# A TOOL FOR COMPARING RELATIVE RISKS TO ECOLOGICAL COMPONENTS ASSOCIATED WITH DIFFERENT OIL SPILL RESPONSE OPTIONS

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## ABSTRACT

689135: Subsea dispersant injection (SSDI) applied to a deepwater blowout has been shown to be a highly efficient oil spill response (OSR) tool that, under appropriate conditions, can substantially lessen and delay oil surfacing as well as reduce the persistence of surface oil slicks. Bock et al. (2018) explored the relative ecological and societal risks associated with integration of SSDI into OSR strategies in the northern Gulf of Mexico using a comparative risk assessment (CRA) desktop analysis tool. The CRA analysis tool was developed with regulatory and stakeholder engagement and communication in mind; the user interface and emphasis on visualization of the assessment results were intended to facilitate rapid examination of the consequences of different spill scenarios in the presence and absence of SSDI and other OSR technologies. Using the CRA tool, decision makers are now better able to predict the nature and extent of the likely consequences to shoreline and aquatic valued ecological components (VECs) and environmental compartments (ECs), and examine the relative consequences of deploying different response technologies.

The CRA tool has been substantially improved and has been redesigned from an Excel spreadsheet into a web-based application with enhanced interactive data visualizations and collaboration tools. The new web-based CRA tool is based on the Shiny application framework, an R based open source system for building interactive web-based applications. The updated CRA tool (https://nert.shinyapps.io/CRA_viewer/ ) now includes improved visualizations of the oil spill modeling results, depictions of the spatial footprint of different ECs, and the interactive exploration of the CRA results and intermediate calculations. Stakeholders are able to drill down into the components of the analysis and more easily explore the parameters that drive CRA scores, as well as explore alternative scoring options. The tool has also been modified to facilitate updating the CRA tool for new oil spill scenarios and OSR options. This web-based interactive CRA tool greatly enhances the usability of CRA as a collaborative tool for evaluating OSR options during planning and can also be used to inform the evaluation of response options during planning, training, and during an incident.

## INTRODUCTION

The goal of oil spill response (OSR) is to mitigate the impacts of spilled oil on valued resources while limiting negative effects. OSR planning seeks to strike a balance between reducing injury to important resources without unacceptably increasing the injury to others. Balancing these considerations, OSR planning is dependent on (1) the oil release conditions, (2) the fate and transport of the released oil, (3) the exposure of valued resources to both oil hydrocarbons and response activities, (4) the potential effects of this exposure on valued resources, and (5) comparing how different oil spill response strategies influence these factors.

Modern OSR response planning allows groups of stakeholders to provide input on these factors and develop consensus on best response approaches.

Subsea dispersant injection (SSDI) is a relatively recent addition to the OSR toolbox. Recent studies have concluded that when applied appropriately the use of SSDI in a deepwater oil and gas well blowout can have many benefits including: reducing the volume of oil that reaches the water surface; reducing the exposure of humans and wildlife to volatile organic compounds (VOCs); dispersing the oil over a large water volume at depth, thereby reducing the concentration; reducing the persistence of oil; enhancing biodegradation; and reducing surface, nearshore and shoreline exposures to oil (e.g., Brandvik et al. 2017; Daling et al. 2016; French-McCay et al. 2018a,b, 2019). Potential negative effects of SSDI include increasing the exposure of water column and benthic resources at depth and the introduction of dispersants into the environment. These considerations were evaluated in a recent National Academy of Sciences report which highlights the value of the CRA approach in OSR (NASEM 2019). CRA is a methodology for OSR decision making that is based on net environmental benefits analysis (NEBA) (ASTM 2013, IPIECA 2015). Consensus ecological risk assessment (C-ERA) (Aurand and Essex 2012) and Spill Impact Mitigation Assessment (SIMA) (Coolbaugh and Varghese 2016, Robinson et al. 2017) are similar recent refinements to the original NEBA approach.

A recent series of papers presented a Comparative Risk Assessment (CRA) approach and considered the implications of SSDI use for a hypothetical deepwater well blowout in the northern Gulf of Mexico (GOM), assuming either (1) no intervention; (2) use of mechanical recovery, in-situ burning, and surface dispersant application (MBSD); and (3) MBSD plus SSDI (French-McCay, et al. 2018a; Bock et al. 2018; Walker et al. 2018). In brief, probabilistic modeling was used to evaluate the influence of variable metocean conditions (i.e., winds, currents and temperature) on oil trajectory and fate (French McCay et al. 2018a), with two model scenarios retained for further evaluation: (1) median surface oiling (MedSO) and (2) high shoreline oiling (HiShO) (French-McCay et al. 2018a). A comparative risk assessment methodology was used to compare the various OSR options (Bock et al. 2018) and to provide quantitative information to decisionmakers so they could evaluate potential impacts and tradeoffs related to use of dispersants, in situ burning, and mechanical removal activities. This work was undertaken in consultation with a large group of stakeholders who provided input, review and feedback on all aspects of the modeling, input assumptions, and assessment (Walker et al. 2018). The CRA process is depicted in Figure 1.

