductive Turnover Rate	0.436	-0.151	-0.143	-0.672
Diet/Habitat Specialization	-0.484	0.415	-0.240	-0.488

Figure 6. Scatterplot of PC2 by PC1 for Sharks/Rays (PCA)



CHAPTER 5

DISCUSSION

Overall PVI scores are meant to be indicative of population level, rather than individual, risks of adverse impacts related to oil and gas activity in the Gulf. For example, in the absence of data on the proportion of petrochemical activity within each species' range, depth interval/horizontal range were used as a surrogate (e.g. Distribution, under Likelihood of Exposure). However, depth interval/horizontal range are typically more indicative of population resilience rather than exposure (Mace et al. 2008). In general, species' extinction risk is driven by population size, range, and rate of decline; however, all three should be considered with additional biologic traits to adequately determine species' vulnerabilities (Mace et al. 2008; Polidoro et al. 2012). For example, small population sizes are generally associated with increased extinction risk, but relative extinction risk amongst species will depend on recruitment, age structure, etc. (Mace et al. 2008). This is the purpose of the PVI's multi-metric design.

The bony fishes' and sharks/rays' results each had interesting implications. First, the three most vulnerable bony fishes (*Cheilopogon exsiliens*, *Mycteroperca bonaci*, *Eustomias furcifer*), based on the PVI, all scored high under Habitat, Pre-Adult Exposure, Increased Adult Sensitivity to UV Light, and Increased Pre-Adult Sensitivity to UV Light (Table 9). Therefore, it appears from initial glance the critical metric indicative of bony fishes' vulnerability under the PVI is linked to presence in more exposed, sensitive, and/or unique habitat (e.g. Epipelagic (+ 200 m)). This information is valuable; in the absence of additional species-level data, as habitat information is often used by proxy to determine conservation policy (Polidoro et. al 2012). Effects of the *Deepwater Horizon* (2010) oil spill also support the apparent relationships within bony fishes' results. Wetland (or Estuarine habitat), which drives Habitat and Pre-Adult Exposure up, was significantly affected by *Deepwater Horizon* (Corn & Copeland 2010). Wetlands are both upland and open water, resulting in richer-than-average flora/fauna (Corn & Copeland 2010). The wetlands and estuaries of the Gulf serve as breeding grounds, nurseries, migration-stopover points, and homes for extensive species, among which are plankton, algae, zooplankton, fish, shellfish, etc. (Corn & Copeland 2010). The porous nature of wetland habitat can permit high concentrations of oil to entrain within sediment, making the area incredibly difficult to clean, resulting in increased duration of exposure (Scott et. al 2013). Plus, given the importance of wetland and estuarine areas as breeding grounds, larvae were also significantly affected by the *Deepwater Horizon*, as represented by the high Pre-Adult Exposure metric. In addition, Rooker et al. (2013) worked to ascertain the impact of *Deepwater Horizon* on pelagic fishes, specifically blackfin tuna (*Thunnus atlanticus*), blue marlin (*Makaira nigricans*), dolphinfish (*Coryphaena hippurus*), and sailfish (*Istiophorus platypterus*). It was not conclusive that the *Deepwater Horizon* spill and the abundance of the fishes' larvae were directly linked; however, the overlap of the spill and each species' suitable larval habitat indicated larvae were impacted by the spill. As a potential consequence, Blue marlin and sailfishes declined somewhat, which Rooker et al. (2013) attributed to the species' larvae being restricted to the surface relative to other taxa surveyed, resulting in increased Pre-Adult Exposure. Although Rooker et al. (2013) do not consider UV irradiation in the context of blue marlin and sailfishes' surface-level larval habitat, it is possible this drove decline as well, evidencing Increased Pre-Adult Exposure due to UV light as a factor. UV irradiation of PAHs has been observed to increase toxicological sensitivity, and consequential death, for certain fish species, especially in the pre-adult stage (Logan 2007; Buskey et al. 2016). Interestingly, although oil might have affected surface-restricted larvae, Rooker et al. (2013) claim effects of oil from *Deepwater Horizon* would be modest as a whole, given the majority of all four species' suitable larval habitat was outside the area of the Gulf affected by the spill. This could suggest the importance of Distribution as a driver of bony fishes' resilience, which the PVI also suggests; in that the most vulnerable bony fishes under the PVI occupy a smaller Distribution. The PCA validates the findings and research above. Increased Adult Sensitivity due to UV Light, Increased Pre-Adult Sensitivity to UV Light, Habitat, and Pre-Adult Exposure (PC1), account for 24% of variation in the data. Habitat, Pre-Adult Exposure, and Distribution (PC2), explain a further 16% percent (40% total).

