

Large-Scale Impacts of the Deepwater Horizon Oil Spill: Can Local Disturbance Affect Distant Ecosystems through Migratory Shorebirds?

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The 2010 Deepwater Horizon oil spill, the largest ever accidental release of oil into marine waters, affected hundreds of miles of US northern Gulf of Mexico coastline that is important habitat for migratory shorebirds. Shorebirds are particularly susceptible to oil contamination because of their subsurface probe-foraging behavior and reliance on intertidal habitat. More than one million migratory shorebirds representing 28 species were potentially exposed to Deepwater Horizon oil during their 2010–2011 nonbreeding season. Although only 8.6% of the shorebirds trapped from fall 2010 to spring 2011 showed visible signs of oiling, nonlethal effects and degradation of habitat can affect populations in ways that carry over into subsequent seasons. Here, we discuss how the spill could affect populations of migratory shorebirds through acute mortality, as well as through long-term and indirect pathways. We also discuss the potential impacts on ecosystems far from the spill, including prairie grasslands and the Arctic, where migratory shorebirds breed.

Keywords: shorebirds, migration, deepwater oil well blowout, carryover effects

On 20 April 2010, the *Deepwater Horizon (DWH)* oil platform, situated 45 miles southeast of Venice, Louisiana, exploded and sank, causing the subsequent release of an estimated 4.9 million barrels of oil, the largest accidental marine oil spill in US history (Graham et al. 2011). More than 650 miles of the northern Gulf of Mexico (GOM) coastline was directly affected by the spill (Graham et al. 2011), as a mixture of crude oil and chemical dispersants soiled beaches, mudflats, and coastal wetlands. Although much of the oil was collected, dispersed, or dissolved, as of July 2011, one year after the DWH oil well was capped, at least 490 miles of northern GOM coastline remained contaminated by oil (as was reported by Polson 2011).

Shorebirds (order Charadriiformes, excluding suborders Lari and Turnici) are particularly vulnerable to oil spills, because they spend much of their time foraging in readily oiled, intertidal shoreline habitat (Peterson et al. 2003, OSAT-2 2011). Shorebirds are also of high conservation concern because many shorebird populations are declining (Morrison et al. 2006), and their habitat is vulnerable to sea-level rise and other effects of climate change. The beaches and wetlands along the northern GOM affected by the

DWH oil are important habitats for 34 species of shorebirds (Withers 2002). Of these, 6 species are considered resident and 28 are migratory species that spend all or part of their nonbreeding seasons on the GOM coast. The breeding range of the nonresident species extends from the temperate prairie and wetlands of North America to the high Arctic (figure 1). For many species, the wetlands and barrier islands of the GOM coast represent the first areas of suitable wintering habitat or stopover habitat between northern breeding grounds and distant wintering grounds in South America (Withers 2002).

Oil can affect birds in a variety of ways, and exposure to oil is not necessarily fatal. Instead, repeated exposure to oil within and between seasons may have sublethal effects that can lead to population-level impacts through diminished health and reproductive fitness. Some shorebirds have strong site fidelity to wintering and stopover sites (Drake et al. 2001), which makes them susceptible to repeated exposures as they return to contaminated habitats year after year. The importance of nonbreeding habitats to the conservation of migratory populations is becoming clearer as many species face increasing rates of habitat degradation

Breeding distributions of shorebird species with populations that overwinter or stop over in the Gulf of Mexico

