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Ecological and Indigenous Community Impacts of Oil Spill Mortality in Alaskan Marine Ecosystems

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Ecological and indigenous community impacts of oil spill mortality in Alaskan marine ecosystems

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Abstract

While hydrocarbon exploration and extraction in the Arctic ebbs and flows, reduced sea ice has opened new travel routes across the Arctic. The opening of the Northwest Passage has allowed larger ships (including oil tankers) and higher traffic into remote regions. More ice loss is expected in the future. With this comes the potential for hydrocarbon spills. To quantify the ecosystem impacts of a spill in the Alaska North Slope region, an Ecospace model using the Ecopath with Ecosim software was developed. We highlight the impacts of four potential hydrocarbon contamination scenarios: a subsurface crude oil pipeline release, a surface platform oil spill, a surface cruise ship diesel spill, and a surface tanker oil spill. Hydrocarbon contamination was modeled using SIMAP (Spill Impact Model Analysis Package), which was developed from the oil fate sub-model in the Natural Resource Damage Assessment Model for the U.S. Department of the Interior and under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA). Spatial-temporal SIMAP results were coupled to the Ecospace model. We show that in all four hydrocarbon contamination scenarios there are spatial changes in harvested species resulting in long-term declines in harvest levels for the communities within the model area (Nuiqsut, Kaktovik, and Barrow Alaska), depending on the severity of the scenario. Responses to hydrocarbon events are likely to be slow in the Arctic; limited by the ice-
free season. We highlight this area for scenario testing as ecological impacts are also an issue of food security to the local communities, and a human health issue.

**Introduction**

Hydrocarbon development has and continues to remain a polarizing issue in Arctic regions. Despite contamination from drilling and potential spills, it offers economic benefits to isolated communities. Hydrocarbon contaminants impact marine animal growth, reproductive success, respiration rates, feeding rates, ability to avoid predation, blood chemistry, acclimatization, and health (Englehardt et al. 1977, Babcock 1985, O’Clair & Rice 1985, AMAP 2010, McIntosh et al. 2010). Hydrocarbon exposure may also result in animal death. Hydrocarbons include oil and diesel fuel, as well as their chemical constituents, polycyclic aromatic hydrocarbons (PAHs). The PAHs are the soluble components of weathered oil or diesel that include a suite of toxins including benzene and naphthalene (Laender et al. 2011, Collier et al. 2013). Hydrocarbon exposure pathways include inhalation, ingestion, and absorption (NRC 2003). In general, hydrocarbon contamination impacts may be more severe to Arctic animals than animals acclimatized to warm climates (Korn et al. 1979, Yunker & Macdonald 1995), and PAHs may be more abundant in high latitudes (Maher 1992, Perkins et al. 2005, Rice et al. 2013).

In studies testing the toxicity of hydrocarbons in relation to temperature, species-specific responses vary (AMAP 2010). In cold-water environments marine phytoplankton can have a low tolerance to hydrocarbon exposure (Østgaard et al. 1984). Hydrocarbons are believed to limit light transmission and photosynthesis (González et al. 2009, AMAP 2010, Brussaard et al. 2015), and change phytoplankton community assemblages (González et al. 2013). Lipophilic compounds may accumulate in and damage cellular membranes (Sikkema et al. 1995). Impacts such as these have also been observed in benthic plants (e.g. macroalgae; Stepaniyan 2008)). Ultraviolet B (UVB) may enhance hydrocarbon toxicity (Almeda et al. 2016). Marine zooplankton mortality generally increases with increasing hydrocarbon
concentrations, PAHs associated heavy metals may bioaccumulate, and egg production or hatching rates are reduced (AMAP 2010, Almeda et al. 2013, Almeda et al. 2014). Benthic invertebrates, from bivalves to echinoderms, demonstrate similar impacts when exposed to hydrocarbons (Stickler et al. 1984, 1985, Mageau et al. 1987, Karinen et al. 1990, Geraudie et al. 2014, Dornberger et al. 2016). Fish, having been more extensively studied, show hydrocarbon toxicity impacts across all life stages. Fish exposed to hydrocarbons may experience inhibited spawning, altered gonadal development, and growth, as well as heart arrhythmia and increases in toxicopathic liver lesions (Heintz et al. 2000, Incardona et al. 2009, Collier et al. 2014). Although less work has been done to understand the impacts of hydrocarbons on marine mammals and birds, studies indicate effects ranging from the loss in their ability to insulate themselves from the cold climate to death via ingested toxins (Englehardt et al. 1977, Øritsland et al. 1981, Stehn & Platte 2000).

In the coming decades, oil production, oceanic shipping, and ecotourism are predicted to increase (BREA 2013, ANDR 2015, Dennis & Mooney 2016). An increase in these types of activities also increases the potential for hydrocarbon contamination in the Beaufort Sea (BREA 2013). From 1996 to 2008 the U.S. Department of Environmental Conservation reports thousands of hydrocarbon spills, equating to 2.7 million gallons of hazardous/toxic substances and 396,000 gallons of crude oil being released from the North Slope oil fields alone, with the frequency of spills increasing (NAEC 2015). Of the thousands of oil spills, many hundreds took place in the Beaufort Sea marine ecosystem (Robertson et al. 2013). On the Canadian side of the Beaufort Sea hundreds of hydrocarbon reserves have been identified (Osadetz et al. 2005), and drilling programs have been developed (IORVL 2012) or are currently underway (BREA 2013). Programs that cross both the U.S. and Canadian areas of the Beaufort Sea include the Izok Corridor Project (http://www.mmg.com/en/Our-Operations/Development-projects/Izok-Corridor.aspx), which plans to use large shipping vessels to transport materials, as well as the emergence of tourism operators that use large cruise ships (i.e. the Crystal Serenity) to transport passengers. In both cases,
these marine vessels store tens of thousands of barrels fuel. The danger of a spill from a vessel was highlighted by the M/V Selendang Ayu, which experienced engine failure, ran aground, broke apart, and spilled over a million liters of heavy bunker C fuel oil into Alaskan waters in 2004. While shipping vessels may present a low probability of producing a hydrocarbon contamination event (i.e. oil or diesel spill), cruise ships have a high probability (NRC 2014). These types of potential hydrocarbon contaminations are considered worst-case scenarios (NRC 2014).

In addition to hydrocarbon contamination events in the Beaufort Sea, the geographical and seasonal inaccessibility of the high latitudes could make hydrocarbon spill response efforts essentially ineffective. "The U.S. is not adequately prepared to respond to a large spill in broken ice conditions in the Arctic and sub-Arctic region," stated Dr. Amy Merten, co-director of the Office of Response and Restoration's Coastal Response Research Center (NOAA online news feature, 2017; [https://oceanservice.noaa.gov/news/features/jun09/arctic.html](https://oceanservice.noaa.gov/news/features/jun09/arctic.html)). Although hydrocarbon contamination response research was started in the 1970s (Lewis 1976), more collaborative work has taken place in recent years (Hansen & Lewandowski 2011, Mullin 2012). Hydrocarbon contaminant response efforts may require ice breakers to reach impacted areas or under sea-ice controls to keep the spill from spreading. In worst-case scenarios (NRC 2014) toxic exposures would persist longer in Arctic ecosystems (MacGregor & McLean 1977, Venosa & Holder 2007, Baussant et al. 2009). This is due to the seasonal low temperatures and high sea-ice extent during the fall to winter transition, which could hinder open-ocean response efforts and thereby lead to acute and chronic toxic hydrocarbon exposures to marine animals.

If hydrocarbon contamination occurs in the Beaufort Sea marine ecosystem, what are the impacts to Arctic animals and the indigenous communities that rely on them for subsistence? The Beaufort Sea marine ecosystem includes the Iñupiat subsistence use areas of northern Alaska, and the Inuvialuit Settlement Regions (ISR) of the Inuit in northern Canada (Canada 1984). Collectively, the Beaufort Sea is
home to nine Arctic indigenous communities. US indigenous communities live in Barrow, Nuiqsut, and Kaktovik, and the Canadian indigenous communities live in Aklavik, Inuvik, Tuktoyaktuk, Paulatuk, Ulukhaktok, and Sachs Harbour. These communities heavily rely on the harvesting (catch) of marine animals for traditional foods, which have an important cultural value, provide essential nutrition, and contribute to reoccurring food security (NDH 2013, Hoover et al. 2016, Hoover et al. 2017). Thus, the condition of the Beaufort Sea marine ecosystem influences the health of harvested animals, thus the health of each indigenous community.