Table 9. Top Three Scoring Bony Fishes and Sharks/Rays

Group	Genus Species	Global RL	[Score] Distribution	[Score] Longevity	[Score] Mobility	[Score] Habitat	[Score] Pre-adult Stage Length	[Score] Pre-adult Exposure	[Score] Increased Adult Sensitivity Due to UV Light	[Score] Increased Pre-adult Sensitivity Due to UV Light	[Score] Abundance]	[Score] Reproductive Turnover Rate	[Score] Feeding or Habitat Specialization	[Total Score] Likelihood of Exposure	[Total Score] Individual Sensitivity	[Total Score] Population Resilience	[Final] Petrochemical Vulnerability Score
Bony Fishes																	
	Cheilopogon exsiliens	LC	3.5	3.0	3.0	5.0	3.0	5.0	5.0	5.0	5.0	2.5	5.0	22.5	10.0	12.5	45.0
	Mycteroperca bonaci	NT	3.5	5.0	3.0	5.0	3.0	5.0	5.0	5.0	3.0	3.5	4.0	24.5	10.0	10.5	45.0
	Eustomias furcifer	LC	4.0	3.0	3.0	5.0	3.0	5.0	5.0	5.0	5.0	3.0	3.0	23.0	10.0	11.0	44.0
Sharks/Rays																	
	Scyliorhinus meadi	DD	4.0	3.0	3.0	5.0	3.0	5.0	5.0	5.0	5.0	4.0	3.0	23.0	10.0	12.0	45.0
	Oxynotus caribbaeus	DD	4.0	3.0	3.0	5.0	3.0	5.0	5.0	5.0	3.0	3.5	4.0	23.0	10.0	10.5	43.5
	Apristurus parvipinnis	DD	3.5	3.0	3.0	5.0	3.0	5.0	5.0	5.0	3.0	4.0	4.0	22.5	10.0	11.0	43.5

Sharks/rays, the top predators, are also an important part of the Gulf ecosystem, and results merit examination. The top three most vulnerable sharks/rays (*Scyliorhinus meadi, Oxynotus caribbaeus, and Apristurus parvipinnis*), based on the PVI, also all scored maximum vulnerability under Habitat, Pre-Adult Exposure, Increased Adult Sensitivity to UV Light, and Increased Pre-Adult Sensitivity to UV Light (Table 9). However, despite this similarity, sharks/rays had higher overall PVI scores than bony fishes. The histogram of bony fishes' PVI scores is bimodal; in contrast, the histogram of sharks/rays' PVI scores is substantially left skewed. Breaking down the results into Low [20, 30), Moderate [30-35), and High [35-45), the skew is even more apparent (Table 10). There are a few reasons for this. Chondrichthyans, to which sharks/rays belong, have different life histories compared to marine bony fishes. For example, many Chondrichthyans have long lives, are slow-growing, slow-maturing, and have low production/mortality (Cailliet et al., 2005; Musick et al., 2000a; Stevens et al., 2000; Field et al. 2009). As a result, sharks/rays are thought to be particularly vulnerable to disturbance (Field et al. 2009). The skewed vulnerability of sharks/rays compared to bony fishes based on the PVI is likely based on sharks/rays' greater longevity combined with specialized or vulnerable Habitat, Pre-Adult Exposure, and regular presence in surface waters (e.g. UV Light). Around 50% of Chondrichthyans live in epipelagic (+ 200 m) coastal or shelf waters (Compagno, 1990; Compagno et al., 2005; Field et al. 2009). In addition, pre-adult sharks/rays may be the most at-risk individuals of these species (Field et al. 2009). The PCA of sharks/rays validates this further. Longevity, Pre-Adult Stage Length, Increased Adult Sensitivity due to UV Light, and Increased Pre-Adult Sensitivity to UV Light (PC1) account for 29% of variation in the data; Abundance and Distribution are negatively associated with PC1. Although Longevity is negatively associated with PC2, which explains an additional 19% of the variation (48% total), Pre-Adult Exposure, Habitat, Increased Adult Sensitivity due to UV Light, and Increased Pre-Adult Sensitivity to UV Light are positively associated. There is a key difference, here, in life pattern traits being more present in early PCs than in bony fishes' PCA.