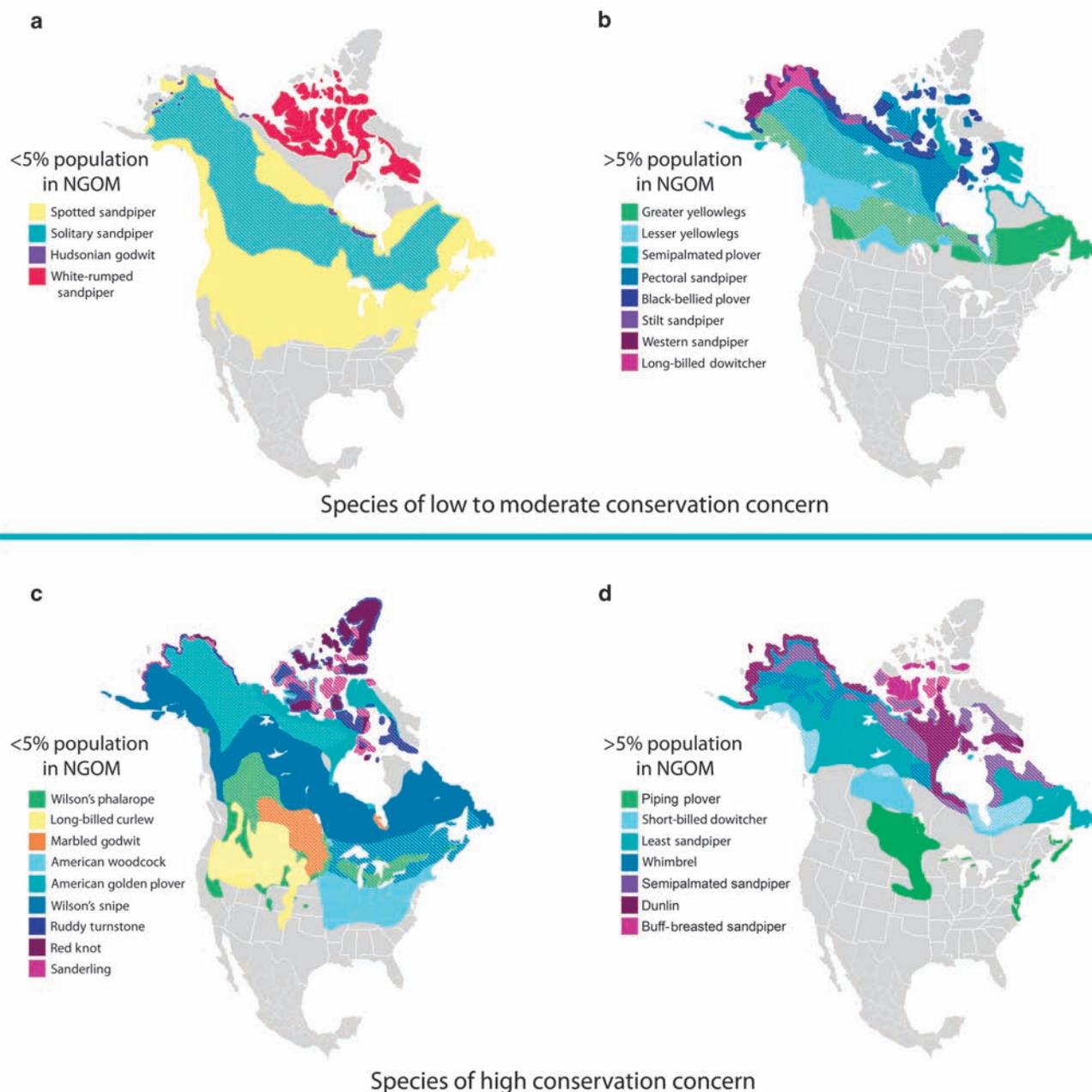


Figure 1. Breeding ground distributions of migratory shorebirds species for which the northern Gulf of Mexico (NGOM) is used as wintering or stopover habitat. (a) Shorebird species of low to moderate concern (conservation trend rank 2–3; Morrison et al. 2006) in which less than 5% of the North American population uses the NGOM. (b) Shorebird species of low to moderate concern (conservation trend rank 2–3), in which more than 5% of the North American population uses the NGOM. (c) Shorebird species of high concern (conservation trend rank 4–5; Morrison et al. 2006) in which less than 5% of the North American population uses the NGOM. (d) Shorebird species of high concern (conservation trend rank 4–5) in which more than 5% of the North American population uses the NGOM (see also table 1). Source: Based on data from the Birds of North America Web site (www.bna.birds.cornell.edu).

and environmental change. In migratory birds, the conditions encountered in nonbreeding habitats can affect survival and reproductive success (reviewed in Harrison et al. 2011).

