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The effects of oil spill dispersant use on marine birds: a review of scientific literature and identification of information gaps

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Abstract

Dispersants, a class of chemical spill-treating agents used to treat oil spills, are commonly used globally as an alternative response measure. Applying dispersants to an oil slick, shortly after the spill has occurred, can protect shoreline environments and sea surface-dwelling animals, such as some marine bird species, limiting individuals or local populations from the consequences of coming into contact with large quantities of oil. However, this benefit comes with the cost of increasing oil exposure risk to marine biota that spend time in the water column. It is generally believed that the benefits of dispersant use outweigh the costs under most circumstances. However, it is rarely acknowledged that the use of dispersants may have negative impacts on marine biota at the individual or local population level, including marine birds. In Canada, Corexit EC9500A, a regulated dispersant, is being proposed for expanded use beyond treating spills from an offshore oil and gas facility. To understand what the potential impacts from dispersant use are to marine birds, we conducted a literature review to identify the direct and indirect effects of their use. We also provide oil spill responders with a Pathway of Effects (POE) conceptual model, a tool for understanding the interactions between dispersants, marine birds, and their environment to support a holistic consideration as part of the oil spill response decision-making process. Fundamental uncertainties remain, however, and if left unaccounted for in the decision-making process, they may compromise the appropriateness of spill response approaches and outcomes. We recommend that oil spill responders incorporate the known benefits and costs of dispersant use on marine birds into a decision-making framework such as a Net Environmental Benefit Analysis (NEBA) and with consideration of the POE concept models provided. These recommendations are particularly relevant where a decision-making framework such as NEBA is becoming a more standardized component of the response process. Additionally, greater investment in lab and field-based research, and field observations through monitoring, is required to address existing decision-making uncertainties and provide information gap closure.

Key words: dispersant, Corexit, net benefits analysis, Pathway of Effects, exposure risk

Introduction

With the increase in global oil demand and a rise in oil transportation (Chang et al. 2014; IEA 2022), the potential for a large oil spill event is a persistent potential reality. In Canada, the volume of marine pollution spills has varied over the past decade; however, the frequency of spill incidents, particularly in coastal environments, has shown a marked increase (ECCC 2021). For Canadian shorelines impacted by spill incidents, 70% of spills are sourced from marine vessels (Feng et al. 2021). In Canada and elsewhere, it is well documented that oil can be lethal to marine organisms, having extensive and lasting consequences on individuals, populations, and ecosystems (e.g., Irons et al. 2000; Peterson et al. 2003; Lincoln et al. 2020). Oil pollution is estimated to impact upwards of hundreds of thousands of marine birds in Canada each year (Government of Canada 2017). Marine birds can be especially sensitive to the effects of oil exposure with some species demonstrating slow population recovery times (Albers 1984; Wiese et al. 2004; O'Hara and Morandin 2010; Esler et al. 2018).

Natural attenuation of an oil spill, a no-intervention response method, in some circumstances may not adequately protect ecosystems from the harmful effects of oil, thus necessitating intervention to minimize the environmental effects of spilled oil (Pequin et al. 2022). The primary approach in responding to an oil spill is to mechanically remove the oil from the marine environment, however, this is not always feasible nor entirely effective (NRC 2005; DFO 2021; Transport Canada 2022). Under certain conditions, it may be advantageous to integrate an alternative response measure, which include spill-treating agents, in situ burning, translocations, and decanting, to enhance the dispersal or removal of oil or to protect high priority habitat, wildlife, and other ecologically, economically, or culturally valuable resources. Spill-treating agents include several classes of chemical and biological treating agents such as dispersants, herding agents, solidifiers, surface washing agents, demulsifiers, recovery agents, gelling agents, biodegradation enhancers, sinking agents, and elasticity modifiers. They are used to reduce overall adverse impacts of an oil spill and each class achieves this in a different way (Walker et al. 1999; Brown et al. 2011).

Dispersants, the focus of this review, are a mixture of solvents and surfactants. They can be applied to an oil slick to redistribute the oil from the water's surface into the water column by reducing the interfacial tension between oil and water, which enhances the natural process of oil dispersion (NRC 2005). The advantage of dispersants stems from their ability to redirect oil from stranding along shorelines and presumably, reducing the effect of oil exposure for sensitive surface-dwelling animals such as marine birds (Prince 2015). Dispersants can be applied rapidly over large areas and under a range of environmental conditions (Transport Canada 2022). There are costs, however, associated with transferring oil from one part of the marine environment (e.g., the water's surface) to another (e.g., the water column). Decision-making frameworks such as Net Environmental Benefit Analysis (NEBA) attempt to account for these trade-offs using a systematic approach for evaluating the benefits and costs associated with their use, considering impacts to individual, local, and regional populations as appropriate (IPIECA 2015). Ultimately, the objective is to make an informed decision on which oil spill response method(s) optimize response success while minimizing impacts to the environment and sensitive receptors (IPIECA 2015).

A broadly defined literature search using two commonly used search engines (Google Scholar and Web of Science) returned complementary (i.e., few repeats between the two search engines) lists of papers using the following search terms: ("marine bird" OR seabird) AND (dispers OR "dispersed oil"). Each identified paper was scrutinized resulting in 9 relevant papers from Google Scholar (from a total of 47 papers identified) and 14 papers from Web of Science (from a total of 50) linking direct effects on marine birds from dispersant use. Interestingly, several important earlier experimental papers were not identified in either search engine (Albers 1979; Peakall et al. 1981; Albers and Gay 1982 for example). Most existing data on effects of dispersant use on marine birds come from papers published in the 1970s and early 1980s, producing mixed results in terms of dispersant impacts. Since then, little has been published until the 2010s, with the notable exception of Jensen and Ekker (1991). Data from three recent papers (Duerr et al. 2011; Fiorello et al. 2016; Whitmer et al. 2018) indicate concerns or caveats that should be considered when deciding whether or not to deploy dispersants. Many of the remaining papers identified by the two search engines were policy oriented or model based, with the explicit yet often unsubstantiated assumption that dispersant use is beneficial to marine birds. It is difficult to identify when this largely untested assumption became a rationale for dispersant use in the literature. Indeed, as an example of how accepted this assumption is, minimizing oil spill impacts on marine birds as a principal reason for the use of a dispersant was introduced in the abstract of a recent paper, with no further discussion in the text or citations to support this claim (Zhu et al. 2022).