The condition of the Beaufort Sea also impacts animal distribution, therefore availability to indigenous communities. Beluga and bowhead whales are caught throughout the Beaufort Sea marine ecosystem, although sea-ice extent influences their seasonal distributions and migrations, therefore availabilities to each indigenous community (Fraker 1980, Harwood & Smith 2002). Walrus and seals also have seasonal distributions that are influenced by sea-ice extent and migration. For example, walrus can be found around the Alaskan North Slope at certain times of the year (BOWFEST 2009), and spotted seals travel to the Beaufort Sea during the summer and fall (Porsild 1945, Shaughnessy & Fay 1977). Fish, such as salmon and Arctic char, can be anadromous, can be anadromous, or they can be year-round ocean residents, such as Arctic and polar cods, whose life cycles are intimately tied to the seasonal sea-ice extent. All of these animals are considered traditional foods. In general, species-specific relationships with seasonal, environmental changes alter animal distributions, therefore availability of traditional foods for Beaufort Sea indigenous communities. These important annual cycles of marine-based nutrients have defined indigenous community diets and traditions for generations (Codon et al. 1995, Berkes & Jolly 2001). For example, bowhead whale catch by indigenous communities has occurred along coastal migration pathways for thousands of years (Braham et al. 1980, Marquette & Bockstoce 1980, Stoker & Krupnik 1993).
Beaufort Sea marine animals and communities are not just influenced by seasonal environmental changes but also the growing concern of climate change. Climate change may also impact the annual cycles of food availability or access with changes in sea surface temperature or sea-ice extent. In general, the Arctic Ocean’s sea-ice extent has been reduced by more than 50% since the 1970s (Manabe & Stouffer 1995, Stirling 1997, 2002, Derocher et al. 2004, Stirling & Smith 2004, NOAA 2015), and the loss of this important cryosphere habitat has affected important marine habitats and biodiversity ranging from microbes to polar bears (Horner & Murphy 1985, Francis et al. 1998, Benson & Trites 2002, Gradinger 2002, Higdon & Ferguson 2009). The loss of sea-ice is most pronounced near coastal shelves, which largely affect the sea-ice-pelagic-benthic connections and trophodynamics from the benthos to higher trophic organisms (Bradstreet & Cross 1982, Grebmeier & Barry 1991, Grebmeier et al. 1995). The coastal areas and shelves are important parts of each community’s subsistence use area (Braund 2010).

With so many environmental factors impacting the Beaufort Sea marine ecosystem’s food-web (Suprenand & Hoover unpublished), whole-ecosystem management methods are most appropriate for providing local as well as regional insights into ecosystem functions and management approaches. In lieu of the growing potential for hydrocarbon contamination events, a proactive, whole-ecosystem management approach is vital to protect Beaufort Sea animals and indigenous communities. An ecosystem-based management approach allows for multiple indigenous communities, species, and environmental drivers to the considered simultaneously.

To provide a whole-ecosystem approach to understand environmental and hydrocarbon impacts in the Beaufort Sea marine ecosystem, we developed a spatial-temporal, whole-ecosystem model from 1970 to 2014. We coupled it to four hypothetical oil spill trajectory models and employed a series of species-specific eco-toxicological functional responses in order to develop methods of identifying impacts to subsistence caught species and Inupiat communities. Our model also includes the spatial-
temporal integration of environmental variables and subsistence catch rates from each of the nine Beaufort Sea indigenous communities that influence local and regional trophodynamics.

The four US oil spill scenarios are: 1) a near-shore pipeline spilling Alaskan North Slope (ANS) crude oil into Prudhoe Bay, 2) a near-shore pipeline spilling ANS crude from a platform, 3) a coastal cruise ship spilling diesel off of the ANS, and 4) a shipping tanker spill of medium crude oil near the U.S.-Canadian maritime border. Scenario 1 represents the failure of two segments of the North Slope pipeline system (5,000 bbls per segment; (ADNR 2009)), scenario 2 the Shell Oil 2011 oil spill well blowout (Shell 2010), scenario 3 the Crystal Serenity tourist cruise ship grounded, using diesel instead of heavy fuel oil, and 100% leakage, and scenario 4 a crude oil spill from the tanker used for the Izok Mine Corridor Project.

Spill specifics per scenario also coincide with spatial-temporal probabilities of the hydrocarbon contamination, as the oil dispersion depends on environmental factors such as oceanic currents and wind. Our approach is intended to provide natural resource management strategies that are focused on animal conservation and mitigating indigenous community impacts along Alaska’s North Slope Borough.

Material and Methods

Model Area and Indigenous Communities

The present Ecoapth with Ecosim (EwE) and Ecospace models consider the entire Beaufort Sea marine ecosystem area ranging from 67.5 to 75° N and -112.5 to -158° W, or approximately 476,000 km² that include estuarine, coastal, and oceanic habitats ranging from 0 to 3000 m of water depth (Fig. 1). The Beaufort Sea marine ecosystem also encompasses Iñupiat subsistence use areas of northern Alaska (United States of America), the Inuvialuit Settlement Regions (ISR) of the Inuit in northern Canada (Canada 1984), and the southern Beaufort Sea (SB) management unit for polar bears established by the International Union for the Conservation of Nature and Natural Resources (IUCN) Polar Bear Specialist Group (IUCN 2010). The model area represents a little over three percent of the Arctic Ocean’s area, yet
it is an important habitat for migratory bowhead and beluga whales (Fraker 1980, Harwood et al. 2002, DFO 2013), a distinct population of polar bears (Amstrup et al. 2007), and nine indigenous (Iñupiat and Inuvialuit) communities that rely on subsistence catch of marine animals in coastal waters ranging from Alaska to the Northwest Territories. For the present study, the spatial extent of the subsistence use areas for Barrow, Nuiqsut, and Kaktovik are determined by the combined subsistence catch effort maps reported in Braund (1993, 2010)(Fig. 1).

Fig. 1 Map of the Beaufort Sea marine ecosystem and Ecospace model. Red box outlines this study's area of focus, yellow outline denotes the combined subsistence use areas of Barrow, Nuiqsut, and Kaktovik. The US indigenous community city centers are marked with black dots and community name. Aklavik and Inuvik both have community catch, although city centers are further south than the other coastal communities. Depth legend indicates the habitat demarcation according to labeled depth ranges in Ecospace.

Ecopath with Ecosim and Ecospace Models

Our Ecopath model considers 36 functional groups, which includes single species and aggregated groups of species. These functional groups range from top predators (marine mammals) to primary producers and detritus, and implicitly cover all species within the food web. There are 8 marine mammal groups, 1 bird, 9 fish groups, 6 benthic, 6 zooplankton, and 6 producer/detritus groups (see Table 1 for a full list of model groups). These are referred to as the functional groups of: 1) Polar Bears, 2) Beluga Whales, 3) Gray Whales, 4) Bowhead Whales, 5) Walrus, 6) Ringed Seals, 7) Bearded Seals, 8) Spotted Seals, 9) Birds, 10) Char & Dolly Varden, 11) Ciscoes & Whitefish, 12) Salmonids, 13) Herring &
Table 1 Balanced WAP Ecopath model parameters for basic input. TL is trophic level, P/B (Production/Biomass ratio year$^{-1}$), and Q/B (Consumption/Biomass ratio year$^{-1}$) are described by Hoover et al. in press. Ecotrophic Efficiency (EE), P/B, and Q/B are ratios, therefore dimensionless.