Relatively few oiled shorebird carcasses were collected during and immediately following the DWH spill; most of the bird carcasses found were from larger species (e.g., brown pelicans [*Pelecanus occidentalis*], northern gannets [*Morus*

bassanus], laughing gulls [*Leucophaeus atricilla*]; USFWS 2011). However, out of the 220 shorebirds that we captured with mist nets between October 2010 and May 2011, 19 were visibly oiled. We also expect that a far greater proportion of shorebirds was exposed by oil ingestion, which cannot be detected through visual examination.

Although the Natural Resource Damage Assessment and Restoration program (NRDAR) includes components that are focused on shorebirds, including studies on the endangered piping plover (*Charadrius melodus*) and shorebird abundance surveys (NRDAR 2011), a better understanding of the extent that shorebirds were affected by the spill must wait until these data are released from the NRDAR confidentiality agreement. In addition, plans for a long-term assessment of the effects of the DWH oil on shorebird species are not apparent (NRDAR 2011). Shorebirds and nesting sea turtles are two groups of organisms identified by the US Coast Guard's Operational Science Advisory Team that face longer-term elevated risks of exposure from remnant beached oil (OSAT-2 2011). Although the immediate impacts of oil on shorebirds following smaller oil spills have been assessed (Burger 1997), the indirect and long-term impacts of oil on shorebirds have been measured in relatively few studies (but see Andres 1997). Our aim in this article is to explore the potential consequences of the DWH incident on migratory shorebirds across temporal and spatial scales and to highlight areas of further research necessary to address these effects.

Populations most at risk

Quantifying the impact of the DWH spill on shorebird populations is challenging, given the lack of baseline data regarding the population sizes, habitat use, and migration strategies of nonbreeding shorebirds on the northern GOM. Out of a total of 7258 live and dead birds recovered before 12 May 2011, 85 were shorebirds, and only 23 of those were identified as visibly oiled (USFWS 2011). However, given their small size and the difficulty of finding shorebird carcasses in sufficient condition to determine their oiling status (Burger 1997), we suspect that many more shorebirds were lost. Using population estimates compiled from several sources (see table 1), we calculate that more than one million shorebirds migrate through the northern GOM (from northern Texas to the Florida Panhandle). Considering that 8.6% of the shorebirds captured in the year following the DWH spill showed some signs of visible oiling, as many as 86,000 shorebirds were potentially affected by trace or light oiling of their feathers. However, an unknown but substantially larger number of shorebirds was likely exposed through direct ingestion of tarballs while foraging or through the consumption of contaminated prey (Burger 1997).

During the nonbreeding season, the northern GOM hosts more than 5% of the total North American population for 12 of the 28 migratory species that use its habitats (figure 1, table 1). Within the northern GOM, there are three sites used by 10 of these species that are classified as regionally

important, which means that more than 1% of at least one shorebird species' total population has been documented at the site (table 1; Manomet 2010). For these populations, the potential effects from the DWH spill will be more severe if the same individuals that winter or stopover together on the GOM remain together during the breeding season. Unique-color banding of the endangered piping plover, one of the most intensively studied shorebirds, shows that a relatively large proportion of the breeding populations remain together throughout migration and winter (i.e., strong migratory connectivity; Gratto-Trevor et al. 2012). Although all four breeding populations (defined by their locations in the Canada Prairies, the Great Plains, the Great Lakes, and in Eastern Canada) of piping plover overwinter along the southeast Atlantic and GOM coasts, the eastern and western breeding birds remain relatively segregated during winter. Of the piping plovers color banded at the four breeding locations and resighted on their wintering grounds, 28% of the Great Plains birds and 26% of the Canada Prairies birds were observed in the northern GOM (figure 2; Gratto-Trevor et al. 2012). In comparison, none of the Eastern Canada population and only 4.6% of the US Great Lakes population was observed in the northern GOM. This highlights the importance of understanding migratory connectivity to better assess the impacts of disturbance to the nonbreeding grounds on a population. Given the already-degraded habitat, low population numbers (2959 individuals; Elliot-Smith et al. 2009) and recent flooding of piping plover breeding grounds in the US Great Plains, the impact of the DWH spill on the Great Plains population is likely to be the most acute.