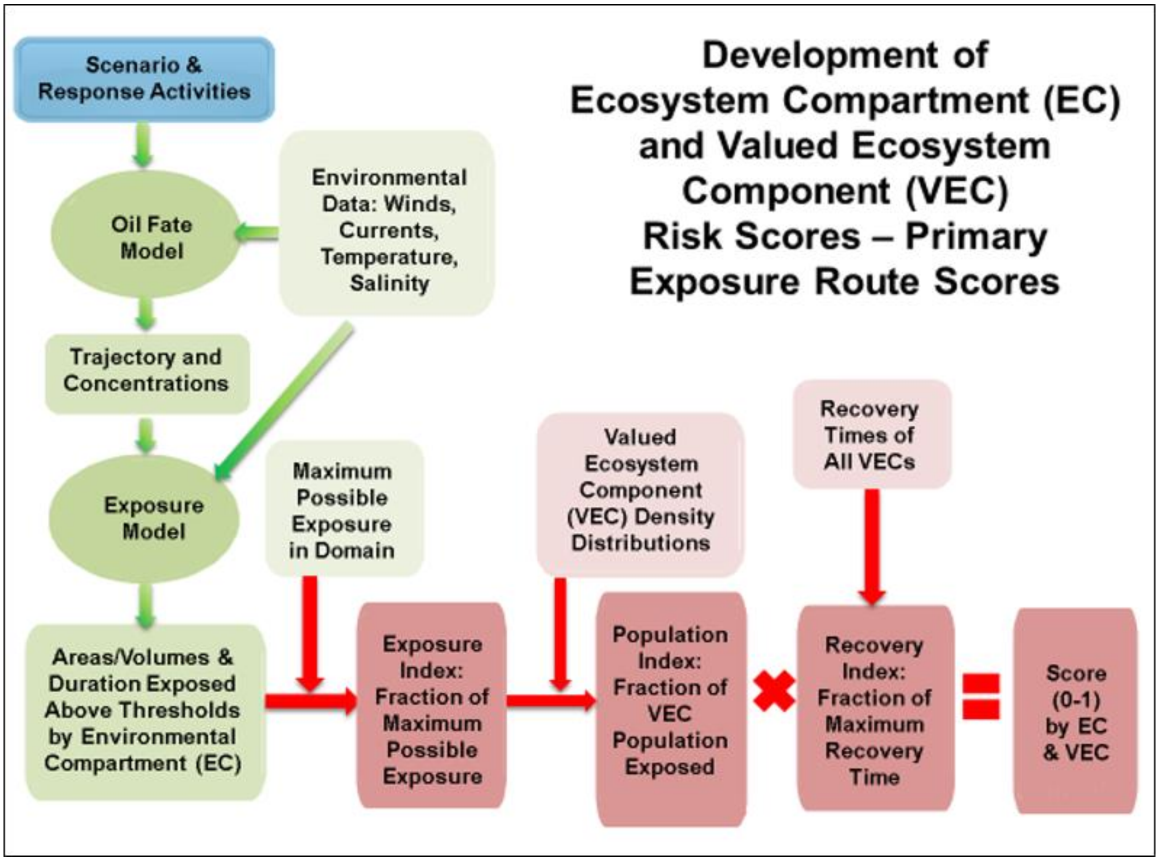

*Figure 1. Overview of the complete CRA process.*

The objective of this work is to build on the previous CRA approach for the comparing risks and benefits of the various response alternatives. The CRA analysis can be difficult to navigate due to numerous scores being calculated for each VEC, EC and OSR option. Although the CRA "roll-up scores" presented in Bock et al. 2018 provide an overview of the various OSR options, much of the detail is missing from these summary scores. The companion Excel CRA tool presented in Bock et al. 2018 provides more detailed results but accessing these results can be numerically burdensome and sharing among teams of stakeholders can be difficult. The process of updating the results can be slow and requires updating the Excel file and distributing that file among the individual stakeholders. To address these shortcomings, we migrated the Excel-based CRA tool to a web-based application using the R Shiny application framework (Beeley and Sukhdeve 2018) and enhanced its functionality. The web tool takes advantage of easy to use filters and pop-ups that allow detailed exploration of the results. Users can test certain assumptions regarding the distribution and resiliency of ECs and explore how these assumptions influence the scores. Updates to the results, such as refinements to the exposure modeling, can be rolled out to stakeholders by simply republishing the app. However, the time required to conduct oil spill fate and transport modeling means that near real-time updates to the exposure metrics during a spill response are not currently feasible.

## METHODS

We briefly summarize the CRA methodology here, and a more detailed explanation can be found in French-McCay et al. 2018a; Bock et al. 2018; and Walker et al. 2018. A critical requirement of any OSR CRA is to understand the habitats (i.e., environmental compartments, ECs) and the ecological resources, represented in terms of valued ecosystem components (VECs), potentially affected by the spilled oil.

ECs are defined by identifying the habitats within the model domain. The ECs for the northern GOM are shown in Figure 2. These ECs were defined based on proximity to shore (e.g., shoreline, coastal, shelf, and offshore). The shoreline habitats were defined based on the substrate (rock shore, gravel beach, sand beach, fringing mudflat, fringing wetland, intertidal artificial). In the other zones, the habitats were further defined based on depth ranges (air, surface, upper epipelagic, lower epipelagic, deepwater, and seafloor). The surface layer was the top 10 centimeters (cm), the upper epipelagic was 10 cm to 20 meters, the lower epipelagic was 20 to 200 meters, the deepwater was greater than 200-meter depth, and the sea floor was defined as within 1 meter of the bottom.