In 1989, the US National Research Council (hereafter, NRC) called for more research on the effects of dispersant use on marine birds as there was no conclusive evidence at the time that dispersants caused less harm (NRC 1989). With minimal progress made in the intervening years (within the US and globally), the NRC reiterated its recommendations in 2005 to increase research efforts on the effects of dispersants to marine birds (NRC 2005). Since then, research efforts have focused elsewhere, and extensive information gaps remain (Whitmer et al. 2018; NASEM 2019). This review identifies the known and potential impacts of dispersant use to marine birds, on an individual physiological and toxicological level as well as the local population and integrated ecosystem level. While we integrate information from a variety of international sources, this review is presented in the context of the Canadian marine oil spill response regime, placing emphasis on the associated species and habitats. To this end, we outline limits in the general understanding of outcomes of dispersant use on marine birds. This includes identification of important information gaps, particularly conditions and climates representative of Canada's coastal ecosystems. Notwithstanding, information provided herein may support the assessment of dispersant use on marine birds in other regions, including crossover applicability in freshwater environments.

In the Canadian context, we focus on Corexit® EC9500A (formally Corexit® 9500). It is the only dispersant regulated within Canada and is limited for use in offshore spills in Atlantic Canada, as defined by applicable offshore petroleum legislation (Government of Canada 2016). Legislative amendments are being proposed to enable the expansion of Corexit® EC9500A use for other designated sectors including marine traffic (Transport Canada 2022). Given the proposed legislative amendments in Canada, we present some timely recommendations to support informed assessment of dispersant use, and on handling the uncertainty that exists around their potential impacts on marine birds. We also focus on the use of NEBA decision-making framework, an approach being developed for use in Canada and one that is used in other countries such as the United States, Australia, the European Union, and the United Kingdom. Thus, this review has a Canadian context, yet is broadly applicable to other international jurisdictions. As future amendments may include legislative requirements on how to determine a net environmental benefit for oil response measures (Transport Canada 2022), we propose Pathway of Effects (POE) conceptual models as a beneficial tool for inclusion in the NEBA process to assess quickly the impacts of dispersant use to marine birds.

Pathway of Effects models

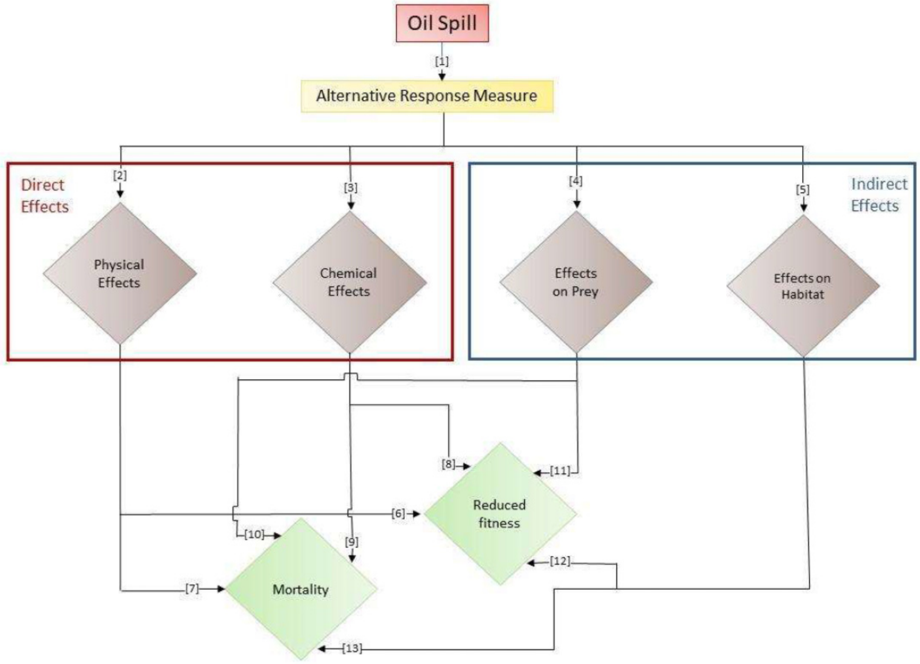
The potential effects anthropogenic activities have on a receptor organism and its habitat can be described using POE

Table 1. Numbered linkages between pathway components in Fig. 1 and their associated supporting evidence in-text descriptions.

Pathways of Effects	Evidence description
ARM [1]—Physical effects [2]—Reduced fitness [6] or Mortality [7]	See "Physical effects" section
ARM [1]—Chemical effects [3]—Reduced fitness [8] or Mortality [9]	See "Toxicological effects" section
ARM [1]—Effects on prey [4]—Reduced fitness [10] or Mortality [11]	See "Toxicological effects on prey" section
ARM [1]—Effects on habitat [5]—Reduced fitness [12] or Mortality [13]	See "Harmful algal blooms" and "Habitat effects and persistence" sections

Note: Alternative response measure (ARM), in this case, applies only to dispersants.