It should be noted that Field et al. (2009), in comparing Teleostei and Chondrichthyans, found that while sharks/rays might be predisposed to extinction, it could not be determined chondrichthyans are more vulnerable than Teleostei, marine fishes. Field et al. (2009) suggest that, given sharks/rays life histories, the rate of environmental change is critical; in the case of rapid change, the survival rates of sharks/rays could be essentially outpaced. The sudden environmental changes caused by an oil spill, for example, for which the PVI was developed, could certainly result in increased shark/ray vulnerabilities. In addition, Field et al (2009) argue that shark/rays' potential vulnerabilities, even if not dissimilar to bony fishes, merit increased attention; in terms of biological diversity, Teleostei include 30 times the species of Chondrichthyans. In this sense, any loss of Chondrichthyans, as top predators in many cases, would more significantly affect biodiversity. However, impacts to either group will most certainly cause ecosystem changes, as sharks/rays also depend on the preservation of their prey and other important ecological relationships with bony fishes (Field et al. 2009).

Table 10. Low, Moderate, and High Vulnerability of Bony Fishes and Sharks/Rays

	Bony Fishes	Sharks/Rays
Low [20 – 30)	502 (31.83 %)	5 (6.02%)
Moderate [30 – 35)	700 (44.39%)	29 (34.94%)
High [35 – 45]	385 (24.41%)	49 (59.04%)

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

Utilization of the Index

The resulting PVI can be used to guide attention to the species potentially most in need of immediate attention in the event of an oil spill or other petrochemical influx, lest the species suffer significant damage, as well as those species that may require intensive long-term recovery. The scores can also provide information on species that ought to be the focus of future toxicological research, in indicating which species that lack toxicological data, may potentially experience significant impacts. Through the PCA, key drivers of species' petrochemical vulnerabilities can be determined, which can aid in developing strategies for management and conservation in the Gulf of Mexico. These data can be integrated into spatial decision-tools to determine areas with a high proportion of non-threatened species and/or low petrochemical vulnerability for better management, recovery efforts in the case of influx, and long-term policy recommendations for oil exploitation. In sum, the Petrochemical Vulnerability Index (PVI) provides an objective means with which to prioritize immediate and long-term management for the 1,660 Gulf marine fishes in the case of ecotoxicological disaster or for current petrochemical activity planning and decision-making. The index both identifies at-risk species and provides a mechanism by which to consider drivers of species' vulnerability. It is recommended that the results of this index be utilized in context with developing anticipatory and planning strategies for of petrochemical activities in the Gulf of Mexico.

Validation

To validate results, comparisons of final PVI scores to published information on known species' observed/documented responses to petrochemical exposure would be ideal; for example, the Petrochemical Vulnerability Index for the bony fishes indicates *Cheilopogon exsiliens* (Bandwing Flyingfish) and *Mycteroperca bonaci* (Black Grouper) are most vulnerable to petrochemical influx while *Squalogadus modificatus* (Tadpole Whiptale) and *Scopelogadus beanii* (Bean's Bigscale) are least vulnerable, toxicological data on the responses of the four species to the same suites of petrochemicals could be used to help validate and/or refine the final index weighting methodology and scores. For example, an LC50 value for the same chemical, or suite of chemicals, for multiple species would provide a means of direct validation and comparison of sensitivity. However, currently there are limited published data on toxicological responses for most marine fishes, including LC50 values, particularly for deep sea and lesser-known species. Some species' responses to petrochemical influx, i.e. *Deepwater Horizon*, were unable to be quantified, as species were affected far offshore (Corn & Copeland 2010). Additionally, the deep sea is difficult to sample; it is remote, megafauna is patchily distributed, and most data is derived from grabs/trawls, which only catch a small portion of the area (Fisher et al. 2016). Furthermore, assuming studies on all species were even available, studies are not entirely consistent in how species' response is measured, e.g. LC50, number of lesions, swimming performance, etc., and how each type of response translates to overall petrochemical vulnerability is unclear. The most direct method is lethality toxicity tests but collecting the sample of fishes' life stage and/or specific crude oil compound is difficult (Buskey et al. 2016). As a result, it is unlikely published research at this time will serve as a complete, comprehensive validation of the PVI.

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