<table>
<thead>
<tr>
<th>Functional Group</th>
<th>TL</th>
<th>B</th>
<th>P/B</th>
<th>Q/B</th>
<th>EE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar Bears</td>
<td>4.82</td>
<td>0.0015</td>
<td>0.15</td>
<td>3.03</td>
<td>0.43</td>
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<tr>
<td>Beluga Whales</td>
<td>4.19</td>
<td>0.0305</td>
<td>0.07</td>
<td>17.00</td>
<td>0.16</td>
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<td>Gray Whales</td>
<td>3.33</td>
<td>0.0265</td>
<td>0.06</td>
<td>4.00</td>
<td>0.86</td>
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<tr>
<td>Bowhead Whales</td>
<td>3.38</td>
<td>0.1219</td>
<td>0.07</td>
<td>5.48</td>
<td>0.64</td>
</tr>
<tr>
<td>Walrus</td>
<td>3.13</td>
<td>0.0092</td>
<td>0.07</td>
<td>21.66</td>
<td>0.68</td>
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<tr>
<td>Ringed Seals</td>
<td>3.84</td>
<td>0.0217</td>
<td>0.80</td>
<td>16.05</td>
<td>0.57</td>
</tr>
<tr>
<td>Bearded Seals</td>
<td>3.73</td>
<td>0.0150</td>
<td>0.12</td>
<td>13.85</td>
<td>0.82</td>
</tr>
<tr>
<td>Spotted Seals</td>
<td>4.40</td>
<td>0.0046</td>
<td>0.07</td>
<td>18.70</td>
<td>0.77</td>
</tr>
<tr>
<td>Birds</td>
<td>3.82</td>
<td>0.0026</td>
<td>0.90</td>
<td>10.00</td>
<td>0.08</td>
</tr>
<tr>
<td>Char &amp; Dolly Varden</td>
<td>3.61</td>
<td>0.1407</td>
<td>0.68</td>
<td>2.30</td>
<td>0.67</td>
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<tr>
<td>Ciscoes &amp; Whitefish</td>
<td>3.23</td>
<td>0.7057</td>
<td>0.95</td>
<td>3.80</td>
<td>0.44</td>
</tr>
<tr>
<td>Salmonids</td>
<td>3.59</td>
<td>0.0977</td>
<td>0.85</td>
<td>6.00</td>
<td>0.99</td>
</tr>
<tr>
<td>Herring &amp; Smelt</td>
<td>3.10</td>
<td>0.6640</td>
<td>1.50</td>
<td>4.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Arctic &amp; Polar Cods</td>
<td>3.45</td>
<td>0.6511</td>
<td>0.80</td>
<td>3.90</td>
<td>0.76</td>
</tr>
<tr>
<td>Capelin</td>
<td>3.45</td>
<td>0.1050</td>
<td>0.95</td>
<td>4.00</td>
<td>0.74</td>
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<tr>
<td>Flounder &amp; Benthic Cods</td>
<td>3.34</td>
<td>0.2965</td>
<td>0.75</td>
<td>2.40</td>
<td>0.81</td>
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<td>Small Benthic Marine Fish</td>
<td>3.22</td>
<td>0.7243</td>
<td>1.06</td>
<td>3.50</td>
<td>0.55</td>
</tr>
<tr>
<td>Other Fish</td>
<td>3.08</td>
<td>0.4733</td>
<td>0.51</td>
<td>2.40</td>
<td>0.84</td>
</tr>
<tr>
<td>Arthropods</td>
<td>2.35</td>
<td>3.5000</td>
<td>0.75</td>
<td>3.50</td>
<td>0.91</td>
</tr>
<tr>
<td>Bivalves</td>
<td>2.00</td>
<td>1.9890</td>
<td>0.60</td>
<td>2.40</td>
<td>0.87</td>
</tr>
<tr>
<td>Echinoderms</td>
<td>2.23</td>
<td>5.0000</td>
<td>0.55</td>
<td>1.80</td>
<td>0.53</td>
</tr>
<tr>
<td>Molluscs</td>
<td>2.00</td>
<td>3.0000</td>
<td>0.85</td>
<td>3.40</td>
<td>0.88</td>
</tr>
<tr>
<td>Worms</td>
<td>2.07</td>
<td>2.5000</td>
<td>0.95</td>
<td>4.00</td>
<td>0.83</td>
</tr>
<tr>
<td>Other Benthos</td>
<td>2.08</td>
<td>1.7000</td>
<td>0.80</td>
<td>3.00</td>
<td>0.97</td>
</tr>
<tr>
<td>Jellies</td>
<td>2.33</td>
<td>0.9237</td>
<td>10.00</td>
<td>25.00</td>
<td>0.26</td>
</tr>
<tr>
<td>Macro-Zooplankton</td>
<td>2.64</td>
<td>0.2590</td>
<td>7.50</td>
<td>28.00</td>
<td>0.85</td>
</tr>
<tr>
<td>Medium Copepods</td>
<td>2.12</td>
<td>0.7154</td>
<td>18.00</td>
<td>45.00</td>
<td>0.97</td>
</tr>
<tr>
<td>Large Copepods</td>
<td>2.31</td>
<td>2.7242</td>
<td>5.50</td>
<td>20.00</td>
<td>0.42</td>
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<tr>
<td>Other Meso-Zooplankton</td>
<td>2.34</td>
<td>1.6612</td>
<td>22.00</td>
<td>80.00</td>
<td>0.24</td>
</tr>
<tr>
<td>Micro-Zooplankton</td>
<td>2.00</td>
<td>1.0530</td>
<td>55.00</td>
<td>150.00</td>
<td>0.85</td>
</tr>
<tr>
<td>Producers &gt; 5 µm</td>
<td>1.00</td>
<td>3.7018</td>
<td>30.00</td>
<td>150.00</td>
<td>0.85</td>
</tr>
<tr>
<td>Producers &lt; 5 µm</td>
<td>1.00</td>
<td>4.8081</td>
<td>60.00</td>
<td>150.00</td>
<td>0.85</td>
</tr>
<tr>
<td>Ice Algae</td>
<td>1.00</td>
<td>3.5117</td>
<td>20.00</td>
<td>150.00</td>
<td>0.85</td>
</tr>
<tr>
<td>Benthic Plants</td>
<td>1.00</td>
<td>5.5000</td>
<td>10.00</td>
<td>150.00</td>
<td>0.85</td>
</tr>
<tr>
<td>Pelagic Detritus</td>
<td>1.00</td>
<td>0.5000</td>
<td>10.00</td>
<td>150.00</td>
<td>0.85</td>
</tr>
<tr>
<td>Benthic Detritus</td>
<td>1.00</td>
<td>0.0500</td>
<td>10.00</td>
<td>150.00</td>
<td>0.85</td>
</tr>
</tbody>
</table>
In general, an Ecopath model represents an instantaneous ‘snap-shot’ of material fluxes in the ecosystem according to the constraints of mass-balance and the conservation of energy (Christensen & Walters 2004). The Ecopath portion of the Beaufort Sea model required biomass (tonnes (t)· km⁻²) for each functional group, as well as their respective ratios of production per unit biomass (production ratio, yr⁻¹) and consumption per unit biomass (consumption ratio, yr⁻¹) according to Hoover et al. (2016) (Table 1), and a life table based on natural mortality (Barlow & Boveng 1991). For this Beaufort Sea model, biomass is calculated using information provided from stock assessments, fishery independent monitoring samples, subsistence catch reports, and other published literature. Production of a functional group is determined for all components of the food web, and linked through diet proportions (equation (Eq.) 1), where the production P of the functional group i is represented as:

\[ P_i = \sum B_j * M2_{ij} + Y_i + E_i + BA_i + P_i * (1 - EE_i) \]  

Eq. 1

\( P_i \) was dependent upon the biomass \( B_j \) of each predator group \( j \), with predation mortality on group \( i \) from group \( j \) as \( M2_{ij} \). Here \( Y_i \) represents the subsistence community catch, the net migration rate \( E_i \) is the emigration-immigration, biomass accumulation is \( BA_i \), and the ecotrophic efficiency \( EE_i \) represents the proportion of production accounted for within the system (consumed by predators, exported from the system, fishing or migration) (Christensen et al. 2005).

As Ecopath provides the instantaneous snap-shot of the energy balance between predator-prey relationships according to biomass and parameters in Table 1 (Hoover et al. unpublished model), our Ecosim model performs temporal simulations beginning in 1970 and ending in 2014. These temporal simulations use equation 2:

\[ \frac{dB_i}{dt} = g_i \sum_j Q_{ji} - \sum_j Q_{ij} + I_i - (MO_i + F_i + e_i)B_i \]  

Eq. 2

Where the change in biomass \( dB_i/dt \) over time \( t \) is equal to the net growth efficiency \( (g_i) \) or production/consumption ratio, times the total consumption of group \( i(\sum_j Q_{ji}) \), minus the predation
from all predators on group \( i(\sum_j Q_{ji}) \), combined with all other sources of mortality other than predation \( (M_O) \), the fishing mortality rate \( (F_i) \), immigration rate \( (I_i) \), and emigration rate \( (E_i) \) where net migration equals \( B_i * e_i - I_i \). Ecosim adds a temporal dimension for predicting biomass changes in primary producers and consumers when considering forcing functions according to equations 3 and 4 (below), respectively.

\[
\frac{dB_i}{dt} = cB_i(P - B)EE_i - \sum_{j=1}^{n} f(B_i, B_j) - M_iB_i \quad \text{Eq. 3}
\]

\[
\frac{dB_i}{dt} = cg_i \sum_{j=1}^{n} f(B_j, B_i) - \sum_{j=1}^{n} f(B_i, B_j) + I_i - B_i(M_i + F_i + E_i) \quad \text{Eq. 4}
\]

Where \( B_i \) and \( B_j \) are biomasses of prey \( (i) \) and predator \( (j) \), \( P \) is production rate, \( EE \) is ecotrophic efficiency, \( f \) is a relationship predicting consumption, \( I \) is immigration, \( M \) and \( F \) are natural and fishing mortality, \( E \) is emigration, \( g \) is growth efficiency, and \( n \) is the number of functional groups. The scalar \( c \) is used in this model to introduce forcing functions on productivity, and \( EE \) is the proportion of the production used in the marine ecosystem.