Fig. 1. Pathway of Effects conceptual model of the direct and indirect alternative response measure (ARM) exposure pathways for marine birds.



conceptual models. They illustrate the mechanisms by which potential stressors may act on an organism through direct and indirect effects (Hannah et al. 2020). POE conceptual models for oil exposure on wildlife have been discussed and used elsewhere (Henkel et al. 2012; Hannah et al. 2020). They are a useful starting point in understanding how dispersants may affect wildlife when they are included as a spill-treating option. We propose a generic POE for marine birds that illustrates the pathways through which chemically dispersed oil may affect marine birds (Table 1 and Fig. 1). It should be noted, however, that depending on the circumstances of a spill POEs may differ depending on the nature of dispersant use in combination with life-history strategies of implicated marine bird species (Fig. 2).

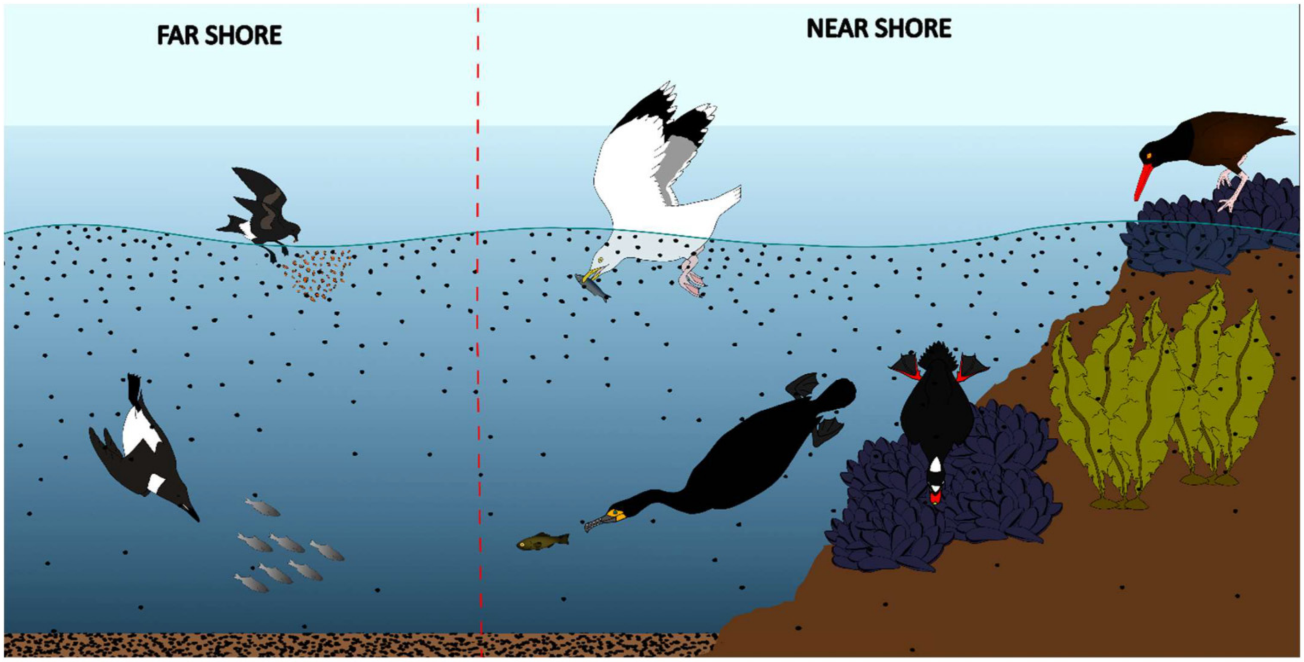
Direct effects

Physical effects

Physical effects from contamination refers to a change in the physical structure or function of parts of a bird that result in a measurable effect. The impacts to marine birds from oiling include the loss of waterproofing, buoyancy, and insulative properties of feathers, leading to hypothermia, starvation, and/or drowning of the animal (Jenssen 1994; King et al. 2021). The water-repellent properties of marine bird plumage depend on the interaction between water surface tension and the microstructure of feathers, which prevent water from penetrating their plumage (Stephenson 1997). This waterproofing mechanism also traps air within the plumage, which provides buoyancy and thermal insulation (Jenssen and Ekker 1991). Dispersants and dispersant–oil mixtures reduce the surface tension of water thereby allowing water to penetrate plumage (Jenssen and Ekker 1991; Jenssen 1994). Marine birds will preen in an attempt to restore the physical structure and waterproofing function of oil-contaminated feathers by realigning hooks and barbules in the feathers (Stephenson 1997; O'Hara and Morandin 2010). However, exposure to chemically dispersed oil has been found to result in similar disruption to maintaining feather integrity (Duerr et al. 2011; Whitmer et al. 2018).

Whitmer et al. (2018) conducted a study to evaluate the effects of dispersants and crude oil on the waterproofing of live common murres (*Uria aalge*) during a simulated dive through

Fig. 2. General habitat, foraging guilds, and direct or indirect exposure pathways for marine birds.



contaminated water. Treatments of increasing contaminant concentrations included a control, dispersant only, and a mixture of Corexit® EC9500A and Prudhoe Bay Crude Oil (PBCO) at an industry standard ratio of 1:20. The authors used contaminant concentrations based on scientific literature that identified representative concentrations found in the upper 10 m of the water column shortly after an oil spill. The treatment with the highest concentration of dispersant alone simulated exposure to dispersant application from a vessel or airplane.

Immediately after treatment exposure, catastrophic loss of waterproofing occurred. Loss of waterproofing also occurred at the medium and low concentrations of dispersant only, but the effects were less severe. These results indicate that exposure to high concentrations of dispersant (e.g., being accidentally sprayed during dispersant application) or significant dispersant–oil concentrations, morbidity and mortality is a likely outcome without human intervention. Whitmer et al. (2018) also showed over a 2 day experimental period, that dispersant does not change the effects oil has on plumage waterproofing, nor are birds more likely to regain waterproofing after exposure. Therefore, for diving birds, the impacts of exposure to a surface slick could be comparable to the impacts of exposure to chemically dispersed oil within the water column (Fig. 2).