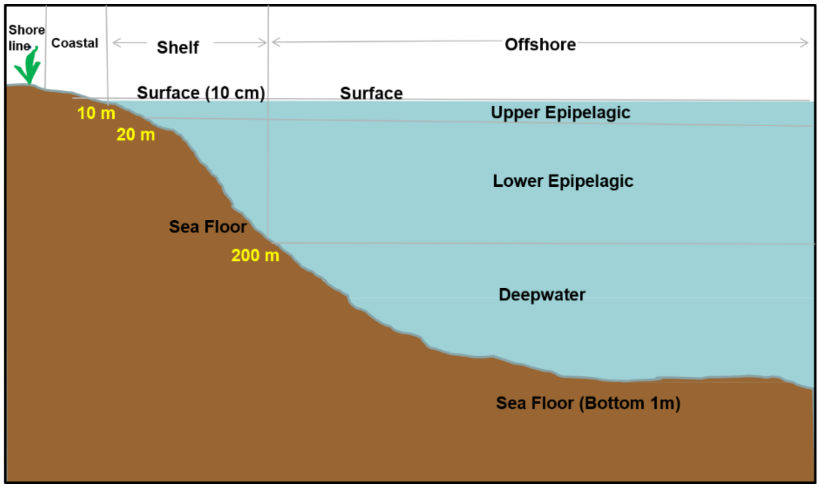

*Figure 2. ECs used in the CRA model.*

VECs are defined to represent groups that are important to the food web; occupy a predominant position in the ecosystem; are relatively abundant; or have indigenous cultural value or commercial importance (DWH NRDA Trustees, 2016). Phytoplankton and microbial communities were not included as VECs because of their rapid recovery times. The VECs were chosen in consultation with the project’s stakeholder advisory group based on the professional judgment of the group’s members (Walker et al. 2018). The selected VECs include sargassum communities, zooplankton, ichthyoplankton, small pelagic fishes (water column fishes), large pelagic fishes, demersal fishes (bottom fishes), soft bottom macrobenthos (benthic and epibenthic invertebrates), coral reef communities, marine mammals, sea birds, and sea turtles.

Estimates of exposure to spilled oil are based on (1) the oil concentrations or thicknesses estimated by the transport, fate and exposure model; and, (2) the area or volume, through time, in which conservative screening threshold values were exceeded. As described in French-McCay et al. (2018a), the threshold values were selected to quantify oil exposures and enable comparisons across the ECs and VECs. These were not intended to be definitive effects thresholds for aquatic life, although review of the scientific literature suggests plausible ranges that may be indicative of sublethal or potentially lethal effects levels. The oil exposure thresholds are summarized in Table 1 and are described in detail in French-McCay et al. 2018 and Bock et al. 2018.

*Table 1.Oil exposure thresholds.*

| VEC Type | Exposure Measure | Lower Threshold | Upper Threshold |
|---|---|---|---|
| Birds, Mammals, & Reptiles | Surface floating oil mass per unit area | 10 g/m$^2$ (10 µm) | 100 g/m$^2$ (100 µm) |
| Plankton in Upper 20m | PAH concentration in water | 1 µg/L (ppb) | 10 µg/L (ppb) |
| Other Water Column | PAH concentration in water | 10 µg/L (ppb) | 100 µg/L (ppb) |
| Vegetation & Habitats | Shoreline oil mass per unit area | 100 g/m$^2$<br>(100 µm) | 1 kg/m$^2$<br>(1 mm) |
| Intertidal Invertebrates | Shoreline oil mass per unit area | 10 g/m$^2$<br>(10 µm) | 100 g/m$^2$<br>(100 µm) |

The exposure scores for surface-dwelling and shoreline organisms are based on the output of the model from French-McCay et al. (2018a) and represent an estimate of area exposed above the thresholds for oil thickness multiplied by duration of the exposure. The exposure scores for water-column organisms are based on the volume of water in the EC that had a 24-

hour average concentration greater than the threshold, or the “dose” (as µg/l - hours), assuming a linear dose-response relationship. French-McCay et al. (2018a) provides further details. Inhalation exposures are not included in the current web-based version of the CRA tool.

The population density values provide an absolute or relative estimate of the mass or number of individuals per unit surface area or unit water volume for each VEC. The population index, which represents the proportion of a VEC’s population in a specific EC, is calculated using the population density and total area or volume of that EC in comparison to the total model domain (e.g., the northern Gulf of Mexico). The default population densities and distributions among ECs were based on observations of animal densities in the field reported by the Trustees in the Deepwater Horizon (DWH) Natural Resource Damage (NRD) assessment (DWH NRDA Trustees, 2016) and on estimates derived from the literature, described in detail in French-McCay et al. (2018a). Table 2 summarizes the default population density values. Sea turtle and small pelagic fish densities were updated from those in French-McCay et al (2018a) using data developed from studies performed as part of the DWH NRD. Offshore densities of 1-2-year-old juveniles are assumed 3.32 turtles/km$^2$ (McDonald et al., 2015), i.e., 6.64 kg/km$^2$. Densities of large juvenile and adult turtles on the shelf are assumed 3/km$^2$ for Kemp’s Ridley and 1.5/km$^2$ for loggerheads (Garrison 2015), with total biomass 345 kg/km$^2$. Average hatchling density over all shorelines (9.8 kg/km$^2$) is estimated from DWH NRDA Trustees 2006, assuming 54 hatchlings per nest, 21 g/hatchling, and 1 nest per km on sandy beaches, which represents 8.6% of the shoreline. Small planktivorous fish biomass estimates, made by Sagarese et al. (2017) based on a literature review and by French-McCay et al. (2015c) for the Myctophidae and Gonostomatidae, were assigned to zone (coastal and shelf and/or offshore) and depth range (<200m or all depths) based on their behavior. In the web tool, these density values can be edited by the user under the "VECs" menu. As the user adjusts the density values, the tool recalculates the appropriate indexes, the CRA scores, and updates the charts.