The Ecospace model map is comprised of a grid of pixels, or cells, and each cell represents an individual Ecosim simulation and habitat type. All functional groups in the model are assigned a set of habitat preferences (Table 2 - Depth). Each map cell, with the exception of land cells, thus predicts biomass (population) densities of multiple species and age classes, predator-prey interactions, and fishing mortalities based on trophodynamics, which affects adjacent cells and spatial distributions according to equation 5. Eight habitat types are created to describe the depth ranges that are 0-10 m, 10–20 m, 20-50 m, 50-100 m, 100-200 m, 200-300 m, 300-1000 m, and > 1000 m. Depth ranges are assigned to each Ecospace pixel using Grid Extract from the National Centers for Environmental Information, National Oceanic and Atmospheric Administration (http://maps.ngdc.noaa.gov/viewers/wcs-client/) at the 0.1 by 0.1 decimal degree resolution. This is the resolution of the Ecospace model and all additional map layers (discussed below) that impact functional group foraging arenas.
\[
\frac{dB_{i,x,y}}{dt} = GE_i \sum_{\text{prey}} Q \left(B_{i,x,y}, B_{\text{prey},x,y}\right) - F_{i,x,y} B_{i,x,y} - M_{0i} B_{i,x,y} - \sum_{\text{pred}} Q \left(B_{\text{pred},x,y} B_{i,x,y}\right) + l_{i,x,y} - m_{i,x,y} B_{i,x,y}
\]

Eq. 5

Where equation 4 describes the biomass movement according to the Ecosim equations, with the addition of x and y coordinates referring to individual Ecospace cells, as well as movement into and out of those cells. The first term \((GE_i \sum_{\text{prey}} Q \left(B_{i,x,y}, B_{\text{prey},x,y}\right))\) describes the consumption gain, the second term \((F_{i,x,y} B_{i,x,y})\) the loss due to fishing, the third term \((M_{0i} B_{i,x,y})\) the loss due to other mortality, the fourth term \((\sum_{\text{pred}} Q \left(B_{\text{pred},x,y} B_{i,x,y}\right))\) the loss due to predation, the fifth and sixth terms biomass gain due to immigration \((l_{i,x,y})\) and loss due to emigration \((m_{i,x,y} B_{i,x,y})\).

Additional map layers include spatial-temporal sea-ice extent, sea surface temperature, and chlorophyll a for every month from January 1970 to December 2014. Sea-ice extent and sea surface temperature data come from the British Atmospheric Data Centre (2010), and are converted into mean monthly Ecospace maps to match the 0.1 by 0.1 decimal degree resolution. Similarly, remotely sensed chlorophyll a data from 2003 to 2014 come from the Giovanni online data system (Giovanni MODIS-Aqua data) and are also converted into mean monthly Ecospace maps with the same resolution. To create mean monthly chlorophyll a maps from 1970 to 2014 we first calculate monthly means for each month using all years of available remotely sensed data, then create one mean map for each month to be used throughout the Ecospace simulations. Monthly mean maps are necessary in dynamic Ecospace simulations, because they update environmental variable values in each Ecospace cell and for each time step (month) throughout the 45-year simulation according the methods of Steenbeek et al. (2012). This allows for the suite of environmental variables to synergistically influence spatial-temporal functional group distributions through a series of functional responses to produce habitat-adjusted biomasses.
Table 2  Functional group responses to depth, sea-ice extent, chlorophyll a, and sea surface temperature (SST).

<table>
<thead>
<tr>
<th>Functional Group/Functional Response</th>
<th>Depth (0 - 1000 m)</th>
<th>Sea-Ice Extent (0 - 100 %)</th>
<th>Chlorophyll a (0 - 8 mg m⁻³)</th>
<th>SST (0 - 2 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar Bears</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beluga Whales</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gray Whales</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bowhead Whales</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walrus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ringed Seals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearded Seals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spotted Seals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Birds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arctic &amp; Polar Cods</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Producers &gt; 5µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Producers &lt; 5µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice Algae</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A functional response describes the nature of the relationship a functional group has with an environmental variable. For example, whales migrate to the Beaufort Sea marine ecosystem when sea-ice extent decreases (Hornby et al. 2016) and sea surface temperature increases, giving them greater access to prey (Table 2). In contrast, polar bears traverse, forage, and den more throughout the Beaufort Sea marine ecosystem when the sea-ice extent increases. Thus, the change in sea-ice extent drives distributional changes marine mammal biomass, which impacts related prey, productivity, and distribution. Similarly, chlorophyll $a$ is used to focus Beluga and Bowhead Whales feeding in Ecospace areas, as their zooplankton prey feeds on primary producers. For example, the majority of Beluga and Bowhead Whales’ prey, fish (Loseto et al. 2008) and zooplankton (Moore et al. 2010), respectively, have significant proportions of their diets consisting of primary producers. In total, we created functional group responses for depth ranges, sea-ice extent, sea surface temperature, and chlorophyll $a$, which are linked to Ecospace map layers and the affected functional group(s) according to Table 2. The validation, sensitivity analyses, and other tests of model robustness are discussed in Suprenand and Hoover (unpublished). Furthermore, annual subsistence catch rates and efforts are defined in Suprenand and Hoover (unpublished), which describes the 117 fisheries we created, one for each community and functional group they catch (e.g., Barrow Polar Bears, Barrow Beluga Whales, etc.).

**SIMAP (Spill Impact Model Analysis Package) Modeling**

We used the model algorithms in SIMAP (Spill Impact Model Analysis Package) (French 2003, 2004) that have been developed over the past three decades to simulate fate and effects of hydrocarbon contamination events under a variety of environmental conditions. SIMAP originated from the oil fates sub-model in the Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME) for the U.S. Department of the Interior for use in “type A” Natural Resource Damage Assessment (NRDA) regulations under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA). The most recent version of the type A model, the NRDAM/CME (Version
2.4, April 1996) was published as part of the CERCLA type A NRDA Final Rule (Federal Register, May 7, 1996, Vol. 61, No. 89, p. 20559-20614). The technical documentation for the NRDAM/CME is in French et al. (1996). The model has been validated with more than 20 case histories, including the Exxon Valdez and other large spills (French et al. 1997, French 2003, 2004, French & Rowe 2004) as well as test spills designed to verify the model (French et al. 1997).

Overall, SIMAP is a 3-dimensional Lagrangian model, and each component of a hydrocarbon contamination event is represented by an ensemble of independent mathematical particles or “spilllets”. Each spilllet is a sub-set of the total mass spilled and is transported by both currents and surface wind drift. Inherent in the SIMAP modeling are also oil transport and fate in sea-ice (Drozdowski et al. 2011), which can drift rapidly and over great distances in the Arctic (Peterson et al. 2008), transport and interaction with land-fast ice (Drozdowski et al. 2011), and the effects of ice on hydrocarbon fates and weathering processes such as evaporation and emulsification, as spreading and entrainment are slowed (Spaulding 1988). In general, hydrocarbons (containing non-volatile and volatile components not yet volatilized or dissolved from the oil) are simulated as floating slicks, emulsions and/or tarballs.

For our purposes the SIMAP oil fate model estimates distributions and mean concentrations of hydrocarbons in the water column, surface, and sediments for each Ecospace cell over a period of 390 days. This time duration was the longest possible run time that the SIMAP model is capable of, given the specifics of our hydrocarbon contamination scenarios. Processes simulated in the physical fates model include hydrocarbon droplet and surface hydrocarbon transport and dispersion, hydrocarbon surfacing, surface hydrocarbons spreading, evaporation of volatiles from surface hydrocarbons to the atmosphere, emulsification of hydrocarbons, entrainment of hydrocarbons as droplets, re-surfacing of hydrocarbons, dissolution of soluble components into the water column, volatilization from the water column to the atmosphere, partitioning of hydrocarbons between water and suspended particulates, sedimentation of hydrocarbon droplets, and degradation. The SIMAP model requires wind, current, and
other environmental data as inputs for drive the movement and fate of a hydrocarbon contamination in the Beaufort Sea marine ecosystem. The environmental database is geographical, which includes data for coastlines, bathymetry, shorelines, ecological habitats, and temporally varying land-fast ice coverage, temperature and salinity. The properties of the oil and diesel and their composition are input based on bulk and hydrocarbon chemistry measurements of representative oil samples. In our study, the properties of oil and diesel characteristics in hydrocarbon contamination scenarios are detailed in Table 3.

**Table 3** Oil properties of the crude oil simulated in modeling from Environment Canada ([http://www.etc-cte.ec.gc.ca/databases/oilproperties/](http://www.etc-cte.ec.gc.ca/databases/oilproperties/)).