In a related study, Duerr et al. (2011) conducted experiments on the structural changes to common murre feathers when exposed to crude oil, Corexit® 9500, and a mixture of the two. They found that dispersants affected the geometry and orderliness of feather structures that affected the waterproofing characteristics by collapsing the feather plume. Given this, the authors found that a pursuit diving marine bird would likely lose insulation and buoyancy once contamination occurred, and subsequent swimming through uncontaminated waters would not be sufficient to remove the contamination. To restore plumage aeration, preening would be necessary. In a study by Lambert et al. (1982), mallards (*Anas platyrhynchos*) were placed in a cold chamber following exposure to oil, dispersant (Corexit® 9527), or dispersant–oil mixtures (30:1 ratio) for 1 h. The ducks exposed to the oil and mixture in this study showed a similar and significant increase in basal metabolic rate and loss of plumage waterproofing. Ducks exposed to dispersant only did not show an increase in basal metabolic rate but did show loss of buoyancy and plumage waterlogging.

Additional research has further demonstrated differences in response between species. Jenssen and Ekker (1991) found that Statfjord A crude oil and dispersant–oil mixture (with Finasol OSR-5 or Finasol OSR-12) reduced plumage waterproofing in common eiders (*Somateria mollissima*) and mallards, leading to heat loss and a subsequent increase in heat production. Effects on insulation for eiders occurred at a much smaller volume of chemically dispersed oil than oil alone; surfactants may be the ingredient responsible for the increased effects by allowing water to pass through the plumage (Jenssen and Ekker 1991; Stephenson 1997). Common eiders were more vulnerable to dispersant–oil mixtures compared to mallards, potentially due to differences in feather structure (Jenssen and Ekker 1991). After plumage became contaminated, preening spread the contamination throughout the plumage, thereby increasing the loss of waterproofing and subsequently enhancing thermoregulatory impairment compared to the immediate effects of contamination (Jenssen and Ekker 1991). However, these studies are species-specific and lab-based, therefore do not account for the wide variability of factors (e.g., species, season, marine habitat, and contaminant properties) that could affect a bird's sensitivity to chemically dispersed oil exposure.

Toxicological effects

Early studies have shown that the acute physiological effects of oil to marine birds do not change significantly with the use of dispersants (for a review see Peakall et al. 1987). Most of these studies used PBCO and Corexit® 9527 in their experiments (Peakall et al. 1987). Stroski et al. (2019) indicate that Corexit® EC9500, which is regulated in Canada, uses a solvent that is less toxic to marine organisms than its predecessor Corexit® 9527 and has become more commonly used. The basis for testing the toxicity of Corexit® EC9500 remains unclear. As such, more research is needed using Corexit® EC9500A on a wider variety of oils, especially regarding its long term, sublethal, and delayed toxicological effects (Wise and Wise 2011; NRC 2005).

Toxic effects of Corexit® 9527

Previous reviews have discussed at greater length the relevant findings on the toxicological effects of Corexit® 9527 from studies conducted in the 1970s and 1980s (Peakall et al. 1987; Michel et al. 1992). The following is a summary of these relevant findings, followed by current studies not included in Peakall et al. (1987) and Michel et al. (1992).

In embryotoxicity lab experiments, Albers (1979) found that a higher ratio of dispersant to oil had greater embryotoxic effects than oil alone, while Albers and Gay (1982) found that dispersants had no effect and dispersant–oil mixtures had the same effects as oil alone.

In a field study, Butler et al. (1988) found that Leach's storm petrels (*Oceanodroma leucorhoa*) internally and externally exposed to oil or dispersant–oil mixture, demonstrated decreased hatching success and chick survival. Chick growth and survival also decreased more severely when one adult parent was exposed to the dispersant–oil mixture. No long-term effects to reproductive success were observed. In thermoregulation experiments, Eastin and Rattner (1982) found that ingestion of a dispersant and oil combined had fewer toxic effects than oil, and the ingestion of dispersant alone had very little effect. They concluded that the effects of ingesting low levels of dispersant or dispersants with oil is unlikely to harm chicks over a short period. In a similar study, Peakall et al. (1985) found no difference between the effects in weight loss between oil and a dispersant–oil mixture when ingested by herring gulls (*Larus argentutus*). Significant weight loss did not occur for ingestion of dispersant alone. Conversely, they found that external application of the dispersant–oil mixture caused impaired insulation and subsequent weight loss, but oil alone did not.

In immunotoxicity experiments, Rocke et al. (1984) found that ingestion of oil and a dispersant–oil mixture lowered the bacterial resistance in mallards when using Bunker C fuel oil but not South Louisiana crude oil. In endocrine toxicity experiments, Peakall et al. (1982) found that ingestion of oil and a dispersant–oil mixture by herring gull nestlings had similar effects on their growth and organ weights, and that dispersant alone caused minimal effects. In a similar lab and field experiment, Peakall et al. (1981) found that found that dispersant alone caused an increase in corticosterone in gulls on day two of the experiment (for that day only), and the effects of dispersant–oil mixture was similar to that of oil alone.