*Table 2. VEC Densities used in the CRA analysis, these values can be edited by the user in the web tool.*

| | Shore | Coastal/Nearshore | | | Shelf | | | | Offshore | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VECs | Shoreline Habitats | Sea Surface | Water Column | Sea Floor | Sea Surface | Upper Epipelagic | Lower Epipelagic | Sea Floor | Sea Surface | Upper Epipelagic | Lower Epipelagic | Deepwater | Sea Floor | Units |
| Sargassum Community | | | | | 1 | | | | 1 | | | | | units/km$^2$ |
| Zooplankton | | 5.94 | 5.94 | | 0.984 | 0.984 | 0.984 | | 0.622 | 0.622 | 0.622 | 0.0002 | | g/m$^3$ |
| Ichthyoplankton | | 5.59 | 5.59 | | 4.01 | 4.01 | 4.01 | | 1.09 | 1.09 | 1.09 | 0.012 | | #/m$^3$ |
| Small Pelagic Fishes | | | 3.52 | | | 0.440 | 0.265 | | | 0.289 | 0.00607 | 0.00607 | | g/m$^3$ |
| Large Pelagic Fishes | | | | | | 0.0952 | 0.0952 | | | 0.095 | 0.095 | 0.005 | | #/10^6 m$^3$ |
| Demersal Fishes | | | | 314 | | | | 1583 | | | | | 191 | kg/km$^2$ |
| Soft Bottom Macrobenthos | 145 | | | 145 | | | | 234 | | | | | 4.76 | kg/km$^2$ |
| Coral Reef Community | | | | 1 | | | | 1 | | | | | 1 | units/km$^2$ |
| Marine Mammals | | 83 | | | 35 | | | | 6.53 | | | | | #/km$^2$ |
| Birds | 320 | 115 | | | 1.53 | | | | 0.56 | | | | | #/km$^2$ |
| Sea Turtles | 9.8 | 345 | | | 345 | | | | 6.64 | | | | | kg/km$^2$ |

The CRA scoring also incorporates estimated recovery times of the VECs. Default recovery times were developed based on the concept that VEC resilience and potential for recovery is based on recruitment and reproductive success (Kingston 2002; ITOPF 2011). Key characteristics informing recruitment include life span, habitat specificity and connectivity, and migratory patterns. VEC recovery times derived by the trustees in the DWH NRD assessment were used if available. If no recovery estimates were provided, the literature was used to estimate VEC recovery times (Table 3). The derivation of these values is described in more detail in French-McCay et al. 2018a and Bock et al. 2018. The recovery index is defined as the ratio of the recovery time of a VEC to the maximum recovery time in any VEC:EC. As with the density values, these recovery values can be edited by the user under the "VECs" menu. As the user adjusts the recovery times, the tool recalculates the appropriate indexes, the CRA scores, and updates the charts.

*Table 3. VEC Recovery Times (years), these values are user editable in the tool.*

| | Shore | Coastal | | | Shelf | | | | Offshore | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VECs | Shoreline Habitats | Sea Surface | Water Column | Sea Floor | Sea Surface | Upper Epipelagic | Lower Epipelagic | Sea Floor | Sea Surface | Upper Epipelagic | Lower Epipelagic | Deepwater | Sea Floor |
| Sargassum Community | | | | | 1 | | | | 1 | | | | |
| Zooplankton | | 0.13 | 0.13 | | 0.13 | 0.13 | 0.13 | | 0.13 | 0.13 | 0.13 | 0.13 | |
| Ichthyoplankton | | 1 | 1 | | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | |
| Small Pelagic Fishes | | | 4 | | | 4 | 4 | | | 4 | 4 | 4 | |
| Large Pelagic Fishes | | | | | | 15 | 15 | | | 15 | 15 | 15 | |
| Demersal Fishes | | | | 10 | | | | 15 | | | | | 15 |
| Soft Bottom Macrobenthos | 5 | | | 10 | | | | 10 | | | | | 100 |
| Coral Reef Community | | | | 20 | | | | 20 | | | | | 200 |
| Marine Mammals | | 40 | | | 40 | | | | 40 | | | | |
| Birds | 8.96 | 8.96 | | | 8.96 | | | | 8.96 | | | | |
| Sea Turtles | 50 | 50 | | | 50 | | | | 50 | | | | |

The CRA analysis incorporates the three above-described indices: (1) the exposure index: the surface area or water volume exposed above threshold concentrations multiplied by duration of exposure, then divided by the total possible exposure (area-days or volume-days) in the model domain; (2) the population index: the relative density distributions of the VECs across environmental compartments, which determines the fraction of the VECs in the domain that would be exposed; and (3) the recovery index: the relative ability of the VECs to recover compared to the VEC with the longest recovery time. The exposure, population, and recovery indices are combined into a single non-dimensional index (the VEC:EC score), which represents the relative risks to a VEC within an EC (see description in Bock et al. 2018). The underlying calculations in the CRA analysis are provided below.

$$\text{Exposure Index} = \text{VEC:EC Exposure} / \text{Maximum Possible Exposure} \qquad \text{(Eq. 1)}$$

$$\text{Population Index} = \text{VEC:EC Population} / \text{Total VEC Population} \qquad \text{(Eq. 2)}$$

$$\text{Recovery Index} = \text{VEC:EC Recovery Time} \,/\, \text{Maximum VEC:EC Recovery Time} \qquad \text{(Eq. 3)}$$

$$\text{VEC:EC Score} = \text{Exposure Index} \times \text{Population Index} \times \text{Recovery Index} \qquad \text{(Eq. 4)}$$

The VEC:EC score is a value between zero and one, with zero meaning that there is no exposure and a score of one meaning that the entire EC was exposed above the VEC threshold for the entire model simulation, that the entire population of the VEC resides in that EC, and that the VEC has the maximum (longest) recovery time. By combining the three indexes in this way, the scores can be compared to facilitate the evaluation of the various OSR options. The scores are typically very small fractions of the maximum possible scores and are thus very small numbers. In the original CRA (Bock et al. 2018), the final VEC:EC scores were multiplied by $10^9$ for ease of use, but in the new tool the user has the option of choosing the multiplier (1, 10, 100, 1000, $10^6$, or $10^9$) using a dropdown menu.