Our understanding of migratory connectivity in piping plovers allows researchers to focus impact studies on the most affected populations, optimizing the use of funding and increasing our chances of detecting population-level effects of the spill (NRDAR 2011). There is evidence of similar migratory connectivity in other declining, long-distance migrant shorebird species that are potentially affected by the spill. The breeding range of a subspecies population of dunlin (*Calidris alpina hudsonia*) known to overwinter on the northern GOM coast is believed to be limited to northeastern Canada (figure 2). However, we lack information on demographics and nonbreeding site fidelity along the GOM coast for this subspecies. Additional information regarding the migratory connectivity for shorebirds using contaminated GOM habitats during the nonbreeding season is necessary to make accurate predictions of population-level effects.

The effects of oil on migratory shorebirds

Migratory shorebirds provide a system for evaluating the direct and indirect effects of an oil spill on affected habitats and the potential for carryover effects to other ecosystems. The foraging ecology and habitat-use patterns of shorebirds make them particularly susceptible to oiling through a diverse set of contamination pathways (figure 3) and, since

Table 1. North American and northern Gulf of Mexico (NGOM) population estimates for migratory shorebirds.

Species	Conservation trend ^a	North American population	NGOM population	NGOM population as a percentage of North American population	Regionally important site ^e
American golden-plover	Apparent population decline	150,000 ^{a,d}	1851	0.92	Grand Terre, Louisiana
American woodcock	Endangered or significant population decline	3,500,000 ^{a,d}	49	<0.01	
Black-bellied plover	Apparent stable population or unknown	200,000 ^{a,b}	12,500	6.25	
Buff-breasted sandpiper	Apparent population decline	40,000 ^{a,b}	8360	20.9	
Dunlin	Apparent population decline	1,525,000 ^{a,b}	97,692	6.41	Bolivar Flats, Texas; Grand Terre, Louisiana
Greater yellowlegs	Apparent stable population or unknown	100,000 ^{a,b}	8250	8.25	
Hudsonian godwit	Apparent stable population or unknown	70,000 ^{a,d}	206	0.29	
Least sandpiper	Endangered or significant population decline	700,000 ^{a,b}	43,750	6.25	Bolivar Flats, Texas
Lesser yellowlegs	Apparent stable population or unknown	400,000 ^{a,b}	33,000	8.25	
Long-billed curlew	Endangered or significant population decline	100,000 ^{a,b}	4620	4.62	
Long-billed dowitcher	Apparent population increase	1,000,000 ^{a,b}	59,500	5.95	
Marbled godwit	Apparent population decline	171,500 ^{a,d}	652	0.38	
Pectoral sandpiper	Apparent stable population or unknown	500,000 ^{a,b}	37,800	7.56	
Piping plover	Endangered or significant population decline	8092 ^{c,d}	582	9.39	Bolivar Flats, Texas
Red knot	Endangered or significant population decline	120,000 ^{a,d}	910	0.76	Bolivar Flats, Texas
Ruddy turnstone	Apparent population decline	245,000 ^{a,d}	811	0.35	Bolivar Flats, Texas
Sanderling	Apparent population decline	300,000 ^{a,d}	3565	1.18	Bolivar Flats, Texas
Semipalmated plover	Apparent stable population or unknown	150,000 ^{a,d}	1072	0.72	Bolivar Flats, Texas
Semipalmated sandpiper	Endangered or significant population decline	2,000,000 ^{a,b}	139,000	6.95	
Short-billed dowitcher	Apparent population decline	153,000 ^{a,b}	9869	6.45	
Solitary sandpiper	Apparent stable population or unknown	150,000 ^{a,d}	69	0.05	
Spotted sandpiper	Apparent stable population or unknown	150,000 ^{a,d}	96	0.06	
Stilt sandpiper	Apparent stable population or unknown	820,000 ^{a,b}	114,800	14.0	
Western sandpiper	Apparent stable population or unknown	3,500,000 ^{a,b}	409,500	11.7	Bolivar Flats, Texas
Whimbrel	Endangered or significant population decline	66,000 ^{a,d}	3553	5.38	Anahuac National Wildlife Refuge, Texas
White-rumped sandpiper	Apparent stable population or unknown	1,120,000 ^{a,d}	1687	0.42	
Wilson's snipe	Endangered or significant population decline	2,000,000 ^{a,d}	1370	0.07	
Wilson's phalarope	Apparent population decline	1,500,000 ^{a,b}	11,530	0.77	
Total			1,006,643		