Toxic effects of Corexit® EC9500A

More recent studies have used Corexit® EC9500A on embryotoxicity, ocular toxicity, immunotoxicity experiments. In an embryotoxicity study by Wooten et al. (2012), exposure to Corexit® EC9500A alone resulted in decreased hatching success with increased dispersant dosage. Finch et al. (2012) compared the embryotoxic effects of weathered crude oil from the Gulf of Mexico, Corexit® 9500, and dispersant–oil mixture at 50:1 and 10:1 oil to dispersant ratios. The authors found that Corexit® EC9500A decreased the toxicity of weathered crude oil to mallard embryos at the 10:1 ratio but increased it at the 50:1 ratio. In an ocular toxicity study, Fiorello et al. (2016) conducted experiments on the ophthalmic effects dispersants and dispersant–oil mixture have on marine birds. Common murres were exposed to Corexit® EC9500A and PBCO, and their intraocular pressure and tear production was measured before and after the exposure. Development of conjunctivitis was associated with exposure to dispersant and a dispersant–oil mixture, both products are known to be eye irritants. Corneal ulcers were also associated with dispersant exposure but only when exposed to a high concentration of oil. Untreated corneal ulcers can lead to vision impairment or loss, and thus negatively affect marine bird foraging ability and survival. In an immunotoxicity study, Finch et al. (2012) found that when a dispersant–oil mixture (weathered crude oil collected from the Gulf of Mexico and Corexit® 9500, at a 50:1 ratio), applied to mallard eggs and hatchlings, had lower spleen weights compared to the crude oil treatment. The spleen, an immune organ, is associated with immune responses in wildlife. These results indicate that the dispersants used, at the ratios recommended by the manufacturers, may have affected nesting marine bird hatchlings during the Deepwater Horizon spill.

Exposure risk

The toxicological and physical effects of dispersant alone were also investigated with varying results. Several studies have shown that dispersants alone can cause physical and physiological harm to birds (e.g., Wooten et al. 2012; Fiorello et al. 2016; Whitmer et al. 2018), while others have shown negligible impacts (e.g., Albers and Gay 1982; Eastin and Rattner 1982; Peakall et al. 1982). The application of dispersants to an oil spill may result in a certain amount of unused dispersant partitioning back into the water or through missing the target during application (Peakall et al. 1987). The environmental fate of this unused dispersant following application and its effects on marine birds under real-world environmental conditions are needed to understand whether exposure to dispersant alone adds an extra element of risk to that which exists from chemically dispersed oil. Consequently, it is the exposure risk of dispersants and chemically dispersed oil compared to oil alone that is crucial in understanding their relative harm to marine birds (Peakall et al. 1987; NRC 2005; NASEM 2019).

Experimental results have shown that exposure to chemically dispersed oil causes similar toxic effects to oil alone (Albers and Gay 1982; Peakall et al. 1982; Peakall et al. 1987). Similarly, the physical effects of chemically dispersed oil to plumage waterproofing are similar to that of oil alone (Lambert et al. 1982; Duerr et al. 2011; Whitmer et al. 2018), and some research has shown it can be more harmful than oil alone (Jenssen and Ekker 1991). Physical exposure risk to chemically dispersed oil is threshold dependent; if a bird moves through contaminated water and the feathers come in contact with a certain volume of chemically dispersed oil or dispersant (i.e., a threshold amount of contamination is reached), then a lethal outcome will occur (Whitmer et al. 2018).

Understanding whether the consequences of physical exposure to realistic concentrations of chemically dispersed oil and unused dispersant after an oil spill event may be harmful to a bird hinges on estimating its adsorption to feather structures while moving through a realistic volume of contaminated water (Jenssen and Ekker 1991). Although the adsorption of chemically dispersed oil was not quantified, Whitmer et al. (2018) has shown that chemically dispersed oil and dispersant alone, at realistic concentrations, can be lethal for diving murres which spend more time in subsurface waters than other birds. This, among other research (e.g., Jenssen 1994; Stephenson 1997), challenges the assumptions Peakall et al. (1987) made based on their hypothetical scenario for the adsorption of chemically dispersed oil, which concluded that there is no significant adsorption of chemically dispersed oil to plumage underwater.

In addition to quantifying the adsorption of chemically dispersed oil to estimate exposure risk, it is important to understand how this will change under variable concentrations, weathering, or until the concentration has reached a threshold below which it is no longer a threat regardless of how many dives or how long a bird spends underwater in a contaminated area. This is likely to vary by marine bird foraging guild and species (Peakall et al. 1987; Stephenson 1997; Fig. 2). Seasonality also influences bird foraging behaviour, where an increase in the proportion of time spent diving may be seasonally influenced by energetic demands or resource availability (Burke and Montevecchi 2018). Additionally, factors such as spill and environmental conditions are likely to affect the persistence of a harmful concentration of chemically dispersed oil. Understanding the period for which a chemically dispersed oil spill is estimated to maintain a harmful concentration will help decision makers estimate its relative exposure risk compared to an untreated spill, which among other considerations should be incorporated in NEBA.

Indirect effects

In addition to the direct effects of chemically treated oil, indirect effects on marine birds are also critical in understanding the full scope of impacts of dispersant use to marine ecosystems as a whole (Velando et al. 2005; Quigg et al. 2021).

Toxicological effects on prey

Toxicity of dispersant–oil mixtures are dependent on several factors (e.g., effectiveness of dispersants, concentration, oil type, weathering of oil, etc.) (NRC 2005; Lee et al. 2016). Modern dispersants are reported to have relatively low levels of toxicity to aquatic organisms compared to earlier formulations (NRC 2005; NASEM 2019; Stroski et al. 2019). Some studies indicate that dispersants alone are toxic to aquatic organisms (Almeda et al. 2013; DeLeo et al. 2016; Echols et al. 2016; Ruiz-Ramos et al. 2017; reviewed by Stroski et al. 2019), or that dispersant–oil mixtures are as toxic as oil (Hemmer et al. 2011; NASEM 2019). In some cases, dispersant–oil mixtures can be more toxic than oil alone (Almeda et al. 2013, 2014; Laramore et al. 2014; Vignier et al. 2015; DeLeo et al. 2016; Echols et al. 2016; Ruiz-Ramos et al. 2017; Johann et al. 2020). Fingas (2008) found in his review that most research concluded that chemically dispersed oil was more toxic than physically dispersed oil.