In the CRA analysis there are 52 VEC:EC score combinations, two oil spill scenarios, two sets of threshold values, and three OSR options, which results in more than 600 different score permutations to be displayed and interpreted. While the calculation of so many scores gives the user the ability to investigate risks associated with the OSR options in great detail, this wealth of information presents challenges for efficiently weighing relative risks. To address this concern, the CRA tool offers three methods for synthesizing VEC:EC scores: (1) combining scores by VEC; (2) combining scores by EC; or (3) filtering scores to view a single VEC and EC.

## RESULTS/DISCUSSION

The results of the CRA analysis provide a transparent, scientifically-based method for exploring the relative risks of various OSR strategies based on available knowledge and stakeholder priorities. The web tool eases this analysis and also provides an organized method for incorporating changes to the analysis, such as different stakeholder inputs or modeling scenarios.

The results of the oil spill fate and transport modeling are included in the web tool as a series of maps. These maps are located under the "Oil Dispersion" menu and display the maximum surface water oil concentrations and the shoreline oiling for each scenario (Figure 3). It is relatively easy to update the existing modeling scenarios or add additional visualizations to the tool.

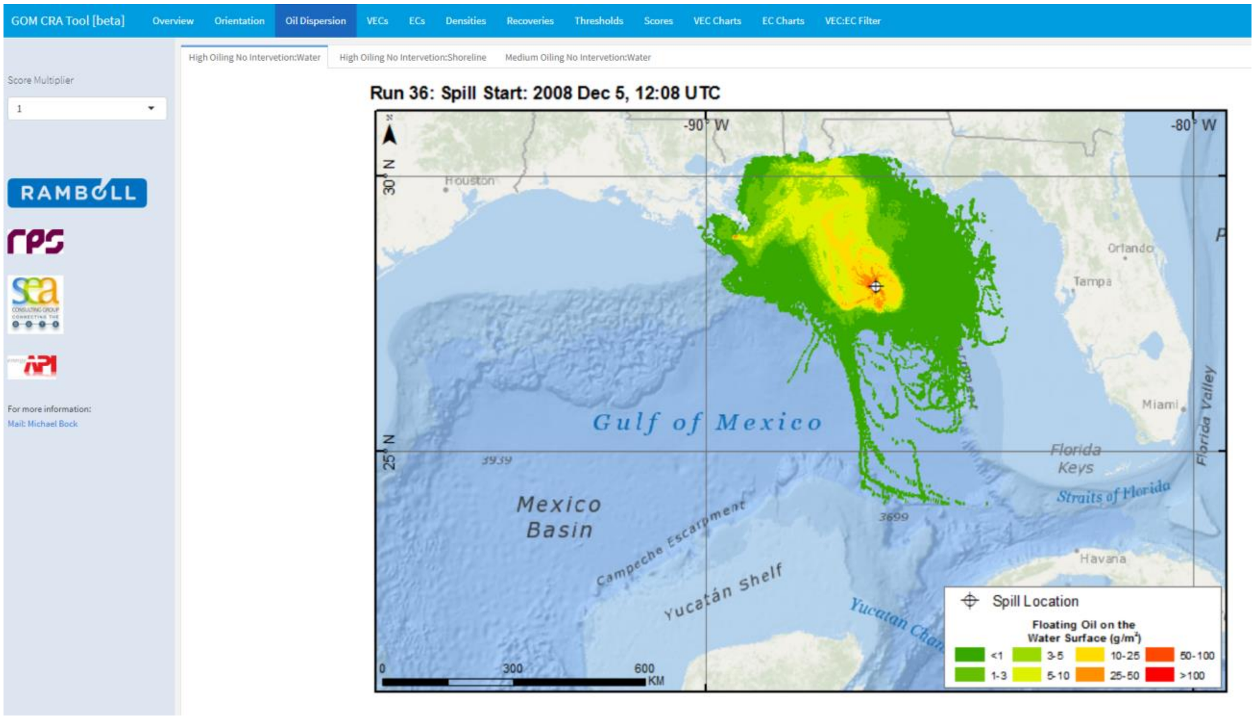

*Figure 3. Example Oil Dispersion Map for the HiShO scenario. Additional maps are included in the tool.*

The numeric scores for each VEC:EC combination are presented under the "Scores" menu, with each modeling scenario presented as a separate column. The scores can be filtered and/or sorted using the interactive boxes at the top of each column. A download function allows the user to obtain the scores as a file so users can use the data analysis tools of their choice to further explore the results. Because there are 104 VEC:EC and threshold combinations corresponding to each row in the table, and six combinations of oil spill scenarios and OSR options, the tool also provides charting functions for exploration of the results.