<table>
<thead>
<tr>
<th>Oil Name / Source</th>
<th>Oil Type</th>
<th>API Gravity</th>
<th>Viscosity (cP at 25°C)</th>
<th>Interface Tension (dyne/cm)</th>
<th>Emulsion maximum Water Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alaska North Slope Crude</td>
<td>Medium Crude</td>
<td>30.9</td>
<td>23.3 @ 0 11.5 @ 15</td>
<td>27.3</td>
<td>72.9</td>
</tr>
<tr>
<td>(2002)</td>
<td>Diesel Fuel Oil</td>
<td>38.8</td>
<td>2.760 @ 25 2.760 @ 15</td>
<td>27.5</td>
<td>0</td>
</tr>
</tbody>
</table>

After the hydrocarbon contamination release in each scenario, the distribution and concentration is modeled for 390 days. After that time we then assume that the hydrocarbons are no longer present in the ecosystem, and are removed from the Beaufort Sea marine ecosystem simulations. This conservative approach is taken so that the potential recovery time of impacted functional groups (and guilds; also discussed below) can be observed once all hydrocarbon-related impacts are removed from trophodynamics and related effects to community catch. Furthermore, SIMAP modeling is limited to simulating hydrocarbon contamination events starting in 2008 and up to present day. As our model is calibrated and validated from 1970 to 2014, we selected a time period after 2008, at least two years before 2014, and during a high ice-free summer for SIMAP model simulations. As indicted in Table 3, all hydrocarbon contamination scenarios start in 2011.
Integrating Impacts of Hydrocarbon Exposure

We use the SIMAP hydrocarbon contamination model output to provide spatial-temporal estimates of Beaufort Sea hydrocarbon concentrations (oil or diesel, g/m^2) in the water column and on the surface as well as in the sediments in four hydrocarbon contamination scenarios (HCES): 1) a near-shore pipeline spilling Alaskan North Slope (ANS) crude oil into Prudhoe Bay, 2) a near-shore pipeline spilling ANS crude from a platform, 3) a coastal cruise ship spilling diesel off of the ANS, and 4) a shipping tanker spill of medium crude oil near the U.S.-Canadian maritime border (Table 4). Lastly, we integrate these concentrations into the Ecospace model using spatial-temporal concentration maps for sediment and water column concentrations for each time step that match the 0.1 by 0.1 decimal degree resolution. Concentrations for each time step are calculated based on the uptake and deprivation rates of the bioavailable oil (discussed below).

Table 4 SIMAP model parameters for 3-dimensional hydrocarbon contamination scenarios.

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location (lat/long)</td>
<td>70.325 °N / -148.35 °W</td>
<td>70.500 °N / -148.35 °W</td>
<td>71.367 N / -148.065 W</td>
<td>70.682 N / -143.646 W</td>
</tr>
<tr>
<td>Location</td>
<td>Prudhoe Bay</td>
<td>Alaska Shelf near Prudhoe Bay</td>
<td>Alaska Shelf near Point Barrow</td>
<td>Alaska Shelf near Kaktovik</td>
</tr>
<tr>
<td>Event Description</td>
<td>Pipeline Oil Release</td>
<td>Platform Oil Spill Cruise Ship Diesel Spill</td>
<td>Tanker Oil Spill</td>
<td></td>
</tr>
<tr>
<td>Depth of Release</td>
<td>Subsurface</td>
<td>Surface</td>
<td>Surface</td>
<td>Surface</td>
</tr>
<tr>
<td>Max. Water Depth</td>
<td>1 m</td>
<td>6.5 m</td>
<td>182 m</td>
<td>360 m</td>
</tr>
<tr>
<td>Oil Name</td>
<td>Alaska North Slope Crude</td>
<td>Alaska North Slope Crude</td>
<td>Diesel</td>
<td>Alaska North Slope Crude</td>
</tr>
<tr>
<td>Oil Type</td>
<td>Medium Crude</td>
<td>Medium Crude</td>
<td>Diesel Fuel</td>
<td>Medium Crude</td>
</tr>
<tr>
<td>Spill Rate</td>
<td>1,000 bbls/day</td>
<td>16,000 bbls/day</td>
<td>Pulse</td>
<td>Pulse</td>
</tr>
<tr>
<td>Spill Duration</td>
<td>10 days</td>
<td>30 days</td>
<td>7 days</td>
<td>7 days</td>
</tr>
<tr>
<td>Total Oil Spilled</td>
<td>10,000 bbls</td>
<td>480,000 bbls</td>
<td>13,523 bbls</td>
<td>533,000 bbls</td>
</tr>
<tr>
<td>Model Run</td>
<td>390 days</td>
<td>390 days</td>
<td>390 days</td>
<td>390 days</td>
</tr>
</tbody>
</table>
**Functional Responses**

We develop eco-toxicological functional responses to hydrocarbon exposure for marine mammals, birds, fish, invertebrates, zooplankton, and primary producers. Eco-toxicological forcing functions represent direct mortality via toxicity and indirect mortality through mechanical impacts and sub-lethal effects to reduce functional group productivity. The hydrocarbon concentration is used as the independent predictor variable in a dose-response model, predicting declines in functional group productivity. The dose-response model was first described by Dorberger et al. (2016), and has been used in similar ecosystem models (Ainsworth et al. 2018). Dorberger et al. (2016) suggested the most parsimonious and best fit model for hydrocarbon-related impacts to group productivity is a ‘hockey stick’ response, which implies that there is an oil concentration threshold, below which there is no effect. Our forcing function for productivity is derived from this hockey stick response, and applied to create productivity scalars between 0-1 (equation 6).

\[
P^* = \begin{cases} 
Z/(Z + m \cdot \varphi \cdot \log[Oil/Oil_{thresh}]) & \text{if } [Oil] < [Oil]_{thresh} \\
otherwise & 
\end{cases} 
\text{Eq. 6}
\]

\(P^*\) represents productivity scalar under oil exposure, \(Z\) is baseline total mortality from Ecopath, \([Oil]_{thresh}\) is the threshold below which there is no mortality from oil, \(m\) is a coefficient describing the slope of the response, and \(\varphi\) represents sensitivity of the group to nearshore oil contamination. \(\varphi\) values are based initially on expert consensus from NCEAS meeting participants (Ainsworth unpublished data), and were determined based on feeding habits and/or how intimately groups associate with the substrate or intertidal area.

Nearshore oil sensitivity is chosen for our forcing function development because the Beaufort Sea marine ecosystem is contained in the nearshore environment. Original sensitivity estimates were between 0-1, with values near 1 representing the most sensitive species. Sensitivities were then scaled to be between 0.5-1.5 (Table 5) for the creation of a productivity scalar, so that the average sensitivity
had a value of 1.0. Lower than average sensitivities (value < 1.0) resulted in a smaller productivity change from oil, while higher than average sensitivities (value > 1.0) increased the magnitude of the productivity decline. These sensitivities are then applied to the slope of the productivity response to estimate the total productivity scalar across oil concentrations (Fig. 2), which are incorporated into the Ecospace model as forcing functions. Hydrocarbon contamination values are provided by SIMAP model simulations, and $Oil_{thresh} = 0.907$ ppm and $m = 0.2885$ yr$^{-1}$ are used to be consistent with Ainsworth et al. (2018); based on an early iteration of the calculations in Dornberger et al. (2016). For primary producers, a productivity scalar of 0.5 was used for all groups whenever oil was present. This was determined based on reduced light transmissions and photosynthesis when oil is present (González et al. 2009, AMAP 2010, Brussaard et al. 2015). In our study we use the SIMAP model outputs. Monthly Ecospace map values thus represent input into the pool of bioavailable oil ($oil$), which depurated according to $oil_{t+1} = oil_t \cdot e^{-\theta}$. Monthly bioavailable oil is calculated by using the daily SIMAP hydrogen concentration per cell, uptake rates of 10% and depurvation rates of 2.4%. This is close to values subsequently calculated in exposure experiments (Miller et al. 2017).

![Fig. 2](image) Hydrocarbon contamination forcing function relating the eco-toxicological response of exposure to change in animal productivity.
Table 5  Sensitivity scalars determined for each functional group, the group’s baseline model mortality (Z), and an example productivity scalar (P*). The oil concentration used to calculate the example P* values was 2.11 ppm, and produces ~10% decline in productivity averaged across fish functional groups. Producers have no assigned sensitivity, as they have a constant productivity scalar.