While effects continue in modern formulations, acute and sublethal severity varies by species (Fingas 2008, 2017; Stroski et al. 2019). The acute toxicity thresholds of dispersants are well documented for many marine taxa, including cnidarians, crustaceans, molluscs, fish, bacteria, seagrass, algae, and polychaete worms (e.g., George-Ares and Clark 2000; Stroski et al. 2019). Chemically dispersed oil can be toxic to marine biota that are present near the water surface immediately following dispersant application; however, due to the rapid dilution and biodegradation of chemically dispersed oil to subtoxicity levels, toxic effects may be short term (Prince 2015; Fig. 2). Notwithstanding, other research has found that dispersants and chemically dispersed oil inhibit the biodegradation of oil by altering the microbial community responsible for oil biodegradation (Kleindienst et al. 2015; Rahsepar et al. 2016). Additionally, Hickl and Juarez (2022) found that dispersants may enhance or inhibit oil biodegradation depending on the oil-degrading bacteria concentration present in the environment. Diel vertical migration of organisms into contaminated waters can further increase the redistribution of contaminants into deeper waters and subsequent exposure of deep-pelagic organisms (Sutton et al. 2020).

Polycyclic aromatic hydrocarbons (PAHs) are widely known to have lethal and sublethal effects on fish (such as embryo abnormalities, early-stage mortality, DNA damage, lesions, swimming impairment, and reproductive failure) (Honda and Suzuki 2020; Sutton et al. 2020). Dispersion (natural or chemical) of oil increases the concentration of PAHs by an estimated 5–50 times (reviewed in Fingas 2017), leading to increased bioavailability and uptake of PAHs in fish (Ramachandran et al. 2004; Schien et al. 2009; Esteban-Sanchez et al. 2021). Chronic exposures of oil-contaminated sediments and suspended organic matter by affiliated species (e.g., bivalves, fish, sea ducks, sea otter (*Enhydra lutris*)) continued long after the *Exxon Valdez* oil spill and delayed recovery in some taxa for years to decades (reviewed in Peterson et al. 2003 and Esler et al. 2018). In Canada, affiliated species such as blue mussels (*Mytilus* sp.) and fish such as sand lance (*Ammodytes* sp.) are important prey to many marine bird species. Given the enhanced toxicity of chemically dispersed oil-contaminated sediments, the risk of exposure to sediment-affiliated species has unknown implications for marine birds.

Beyond facilitating PAH uptake, nonlethal dispersant effects to fish and other prey species include impaired sperm fertilizing ability (Beirão et al. 2018), oxidative stress, gene expression, embryo mortality and abnormalities, and impaired immune system and liver function (reviewed in Stroski et al. 2019). Even at low-level exposure, early life stages of many marine taxa are very sensitive (Kinner 2020; NRC 2005; Stroski et al. 2019). Cold-water species, such as those found in Canada, might have similar sensitivity to oil constituents as temperate species effects may take longer to exhibit (NASEM 2019).

Despite the ongoing establishment of toxicity thresholds, study organisms used for dispersant toxicity testing may not adequately represent local native species, or adequately evaluate long-term effects (DFO 2021). Although lab-based studies provide information on individual (and usually acute) effects, few studies have looked at how exposure may affect populations through reduced fitness, reproduction, and recruitment from long-term and sublethal effects which affect population viability (Vikebø et al. 2015; NASEM 2019). Given this, Stroski et al. (2019)suggests that other response alternatives to dispersants may be advisable for spills that occur within especially sensitive or productive habitats for prey (e.g., spawning locations).

Following large oil spills, marine birds can show delayed recovery. These are due in part to reductions in prey availability resulting from oil-contaminated sediment, changes in prey behaviour, cascades of indirect effects, or direct toxicity effects to prey (see, for example, Golet et al. 2002; Peterson et al. 2003; Velando et al. 2005; Irons et al. 2000; Moreno et al. 2013). Prey-related recovery limitations may be further compounded when accounting for acute and sublethal effects resulting from the introduction of dispersants in the water column and ocean floor (Fig. 2).

Harmful algal blooms

Harmful algal blooms (HABs) have been documented after events in which oil spills have been treated with dispersants (e.g., Smayda 1997; Ozhan and Bargu 2014; Liu et al. 2021). The disrupting effects of oil and dispersants on algal and bacterial communities and available nutrients may promote the formation of HABs (Almeda et al. 2018; Park et al. 2020; Kamalanathan et al. 2021). Surveillance of HABs and research on how dispersant use affects their formation is limited within cold-water marine environments typical of Canada's oceans. Given that many toxin producing species occur in these environments (Pućko et al. 2019), more research will help to determine the extent to which dispersant use may promote HABs.

The life-history strategies of many marine birds make them vulnerable to toxic effects of HABs (Gibble and Hoover 2018). Ingestion can cause central nervous system impairment, mortality, disorientation, and morbidity in birds (Fritz et al. 1992; Work et al. 1993; Bargu et al. 2012; Ayala et al. 2013; Shearn-Bochsler et al. 2014). Plumage fouling caused by *Akashiwo sanguinea* causes loss of waterproofing, hypothermia, illness, and death (NRC 2005; Jessup et al. 2009).

HAB-induced marine bird mass mortality events are well documented for many species (e.g., Coulson et al. 1968; Jessup et al. 2009; Phillips et al. 2011; Ayala et al. 2013; Jones et al. 2017; Van Hemmert et al. 2021). In Canada, the Canadian Wildlife Service maintains an incidental archive of avian mortalities attributed to algae blooms, although the resulting effects from dispersant-associated HABs are not well known.