Summing the results for each VEC provides a simple method for evaluating the scores across scenarios. These score sums are termed “VEC roll-up” scores and are presented in the “VEC Chart” menu. A variety of different roll-up charts are available that share common characteristics. The scores for each scenario are presented in stacked bar charts. Separate chart panels show the scores associated with the lower thresholds and the upper thresholds. In the upper right corner of each chart, there is a pop-up tool that allows the user to download the chart, adjust the axes, or reset the chart to its original configuration. Within each stacked bar, each VEC is shown by color. The charts have hover-over pop-ups that summarize the oil spill scenario, the OSR, the VEC, and the score for that VEC. Clicking on a VEC legend item toggles the chart between including or excluding that VEC. Toggling VECs, or the EC in other charts, allows stakeholders to focus on specific VECs and ECs of interest, much like the weighting feature in the original CRA. Figure 4 shows the VEC roll-up chart. By default, this chart includes all of the VECs and ECs and thus summarizes the total scores in a simple chart. By adjusting the various user settings, more specific comparisons can also be made. The default scenarios plot shows that the scores for the HiShO scenario are higher than those associated with the MedSO scenario. Furthermore, the net scores are highest for the no response options and lowest when SSDI is combined with MBSD. The charts also clearly show which VECs are associated with the highest scores, with surface and shoreline VECs such as birds, sea turtles, and marine mammals having the highest scores.

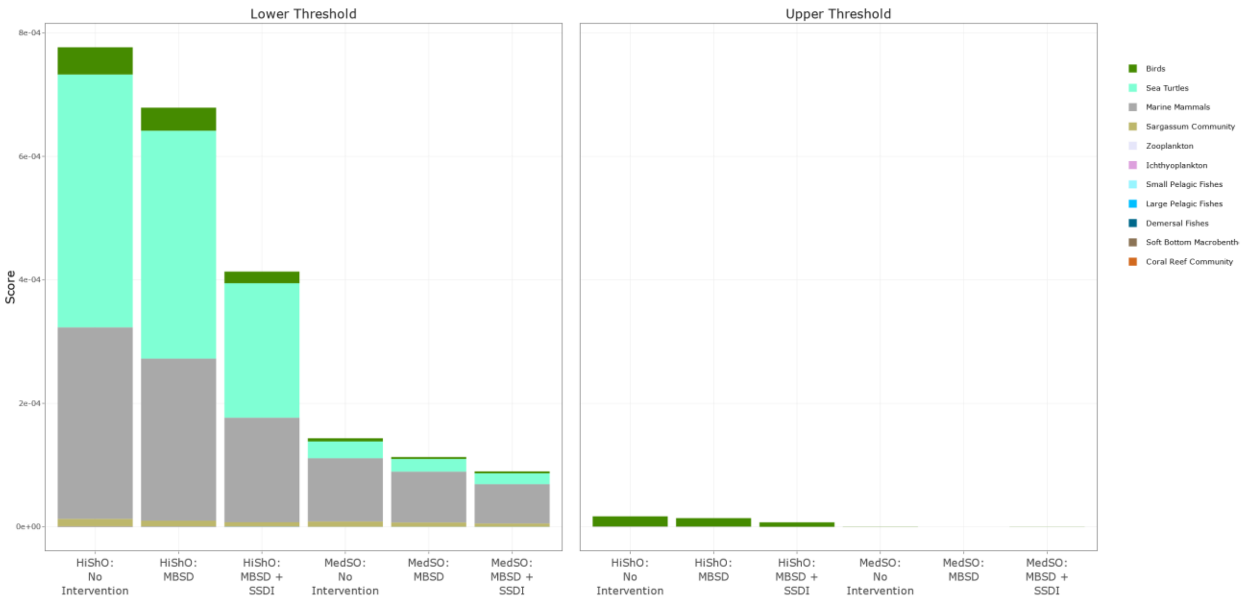

*Figure 4. VEC rollup chart in its default configuration.*

Additional VEC scores are included under separate submenus in the web tool for specific zones: coastal, shelf, and offshore. The charts in each of these zones are subdivided, with each depth range appearing as a row of plots. Figure 5 shows the VEC scores associated with the offshore zone. This group of charts demonstrates many of the trends observed in Figure 4 and described further in Bock et al. 2018. At the sea surface, sea turtles and marine mammals dominate the scores. In deeper water, pelagic fish dominate the scores. For fish, the scores are highest for the MBSD+SSDI scenario. However, these scores are much lower than those observed for the surface VECs (by three to four orders of magnitude). This trend is consistent with the prediction that SSDI causes more oil to remain at depth, reducing exposure to surface VECs but raising exposure to subsurface VECs.