^aMorrison et al. 2006.^bVermillion 2011.^cElliot-smith et al. 2009.^dwww.ebird.org.^eUsed by more than 1% of the population (Manomet 2010).

migration is energetically and physiologically demanding, the sublethal effects of oil may have severe consequences that lead to population-level effects. Migration also provides a mechanism whereby the effects of the spill may be

transported to ecosystems far removed from those in the immediate vicinity of the contamination. Figure 1 shows the breadth of regions that are potentially affected by the DWH spill through migratory shorebirds. Below, we give a brief

Distributions of shorebird species most at risk from the *Deepwater Horizon* oil

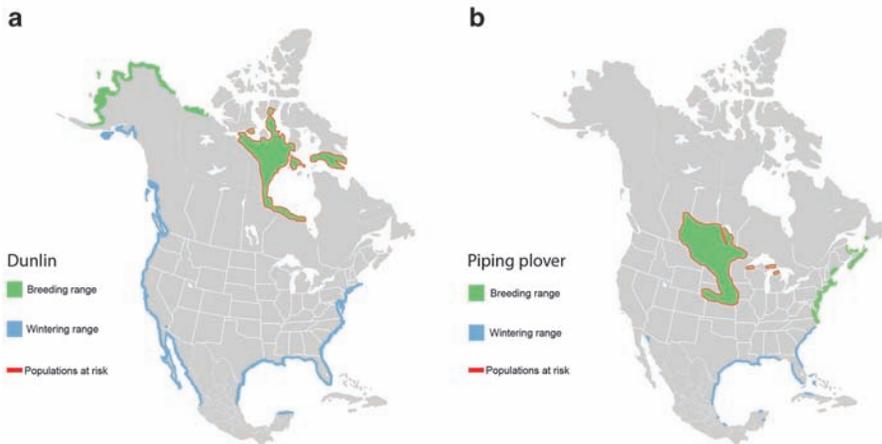


Figure 2. Breeding ground and wintering distributions of (a) dunlin (*Calidris alpina*) and (b) piping plover (*Charadrius melodus*), two shorebird populations assessed to be the most at risk to impacts from the *Deepwater Horizon* spill through migratory connectivity. Source: The distributions are based on data from the *Birds of North America* Web site (www.bna.birds.cornell.edu).

overview of the diverse effects of oil on migratory birds.

Lethal effects. Oil causes the direct, immediate mortality of birds through several pathways (figure 3). Oil on feathers destroys their waterproofing and insulating capabilities, which leads to the birds' death from hypothermia (reviewed in Leighton 1993). Other effects of direct oil exposure include dehydration, starvation, arthritis, gastrointestinal problems, infections, pneumonias, cloacal impaction, and eye irritation (Briggs et al. 1996). Many of these effects are the result of oil ingestion, which can occur through the preening of oiled feathers (Leighton 1993, Briggs et al. 1996). However, in shorebirds, oil ingestion by foraging in contaminated habitats and consumption of contaminated prey

may be a major contamination pathway and warrants further investigation (Burger 1997, NRC 2003, OSAT-2 2011). Mortality from ingested oil is primarily caused by acute toxic effects on the kidney, liver, and gastrointestinal tract (Briggs et al. 1996).