Habitat effects and persistence

There is a need to consider the potential effects of dispersant application on marine bird habitat, particularly when applied near areas of important seasonal aggregations (e.g., breeding and foraging habitats) or within ecologically significant boundaries (e.g., critical habitat, important bird areas; Fig. 2). Additionally, how currents and winds may transport chemically dispersed oil relative to these locations will be important considerations in an NEBA.

Despite the difficulty of discerning the impacts to habitats and tracking the fate of dispersants, researchers have found that dispersants reduce biodiversity resistance and resilience, and increase oiled sedimentation, which reduces the rate of biodegradation (Khelifa et al. 2008; Passow and Lee 2022; Zerebecki et al. 2022). Biodegradation of dispersants is also limited when dispersant-treated oil becomes weathered, mixing with sand, which protects it from dissolution and biodegradation (White et al. 2014). Conversely, older research from the 1980s has shown that dispersants reduce the incorporation and persistence of oil within sediments (reviewed in NASEM 2019).

Experimental results show that low temperatures, such as those found in the Canadian marine environment, slow the degradation process of dispersant surfactants (Campo et al. 2013; reviewed in Péquin 2022; however see McFarlin et al. 2018). In addition to experimental findings, field observations have revealed that dispersant components such as dioctyl sodium sulfosuccinate (a surfactant in many dispersants and major component of Corexit) may persist for long periods of time, likely due to their chemical stability (Farahani and Zheng 2022). Post-application, dispersants have been found in deep water after 64 days, in deep-sea coral after 6 months, and on beached oil–dispersant–sand patties after 4 years (Kujawinski et al. 2011; White et al. 2014; McDaniel et al. 2015). This indicates that dispersant removal from the environment is likely circumstantial. Claims that the long-term effects of dispersant use are negligible or unlikely, based on the premise that dispersant dilutes and degrades rapidly, should be considered with caution until further research is undertaken. More information is needed to better understand the impacts of dispersants on marine bird habitats, especially for conditions and climates representative of colder coastal ecosystems.

Bioaccumulation of contaminants

The uptake and bioaccumulation of PAHs have been documented for various marine taxa, as has PAH metabolism and elimination (Eisler 1987; Honda and Suzuki 2020). The rate of the bioaccumulation is generally found to be greater for vertebrates than marine invertebrates but still relatively less studied among marine birds (reviewed in Meador et al. 1995). Experimental evidence suggests that an increased uptake, biotransfer, and bioaccumulation of highly toxic, low-soluble PAHs may occur in marine food webs begin with the ingestion of chemically dispersed crude oil by low-trophic organisms such as zooplankton (Almeda et al. 2013; Almeda et al. 2014). These organisms are typically consumed in large quantities by higher trophic levels, including marine birds, facilitating the biotransfer and bioaccumulation of PAHs (Buskey et al. 2016).

PAH bioaccumulation potential is also understood to be higher in sedentary filter-feeding organisms (Honda and Suzuki 2020). Gao et al. (2019) demonstrated that the interaction of suspended sediment with dispersant promotes the sinking of oil thereby facilitating entrainment in sediments, the content of PAHs increasing with increasing dispersants-to-oil ratio. Few studies available (e.g., Falk-Petersen et al. 2007; Nørregaard et al. 2015) indicate that PAH metabolism may be inhibited in organisms exposed to dispersant–oil mixtures to some degree, potentially facilitating trophic bioaccumulation. How chemically dispersed oil affects interaction with sediments and organic matter, or the variability in bioaccumulation and biotransfer of PAHs between taxa is an essential component to understand related trophic impacts to marine birds.

Integration with NEBA

The NEBA framework

Net Environmental Benefits Analysis is one of several existing decision-making frameworks used by various international jurisdictions for evaluating oil spill response alternatives. It is used to determine the best operational response before and during an oil spill to minimize the overall impacts to people, resources, and the environment (IPIECA 2015). The establishment of a national framework for enhancing oil spill response in Canada is being developed, and a possible framework has been made available for feedback (Transport Canada 2022). The process used in this framework, like NEBA, evaluates whether there is a net environmental benefit across potential response measures as a means to inform decision-making during an oil spill. The steps involved in the NEBA process are (1) compile and evaluate data and information to identify an exposure scenario and potential response options, and to understand the potential impacts of that spill scenario on receptors, (2) predict the outcomes of the potential response options for the given scenario, (3) balance trade-offs by weighing a range of ecological, socioeconomic, or cultural benefits and drawbacks resulting from each feasible response option, and (4) decide which option will minimize the impacts for a given spill scenario (Interspill 2012; IPIECA 2015).

Since the window of opportunity for dispersant application following a spill can be short, the appropriateness of application should be considered in the NEBA process and be informed by current understanding of the potential impacts on various receptor organisms. When the decision to use dispersants has been supported by a NEBA, their use has the potential to mitigate some of the impacts of an oil spill as a primary or integrated response (DFO 2021). It is recognized, however, that while NEBAs aim to reduce the impacts of an oil spill there are no response options, dispersant use included, that are entirely effective or completely without risk (Passow and Lee 2022).

Assessing the trade-offs

Evaluating the trade-offs associated with dispersant use is a complex and difficult task faced by oil spill responders (NRC 2005). The assumption that the use of dispersants will reduce oil exposure to marine receptors, or that oil–dispersant mixtures are less harmful than oil alone, is often a key deciding factor and important consideration when balancing the trade-offs in the decision process on whether to use dispersants for an oil spill scenario (NRC 2005).

Spilled oil can have long-term impacts on marine bird populations and their recovery can take years if recovery is possible (Cairns and Elliot 1987; Peterson et al. 2003; Esler et al. 2018). Uncertainty remains over the acute and long-term effects of dispersant use to marine birds and to what extent they may reduce the impacts of oil to marine bird populations or habitats or lessen their recovery times. An additional consideration is that marine bird species may vary in the degree of impact and rate of recovery they experience from an oil spill event. This reinforces the notion that oil spill response decision-making frameworks should incorporate site- and spill-specific considerations to evaluate the benefits and costs and acknowledge the trade-offs associated with any given response option. This includes accounting for factors like seasonality, conservation status, as well as the ecological considerations of indirect impacts to prey and habitat.