<table>
<thead>
<tr>
<th>Functional Group</th>
<th>Sensitivity</th>
<th>Z</th>
<th>P*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar Bear</td>
<td>1.40</td>
<td>0.15</td>
<td>0.503327</td>
</tr>
<tr>
<td>Beluga</td>
<td>1.30</td>
<td>0.065</td>
<td>0.321076</td>
</tr>
<tr>
<td>Gray Whale</td>
<td>1.33</td>
<td>0.06</td>
<td>0.298554</td>
</tr>
<tr>
<td>Bowhead</td>
<td>0.70</td>
<td>0.07217</td>
<td>0.493712</td>
</tr>
<tr>
<td>Walrus</td>
<td>1.40</td>
<td>0.069</td>
<td>0.317948</td>
</tr>
<tr>
<td>Ringed Seal</td>
<td>1.40</td>
<td>0.8</td>
<td>0.843867</td>
</tr>
<tr>
<td>Bearded Seal</td>
<td>1.40</td>
<td>0.124</td>
<td>0.455854</td>
</tr>
<tr>
<td>Spotted Seal</td>
<td>1.40</td>
<td>0.068</td>
<td>0.31479</td>
</tr>
<tr>
<td>Birds</td>
<td>1.47</td>
<td>0.9</td>
<td>0.853028</td>
</tr>
<tr>
<td>Char &amp; Dolly Varden</td>
<td>1.00</td>
<td>0.68</td>
<td>0.865441</td>
</tr>
<tr>
<td>Ciscoes &amp; Whitefish</td>
<td>1.00</td>
<td>0.95</td>
<td>0.899854</td>
</tr>
<tr>
<td>Salmonids</td>
<td>1.00</td>
<td>0.85</td>
<td>0.889376</td>
</tr>
<tr>
<td>Herring &amp; Smelt</td>
<td>1.15</td>
<td>1.5</td>
<td>0.925021</td>
</tr>
<tr>
<td>Arctic &amp; Polar Codds</td>
<td>0.80</td>
<td>0.8</td>
<td>0.904383</td>
</tr>
<tr>
<td>Capelin</td>
<td>0.90</td>
<td>0.95</td>
<td>0.908957</td>
</tr>
<tr>
<td>Flounder &amp; Benthic Codds</td>
<td>0.70</td>
<td>0.75</td>
<td>0.910185</td>
</tr>
<tr>
<td>Small Benthic Marine Fish</td>
<td>0.90</td>
<td>1.06</td>
<td>0.917627</td>
</tr>
<tr>
<td>Other Fish</td>
<td>0.93</td>
<td>0.51</td>
<td>0.838185</td>
</tr>
<tr>
<td>Arthropods</td>
<td>1.00</td>
<td>0.75</td>
<td>0.876448</td>
</tr>
<tr>
<td>Bivalves</td>
<td>1.33</td>
<td>0.6</td>
<td>0.809751</td>
</tr>
<tr>
<td>Echinoderms</td>
<td>1.04</td>
<td>0.55</td>
<td>0.83339</td>
</tr>
<tr>
<td>Molluscs</td>
<td>0.80</td>
<td>0.85</td>
<td>0.909498</td>
</tr>
<tr>
<td>Worms</td>
<td>0.75</td>
<td>0.95</td>
<td>0.922962</td>
</tr>
<tr>
<td>Other Benthos</td>
<td>0.57</td>
<td>0.8</td>
<td>0.930328</td>
</tr>
<tr>
<td>Jellies</td>
<td>0.90</td>
<td>10</td>
<td>0.990574</td>
</tr>
<tr>
<td>Macro-Zooplankton</td>
<td>0.75</td>
<td>7.5</td>
<td>0.989538</td>
</tr>
<tr>
<td>Medium Copepods</td>
<td>0.85</td>
<td>18</td>
<td>0.995032</td>
</tr>
<tr>
<td>Lg Copepods (Calanus)</td>
<td>0.80</td>
<td>5.5</td>
<td>0.984855</td>
</tr>
<tr>
<td>Other Meso-Zooplankton</td>
<td>0.90</td>
<td>22</td>
<td>0.995693</td>
</tr>
<tr>
<td>Micro-Zooplankton</td>
<td>0.60</td>
<td>55</td>
<td>0.998848</td>
</tr>
<tr>
<td>Producers &gt;5um</td>
<td>-</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>Producers &lt;5um</td>
<td>-</td>
<td>60</td>
<td>0.5</td>
</tr>
<tr>
<td>Ice Algae</td>
<td>-</td>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td>Benthic Plants</td>
<td>-</td>
<td>10</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Identifying Ecological Impacts to Animals and Indigenous Communities

To identify ecological impacts in each of the hydrocarbon contamination events we examine changes in Ecospace populations, distributions, catch per community, and nutrient content per catch per community, according to functional group guilds (groups of functional groups) found within the subsistence use areas of Barrow, Nuiqsut, and Kaktovik. The functional group guilds are: 1) Polar Bears, 2) Whales, 3) Pinnipeds, 4) Birds, and 5) Fish. Impacts are determined by comparing hydrocarbon contamination scenarios to the reference scenario. Ecological impacts are expressed as the percent change of the total population (biomass), percent change of distributions (biomass) per Ecospace pixel, percent change in spatial-temporal and total subsistence catch, as well as the percent change in nutrient content per community. Ecological impacts are examined as annual means occurring over the duration of the hydrocarbon contamination events (12-month period), running means from hydrocarbon contamination event to model simulation end (41-month period), as well as means in the final year of our Ecospace simulations (2014; 12-month period). Nutrient values (kilocalories (kcal g\(^{-1}\)), protein (g g\(^{-1}\)), lipid (g g\(^{-1}\)), and carbohydrate (g g\(^{-1}\)) per gram per functional group caught, and used in guild-related calculations, are calculated in Table 6. Lastly, we calculate the change factor, referred to in this study as the multiplier of change, for each community's nutrients derived from subsistence catch.
Table 6 Nutrient values per wet gram functional group caught.

<table>
<thead>
<tr>
<th>Functional Groups</th>
<th>Calories (kJ g⁻¹)</th>
<th>Proteins (g g⁻¹)</th>
<th>Carbohydrates (g g⁻¹)</th>
<th>Lipids (g g⁻¹)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar Bears</td>
<td>1.317</td>
<td>0.059</td>
<td>0</td>
<td>0.007</td>
<td>(Farley &amp; Robbins 1994, Atkinson 1996, NativeKnowledge 2016)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Higgs et al. 2011, NanuvutWildlifeManagementBoard 2013, NativeKnowledge 2016, SELFNutritionData 2016)</td>
</tr>
<tr>
<td>Beluga Whales</td>
<td>17.532</td>
<td>0.192</td>
<td>0.002</td>
<td>0.396</td>
<td>NativeKnowledge 2016, SELFNutritionData 2016</td>
</tr>
<tr>
<td>Bowhead Whales</td>
<td>29.233</td>
<td>0.117</td>
<td>0.006</td>
<td>0.269</td>
<td>NativeKnowledge 2016, SELFNutritionData 2016</td>
</tr>
<tr>
<td>Walrus</td>
<td>10.263</td>
<td>0.118</td>
<td>0.001</td>
<td>0.277</td>
<td>(Lu 1972, Fedoseev et al. 1977, Harper 1980, NativeKnowledge 2016, SELFNutritionData 2016)</td>
</tr>
<tr>
<td>Ringed Seals</td>
<td>17.727</td>
<td>0.152</td>
<td>0.004</td>
<td>0.367</td>
<td>(Usher 1971, Lu 1972, Stirling &amp; McEwan 1975, NativeKnowledge 2016, SELFNutritionData 2016)</td>
</tr>
<tr>
<td>Bearded Seals</td>
<td>5.84</td>
<td>0.141</td>
<td>0</td>
<td>0.3</td>
<td>NativeKnowledge 2016, SELFNutritionData 2016</td>
</tr>
<tr>
<td>Spotted Seals</td>
<td>17.727</td>
<td>0.152</td>
<td>0.004</td>
<td>0.32</td>
<td>(Lu 1972, NativeKnowledge 2016, SELFNutritionData 2016)</td>
</tr>
<tr>
<td>Birds</td>
<td>8.256</td>
<td>0.236</td>
<td>0.001</td>
<td>0.106</td>
<td>(Ashley 2002, NativeKnowledge 2016)</td>
</tr>
<tr>
<td>Char &amp; Dolly Varden</td>
<td>6.005</td>
<td>0.204</td>
<td>0</td>
<td>0.02</td>
<td>(Ashley 2002, NativeKnowledge 2016)</td>
</tr>
<tr>
<td>Ciscoes &amp; Whitefish</td>
<td>5.695</td>
<td>0.21</td>
<td>0</td>
<td>0.031</td>
<td>(Ashley 2002, NativeKnowledge 2016)</td>
</tr>
<tr>
<td>Salmonids</td>
<td>4.533</td>
<td>0.203</td>
<td>0</td>
<td>0.031</td>
<td>(Ashley 2002, NativeKnowledge 2016)</td>
</tr>
<tr>
<td>Herring &amp; Smelt</td>
<td>5.586</td>
<td>0.16</td>
<td>0</td>
<td>0.012</td>
<td>(Ashley 2002, NativeKnowledge 2016)</td>
</tr>
<tr>
<td>Arctic &amp; Polar Cods</td>
<td>4.7</td>
<td>0.18</td>
<td>0</td>
<td>0</td>
<td>(Payne et al. 1999, Harter et al. 2013, Kuhnlein &amp; Humpheries 2016)</td>
</tr>
<tr>
<td>Capelin</td>
<td>3.96</td>
<td>0.15</td>
<td>0</td>
<td>0.029</td>
<td>(CalorieSism 2016, SeafoodFromNorway 2016, Ashley 2002, NativeKnowledge 2016)</td>
</tr>
<tr>
<td>Flounder &amp; Benthic Cods</td>
<td>3.838</td>
<td>0.204</td>
<td>0</td>
<td>0.004</td>
<td>(Ashley 2002, NativeKnowledge 2016)</td>
</tr>
<tr>
<td>Small Benthic Marine Fish</td>
<td>4.228</td>
<td>0.18</td>
<td>0</td>
<td>0.015</td>
<td>(Ashley 2002, NativeKnowledge 2016)</td>
</tr>
<tr>
<td>Other Fish</td>
<td>4.33</td>
<td>0.178</td>
<td>0</td>
<td>0.006</td>
<td>(Ashley 2002, NativeKnowledge 2016)</td>
</tr>
</tbody>
</table>
Results