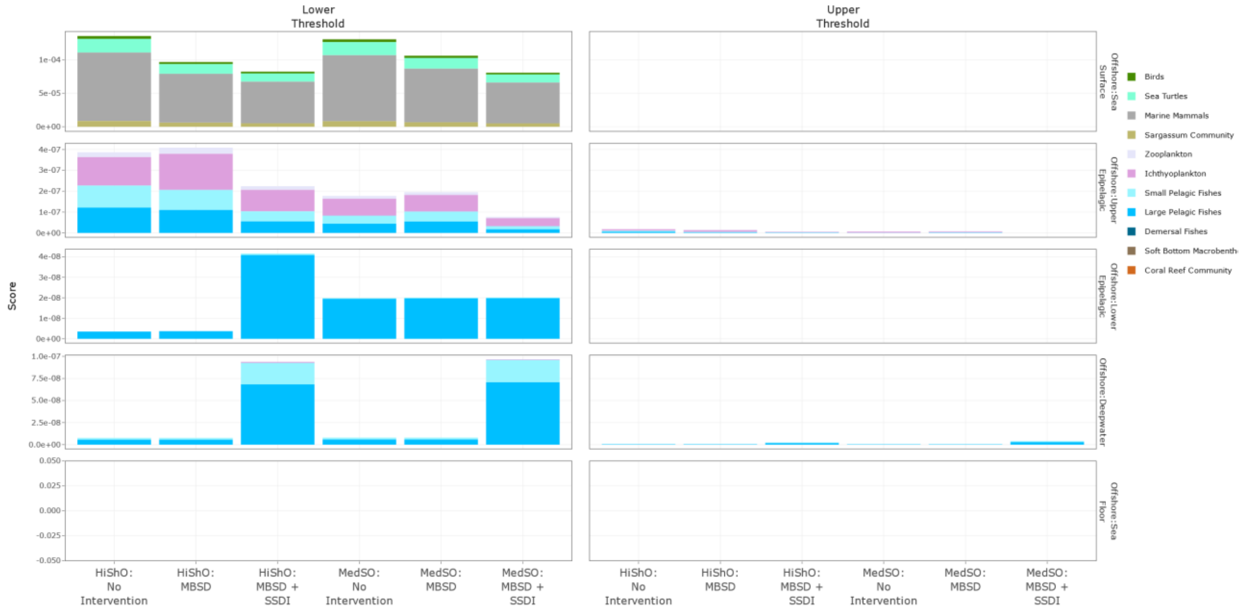

*Figure 5. VEC scores for the offshore zone.*

In addition to allowing the user to explore scores by VEC, the web tool also includes EC roll-up scores, provided in the “EC Charts” menu. Figure 6 shows the EC roll-up chart for the default scenarios, with the bar colors corresponding to each EC. These scores are further divided by VEC groups under submenus, with groups of charts for wildlife, plankton, fish, and benthos. For example, Figure 7 shows the charts for the wildlife VECs, with the scores for birds lowest for MBSD+SSDI. The charts also show that the EC roll-up scores are highest in the offshore zone of the sea surface.