Where trade-offs are concerned, no decision is likely to satisfy all response partners and interest groups, as protection goals and priorities will differ. Given this, decisions should be made transparently and with reference to supporting information (Grote et al. 2018). This is especially true for trade-offs regarding marine bird protection as they are often identified as a high priority. Mitigating the effects of an oil spill on marine birds, however, is just one component of a framework balancing myriad factors and other valued resources that may have contradictory net benefits. Additionally, it is difficult to weigh the importance of each component considered within this framework. This in turn emphasizes the need to quantify as precisely as possible the benefits and costs of dispersant use when considering the mitigation of oil spill impacts on a particular resource. As such, an important part of these formalized decision-making frameworks, beyond transparency, is a structure that facilitates discussion and the identification of knowledge gaps that informs science and policy.

Information gaps and uncertainties

Despite what is known about how dispersants interact directly with marine birds, their prey, and their habitats, many outstanding information gaps influence our ability to predict outcomes and make informed recommendations on their use. Briefly summarized, these include

- the direct and indirect effects and impacts to marine birds from dispersant use (especially Corexit® 9500), and their severity relative to untreated oil.
- the long-term, chronic, sublethal, and delayed effects to marine birds, their prey, and habitats from dispersant use and persistence in the environment.
- how exposure to untreated oil and chemically dispersed oil differs between foraging guilds of marine birds.
- whether, and to what extent, the results of lab-based studies involving birds or other biota are representative of marine birds under natural conditions.
- unintended and unforeseen interactions between marine biota, oil, and dispersants that may include HABs, or bioaccumulation and other trophic and population dynamics.
- whether reduction of an oil slick at the surface from dispersant use will result in a proportional reduction in lethal and/or sublethal effects (Albers and Gay 1982).

Recommendations

Bridging current information gaps and reducing the uncertainty we incorporate into the decision-making process for oil spill response will minimize, as much as possible, the effects and impacts to marine birds. While using conservative assumptions to account for these uncertainties is our best option, we recommend the following approach in addressing these uncertainties.

- Routinely incorporate considerations for marine birds, habitats, and prey into NEBA (or similar) decision-making processes, to evaluate merits of dispersant use based on both the benefits and the costs. This should include POE models, species and foraging guild-specific knowledge as appropriate, integrating best-available science and information with local knowledge.
- Where uncertainties and information gaps exist in an NEBA (or similar) decision-making process, greater transparency is needed in communicating these shortcomings. Documenting decisions, including how uncertainties may affect outcomes. Paired with marine bird monitoring strategies, this will help to address incident-specific information gaps and inform future decision-making processes.

To address information gaps associated with the impacts of dispersant use we offer several recommendations to improve informed, science-based decision-making on dispersant treatment strategies and improve predictions on outcomes to marine birds.

- Continue preliminary research by Peakall et al. (1987) in investigating the extent to which different marine bird foraging guilds are susceptible to chemically dispersed oil exposure relative to an untreated oil spill, at different dispersant efficiencies.
- Incorporate targeted or opportunistic field studies and experiments into controlled spill/dispersant application scenarios and incident response to assess the response of marine bird species to chemically dispersed oil.
- Investigate the relevance of laboratory studies on marine birds (e.g., toxicity testing and mechanical interactions of dispersants) to real-world oil spill scenarios.
- Continue research into improved dispersant formulations, or alternatives, that are less harmful to marine birds, prey, and habitats (e.g., see Dannreuther et al. 2021 for a review of emergent dispersant technologies; Omarova et al. 2018; Guo et al. 2019; Kurita-Oyamada et al. 2020; Farahani and Zheng 2022).
- Advance research on the efficacy of dispersant application at varying volumes and concentrations as well as under a range of conditions, particularly representative of conditions and climates of northern coastal ecosystems, to determine the fate and persistence of dispersants.
- Continue to compile and share information and lessons learned on the relative impacts and sensitivities of marine bird species in Canada to chemically dispersed oil.

Conclusion

Protecting marine birds from the effects of spilled oil is a priority given their documented direct and indirect sensitivities to hydrocarbon pollution, which includes both impacts to prey and habitats. The goal of protecting marine birds from oil spills through dispersant application is clear; however, our scientific understanding of how dispersants and chemically dispersed oil affect marine birds directly and indirectly is still in its infancy. The complexity of how natural processes and interspecific interactions influence on hydrocarbon fate, bioaccumulation, biodegradation, persistence, and recovery factors may be altered by dispersants is only beginning to be explored. Our understanding is further impeded by the need to disentangle the effects of oil, dispersant–oil mixtures, and environmental variability.

Given current knowledge about dispersants, their use is not without the risk of affecting marine birds directly or indirectly. Almost two decades have lapsed since the NRC's (2005) recommendations, yet there has been limited advancement in our understanding of the net benefits of dispersant use. This includes how they compare to an untreated oil spill under a variety of environmental conditions and among marine bird species. To better account for the relative value of the benefits and costs of dispersant use to marine birds, we have offered several recommendations to improve decision-making outcomes, which focus on the direct and indirect effects of dispersant use to marine birds, their prey and habitat. Concurrently, it is important to prioritize the development of less toxic oil spill response measures that have the potential to replace current dispersant formulations. The expanded use of dispersants necessitates increased responsibility in addressing outstanding information gaps and uncertainties on various receptor organisms, marine birds being one. Greater transparency is needed in communicating our uncertainties and greater effort is needed to reduce them.

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