**SIMAP (Spill Impact Model Analysis Package) Modeling**

The SIMAP modeling results in each scenario reveal wide-spread hydrocarbon contamination along Alaska’s North Slope, particularly in subsistence use areas (Fig. 3a-d). Maximum hydrocarbon concentrations in an Ecospace pixel area are illustrated in Fig. S1. Overall, SIMAP modeling shows that the highest concentrations of hydrocarbons are found in nearshore areas in each scenario, which likely impacts polar bear, pinniped, and bird populations more than other marine animals because of their associations with land-sea foraging, and haul-out and nesting areas, respectively.

![Surface, Water Column, and Sediment Hydrocarbon Contamination](image)

**Fig. 3** Hydrocarbon contamination event footprints for scenarios 1 through 4. Scenario 1 pipeline leak, scenario 2 platform leak, scenario 3 cruise ship spill, scenario 4 tanker spill. Black dots represent pixels where hydrocarbon contamination is present, blue represents hydrocarbon contamination absence, and red dots represent the origin of the hydrocarbon contamination.
Identifying Ecological Impacts to Animals and Indigenous Communities

Biomass

Across all hydrocarbon contamination scenarios, the polar bear, pinniped, bird, and fish populations are negatively impacted (Example, scenarios 2 and 4; Fig. 4). A complete set of figures illustrating spatial-temporal impacts to guild populations can be found in Figs. S2-S10. Within each guild the animal-specific population percent change minimums in Ecospace time steps can be found in Figs. S11-S15. In general, whale populations are mostly unaltered. However, their populations are mostly impacted in areas immediately surrounding the hydrocarbon contamination source and not throughout the marine ecosystem. Temporary impacts to beluga whales can be observed in scenarios 1 and 2 (Figs. S7). In the first year of the hydrocarbon contamination events, and looking at acute regional and negative impacts to guild populations, polar bears are mostly impacted in scenarios 2 through 4, whales in scenarios 1 and 2, pinnipeds in scenarios 2 through 4, birds in scenario 2 and 4, and fish in all scenarios (Fig. 4). Chronic regional impacts that continue to impact population dynamics for at least two years following the complete removal of any hydrocarbon contamination are observed in polar bears, pinnipeds, birds, and fish in scenarios 2 and 4 (Figs. S6-10). In the continuum of negative impacts resulting from hydrocarbon contamination in the Beaufort Sea, we consider scenarios 1 and 3 to lightly impact guild populations, whereas scenarios 2 and 4 heavily impact guild populations. These impacts are most notable in the Nuiqsut and Kaktovik subsistence use areas of Alaska, less so near Barrow.
Fig. 4 Spatial-temporal annual biomass (population) means per guild for scenarios 2 and 4. Blue dots represent spatial biomass minimum, and green dots represent spatial biomass maximum. Black cross-hatching indicates open ocean area outside of the subsistence use areas.
**Subsistence Catch**

In terms of subsistence use area impacts per scenario, we also find there is little effect to regional community subsistence catch of marine animals in scenarios 1 and 3 (less than ± 1% across all guilds). There are significant regional effects to subsistence catch in scenarios 2 and 4 (Fig. 5). Overall, effects to subsistence catch in scenarios 2 and 4 are observed immediately following hydrocarbon contamination events, and these effects continue for at least two years following the removal of hydrocarbon-related consequences to marine animals (Fig. S16). As with guild population impacts, subsistence catch of whales is generally not affected in any scenario. The opposite is true for all other animal guilds. Subsistence catch of polar bears is affected in scenarios 2 and 4, and is most markedly affected in the Nuiqsut and Kaktovik subsistence use areas. However, there are excessive increases and decreases (+300%) of Barrow’s subsistence catch of polar bears in areas surrounding Barrow Canyon, due to their ability of polar bears to move to other areas within the model. Pinniped subsistence catch effects from hydrocarbon contamination are more dynamic in scenarios 2 and 4. In scenario 2, the pinniped subsistence catch is significantly reduced in Nuiqsut, and increased in limited areas for the communities of Barrow and Kaktovik as pinniped populations cluster into smaller areas (Fig. 5). In the scenario 4, the pinniped subsistence catch is significantly reduced throughout all subsistence use areas, with a small increase in clustering west of Barrow. The spatial affects to subsistence catch of birds and fish are similar to those observed with pinnipeds.
Fig. 5  Spatial-temporal annual subsistence catch means per guild for scenarios 2 and 4. Blue dots represent spatial biomass minimum, and green dots represent spatial biomass maximum. Black cross-hatching indicates open ocean area outside of the subsistence use areas.
When total catch is examined in scenarios 2 and 4, we find that each indigenous community is affected differently (Figs. 6-7), and those effects alter community-specific nutrients provided by subsistence catch (Figs. 8-9). For example, in scenario 2 Kaktovik catches more pinnipeds for the duration of the simulation. Concurrently, Kaktovik catches less of all other guilds until their subsistence catch of polar bears recovers 22-months after the start of the hydrocarbon contamination event (within 1% of the reference model’s catch). Consequently, the community obtains smaller amounts of proteins and fewer calories. In scenario 4, Kaktovik catches fewer polar bears and pinnipeds until recovery, which occurs 26-months after the start of the hydrocarbon contamination event. Katkovik’s available nutrients are largely reduced throughout scenario 4. Across all scenarios, and indigenous communities, there is: 1) a decrease in polar bear catch with recovery occurring approximately two years after the start of the hydrocarbon contamination event, 2) an overall increased reliance on pinniped catch, 3) a decrease in bird catch, and 4) a decrease in fish catch, at least until December 2014.

Fig. 6 Total community catch per guild and community, scenario 2.
Fig. 7 Total community catch per guild and community, scenario 4.

Fig. 8 Nutrient (proteins, lipids, and calories) change factor per community, scenario 2.
Discussion

In complex marine ecosystems such as the Beaufort Sea, management approaches to control anthropogenic influences may include the use of quotas on marine animal catch (Braund 1992), community conservation plans for community-driven ecological stewardship of their subsistence use areas (Aklavik 2008), as well as model-derived spill fate probabilities to decide oil and gas lease options for oceanic hydrocarbon exploration and extraction (MMS 2003). What is missing in these important management approaches are concerted efforts to understand how they are inter-related, how they might influence animal distributions. It is also necessary to understand how animal distributions are influenced by environmental and anthropogenic drivers. Our present study is aimed at examining these synergisms. Moreover, our model is the first to provide a progressive approach aimed at revealing the complexity and response of Beaufort Sea’s marine ecosystem when it is stressed by potential hydrocarbon contamination impacts that influence marine animal distributions and the Ilñupiat
communities that rely on the animals for traditional foods and their cultural identity. Using this multi-disciplinary data integration approach, the present study is aimed at protecting an Arctic marine ecosystem already undergoing large reductions in sea-ice extent, increases hydrocarbon extraction activities, and increases in shipping and tourism. Our approach is intended to provide natural resource management strategies that are focused on animal conservation along Alaska’s North Slope Borough.