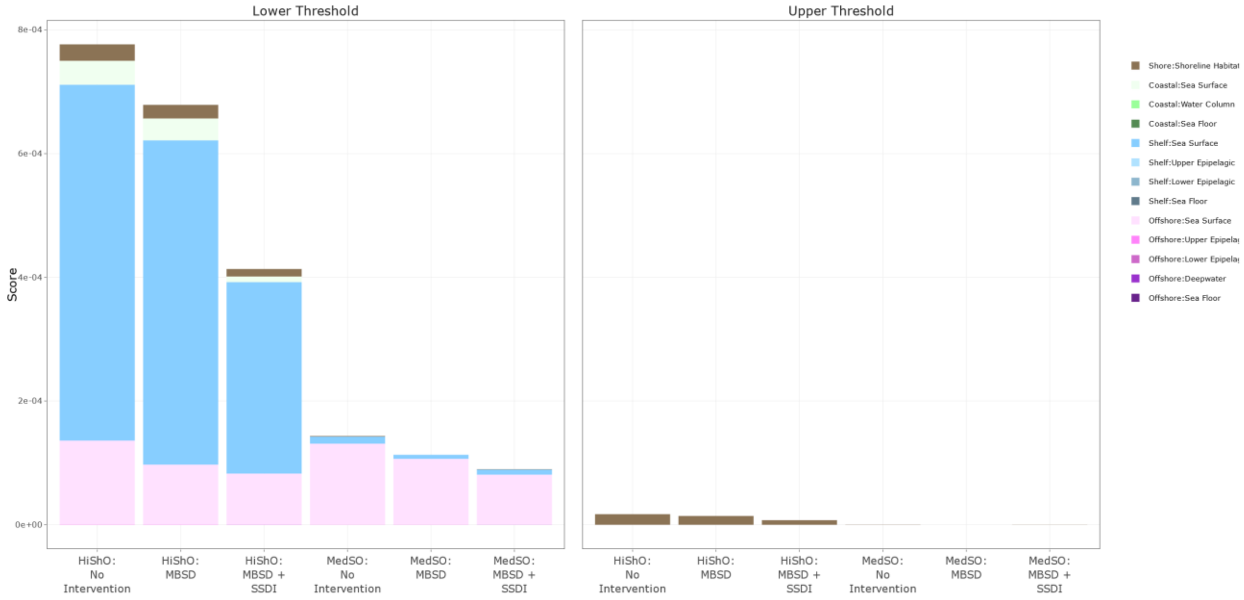

*Figure 6. EC Roll-up chart in its default configuration.*

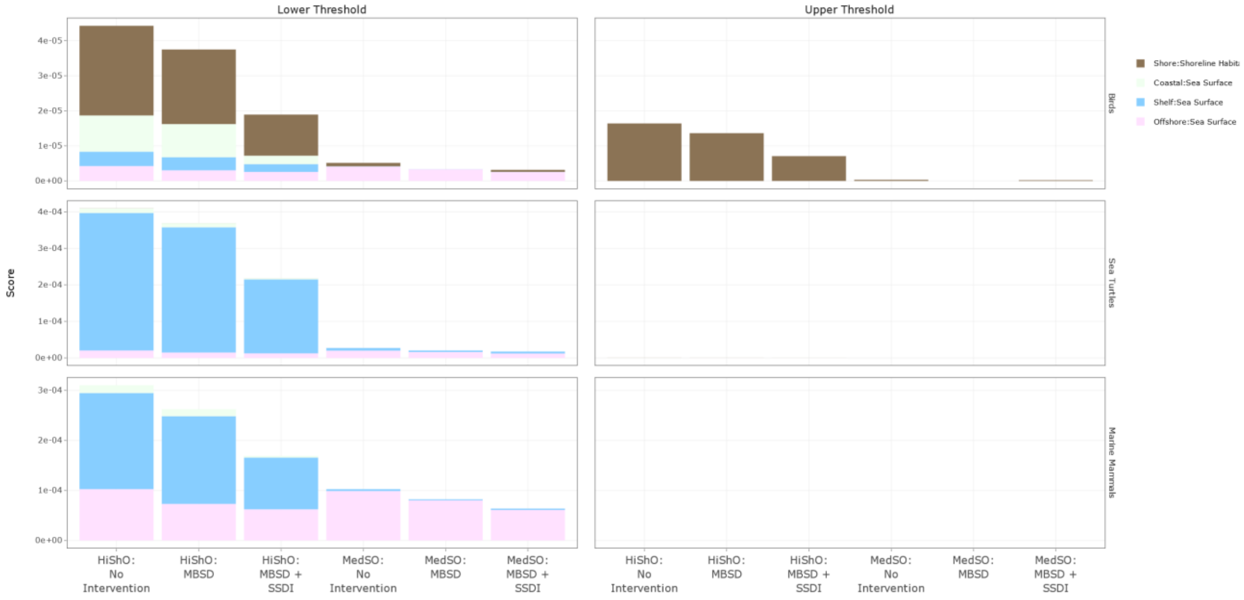

*Figure 7. EC scores for wildlife VECs.*

Finally, the web tool provides an additional way for the user to explore the scores using filter menus. The “VEC:EC Filter” menu allows the user to select the scores for an individual VEC and view the scores for all ECs combined or a single EC (Figure 8).

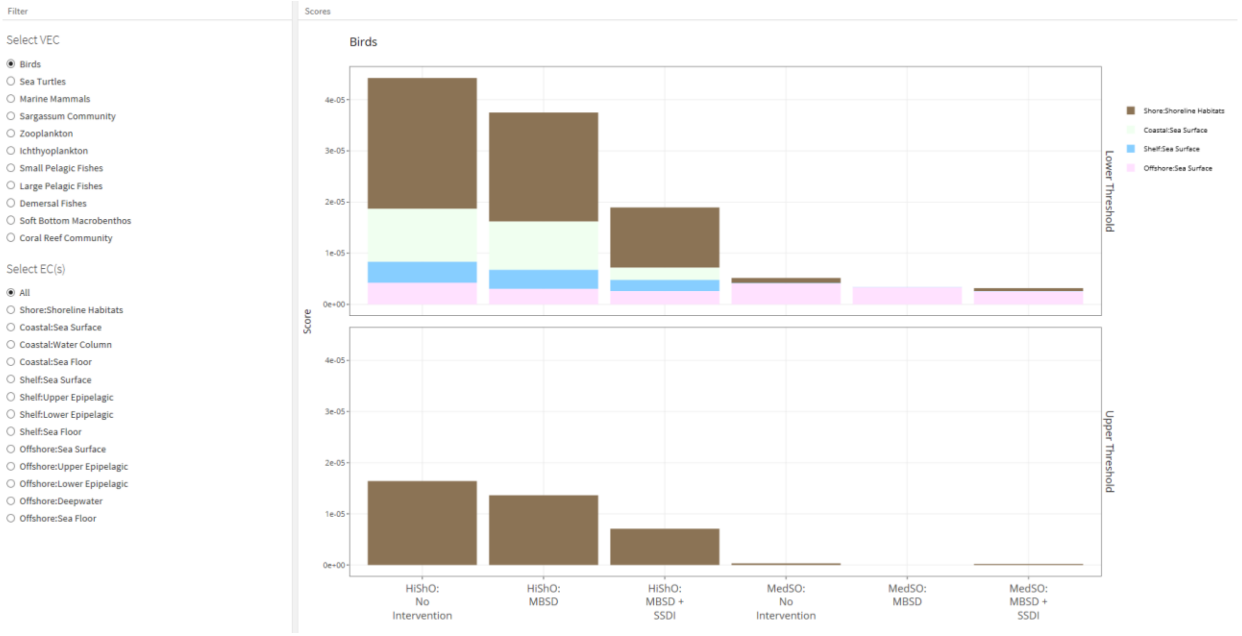

*Figure 8. VEC:EC filter tool.*

## CONCLUSIONS

This web tool demonstrates a significant enhancement to the original Excel-based CRA tool for OSR planning for offshore blowouts (https://nert.shinyapps.io/CRA_viewer/). The new tool is easy to update, more effectively facilitates stakeholder collaboration, and allows users to rapidly explore the results. Critical inputs, such as population density, can be edited by the user and these edits are immediately reflected in the scores. The charts utilize hover-over information pop-ups that provide additional detail. The tool provides subplots and filters that make it easy for the user to explore the results and understand the scores associated with specific VECs and ECs. The tool also makes it easy to identify results that differ from the overall trends, for example the finding that fish are negatively affected by adding SSDI, but that this negative impact is small relative to the benefits to other VECs. Because the results are easy to explore and can be updated rapidly the tool can be used by stakeholders for planning and training to guide OSR option selection. This tool does not provide specific recommendations, but rather provides the stakeholders with access to information they can use and integrate with other considerations, such as worker and community safety, into the decision-making process.

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