The scenarios with the largest hydrocarbon contamination volumes (scenario 2 and 4) demonstrate the most significant changes to marine animal distributions. Unfortunately, these two scenarios represent common Beaufort Sea hydrocarbon extraction and shipping activities. As a whole, shipping is projected to increase as the annual Arctic sea-ice extent continues to diminish (Comiso 2006). This increases the likelihood of a hydrocarbon contamination event. The marine animal guilds most impacted by the large-scale hydrocarbon contamination scenarios, and those also heavily relied upon by the indigenous communities, are polar bears, pinnipeds, birds, and fish. Thus, hydrocarbon contamination impacts the upper food web. For example, polar bear population decreases due to hydrocarbon contamination are further impacted by pinniped population decreases, which are in turn impacted by fish population decreases and increasing community catch of pinnipeds. And, some animal guilds, such as fish, do not recover pre-contamination distributions in the three years following the onset of a hydrocarbon contamination event. Likewise, the timeline for recovery of species is unknown, and therefore not captured in this model timeframe. Hydrocarbon contamination impacts to marine animals vary, but the resident killer whale population (AB pod) in the Prince William Sound exposed to hydrocarbons in the 1989 Exxon Valdez oil spill lost 33% of their members, and another transient population (AT1 pod) lost 41% of their members in one year’s time (e.g., (Fraker 2013)). Almost four decades later, neither killer whale pod has fully recovered.

As indicated in hydrocarbon contamination scenarios 2 and 4, significant changes to marine animal distributions also change the availability of food for indigenous communities. This potential indigenous
community food insecurity from hydrocarbon contamination results in a net-loss of animals caught within subsistence use areas. Community responses to this loss may include an increased reliance on certain food sources, such as the increased subsistence catch of pinnipeds observed in the present study. This increased reliance on pinnipeds for food further impacts the distributions of other subsistence caught animals, such as polar bears or fish; both of which indigenous communities also rely on. This change in subsistence catch for each community ultimately leads to a sustained loss of essential proteins, lipids, and calories from traditional foods.

Changes in scenario 2 and 4 subsistence catch reveals significant and sustained alterations to the animal-based nutrients available to all Inupiat communities. With the concentration of animal distributions in subsistence use areas, communities initially have an increase of available nutrients. This increase remains for approximately 6 months after the onset of a hydrocarbon contamination event, after which communities have a sustained loss in available proteins, lipids, and calories. This loss is most pronounced in the proteins provided by subsistence catch. As the subsistence caught animals are the most important source of proteins for indigenous communities and contribute to overall food security (Wesche & Chan 2010, Huet et al. 2012), the sustained loss of protein in hydrocarbon contamination events strongly suggests food insecurity. In addition to the negative impact on food security, replacement of harvested foods with store-bought foods is expensive, has no cultural relevance, and often provides less nutrition (Pearce et al. 2010, CCA 2014). These compounding financial and cultural impacts are important to consider in the context of remote Arctic Inupiat communities.

Food security is one of the long-standing concerns for Arctic indigenous communities, which includes the concerns of availability and pollution of their traditional foods (ICC 2012). The longest running Arctic Marine mammal program, the Beaufort Sea Beluga Monitoring Program in the Mackenzie River delta of the ISR, has over 40 years of science and hunter observations for the Alaska Canada shared stock of belugas (Loseto et al: in press, Beluga program ref to come). While potential impacts on
beluga populations may be captured here, such extensive programs do not exist to quantify the impacts for other species because of a lack of data. Our present approach to simulating hydrocarbon contamination-related impacts to community food security is also too conservative. This is because hydrocarbon contaminations as large as scenario 2 or 4 would likely persist in the Beaufort Sea’s marine ecosystem for decades. Thus, our removal of hydrocarbons in Ecospace simulations after one year underestimates the chronic impacts to marine animals and indigenous community health that may occur for decades. This is because Arctic animals and people may act as sources and sinks of bioaccumulated toxins (ICC 2012). Finally, the consumption of animals harvested during a spill event can pose a threat to human health if precautions are not taken, and needs to be considered.

“The UN’s Office of the High Commissioner for Human Rights (OHCHR) has recognized the importance of food security for indigenous peoples – not just from a caloric perspective but also from the broader socio-cultural perspective. In its paper on The Right to Adequate Food, the significance of food and its accessibility is acknowledged as being “inextricably grounded in ...socio-cultural traditions and [the] special relationship to ancestral territories and resources (Guatemala 2002). Food and its procurement and consumption are often an important part of their culture, as well as of social, economic and political organization. For Iñupiat, this linkage between food and culture is inextricable.” - The Right to Adequate Food, UNHCHR, Fact Sheet No. 34, and Food security across the Arctic (UN 2010).

Although our model provides novel approaches and insights into ecosystem-wide impacts of hydrocarbon contamination, similar ecological models have been previously developed to capture changes in trophodynamics before and after the 1989 Exxon Valdez oil spill in Prince William Sound (Okey & Pauly 1998). More recently, models have been developed to look back at the impacts of the 2010 Deepwater Horizon oil spill in the Gulf of Mexico (Rohal et al. unpublished). What is distinctly unique in our current Ecospace model is the ability to couple SIMAP modeling to dynamic spatial-temporal changes in all environmental variables influencing Beaufort Sea ecology for each hydrocarbon
contamination scenario and time step. For example, previous Ecospace models required a static map of each environmental variable, such as sea-ice extent, which would drive trophodynamic changes in the summer months the same as in the winter months. As the Arctic marine ecosystem is characterized its changing seasonal sea-ice extent, our Ecospace model is able to capture monthly, seasonal, annual, and decadal influences of important (and rapidly changing) environmental drivers, which define suitable foraging areas (e.g., polar bears and seals), habitable areas (whales and ice algae), as well as seasonal primary productivity. In contrast, the static map approach in ecological modeling limits insights into seasonal and annual changes in Arctic ecology. Thus, we conclude that our novel multi-disciplinary data integration approach, combines many important elements of current Arctic ecological management approaches, and provides more realistic responses of the Beaufort Sea marine ecosystem this is already undergoing large reductions in sea-ice extent, increases hydrocarbon extraction activities, and increases in shipping and tourism.

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Supplemental Materials

Fig. S1
Scenario 1 – Mean Percent Change in Subsistence Use Area Populations

a) Barrow  
b) Nuiqsut  
c) Kaktovik

Fig. S2
Scenario 2 – Mean Percent Change in Subsistence Use Area Populations

Fig. S3
Scenario 3 – Mean Percent Change in Subsistence Use Area Populations

a) Barrow

b) Nuiqsut

c) Kaktovik

Fig. S4
Scenario 4 – Mean Percent Change in Subsistence Use Area Populations

a) Barrow  b) Nuiqsut  c) Kaktovik

Fig. S5
Fig. S6  Mean spatial percent change in populations in the year of hydrocarbon contamination event, and then two years following the event. Blue dot refers to the greatest point of population loss, whereas the green dot refers to the greatest point of population gain. Greatest point of population loss per animal and scenario are illustrated below.
Fig. S7  Mean spatial percent change in populations in the year of hydrocarbon contamination event, and then two years following the event. Blue dot refers to the greatest point of population loss, whereas the green dot refers to the greatest point of population gain. Greatest point of population loss per animal and scenario are illustrated below.
Fig. S8  Mean spatial percent change in populations in the year of hydrocarbon contamination event, and then two years following the event. Blue dot refers to the greatest point of population loss, whereas the green dot refers to the greatest point of population gain. Greatest point of population loss per animal and scenario are illustrated below.
Fig. S9  Mean spatial percent change in populations in the year of hydrocarbon contamination event, and then two years following the event. Blue dot refers to the greatest point of population loss, whereas the green dot refers to the greatest point of population gain. Greatest point of population loss per animal and scenario are illustrated below.
Scenario 1

Scenario 2

Scenario 3

Scenario 4

Fig. S10  Mean spatial percent change in populations in the year of hydrocarbon contamination event, and then two years following the event. Blue dot refers to the greatest point of population loss, whereas the green dot refers to the greatest point of population gain. Greatest point of population loss per animal and scenario are illustrated below.
Fig. 11 The greatest Ecospace pixel population loss (percent change min.) of Polar Bears.
Fig. 12 The greatest Ecospace pixel population loss (percent change min.) of Whales.
Fig. 13 The greatest Ecospace pixel population loss (percent change min.) of Pinnipeds.
Fig. 14 The greatest Ecospaces pixel population loss (percent change min.) of Birds.
Fig. 15  The greatest Ecospace pixel population loss (percent change min.) of Fish.
Fig. 15  The greatest Ecospace pixel population loss (percent change min.) of Fish (continued).
Fig. S16