Potential effects of the *Deepwater Horizon* oil on migratory shorebirds

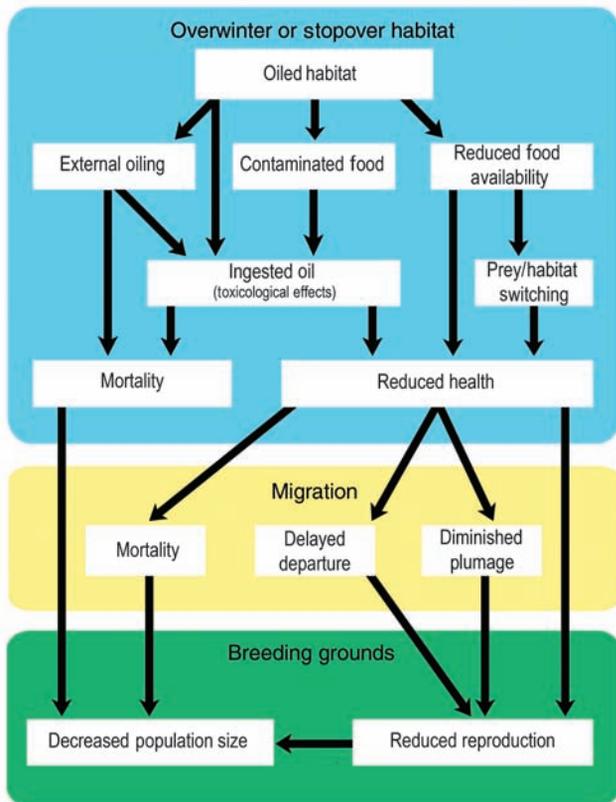


Figure 3. Oil contamination pathways and potential carryover effects at each stage of the annual cycle (overwintering or stopover habitat, migration, and breeding) for migratory shorebirds.

Diminished health. Ingested oil can have several sublethal toxicological effects, including hemolytic anemia, reduced reproduction, and immunosuppression. Hemolytic anemia in birds exposed to oil is caused by an oxidative process that forms Heinz bodies in red blood cells, which eventually destroys the cells (Leighton 1993). Although it is not necessarily lethal, Heinz-body anemia decreases a bird's ability to transport oxygen, which can be particularly detrimental to migratory birds because of the aerobic requirements of long-distance migratory flight and the heightened oxygen demands of the larger body mass of fattened migrating birds. Heinz-body anemia also reduces breeding success by preventing or impairing egg formation and egg laying (Leighton 1993). As a response to the destruction of red blood cells from oil ingestion, there is a compensatory increase in erythrocyte production, which results in immunosuppression and in a decline in white blood cell production. Another pathway through which the immune system may be affected by oil ingestion is damage and inflammation of the gastrointestinal tract (Briggs et al. 1996). This affects the function of the mucosal membrane, which is important in intestinal immune function. The gastrointestinal tract of birds is also important for T and B lymphocyte development. Indirectly, damage to the intestinal tract has negative impacts on nutritional uptake, which can also cause immunosuppression. In addition, oil exposure is associated with increased corticosteroid production, which

has a negative impact on the effectiveness of circulating lymphocytes, which thereby decreases immune function (Briggs et al. 1996).

Oiled birds may also experience decreased foraging success due to a decline in prey populations following a spill (Andres 1997, NRC 2003) or due to increased time preening to remove oil from their feathers (Burger 1997). During both winter and migration, shorebirds spend much of their time feeding and depend on nonbreeding habitats to provide the fuel necessary for migratory flight (Withers 2002). Red knots (*Calidris canutus*) stopping over at Delaware Bay experience a decrease in refueling rates that has an impact on individual fitness for the remainder of the migration and may even be responsible for population declines (Baker et al. 2004). If oil from the DWH spill reduces foraging success and habitat quality for migratory shorebirds, subsequent weight loss and diminished health may delay the birds' departure, decrease their survival rates during migration, or reduce their reproductive fitness.

Prey and habitat switching. Oil can reduce invertebrate abundance or alter the intertidal invertebrate community that provides food for nonbreeding shorebirds (Andres 1997, NRC 2003). Reduced abundance of a preferred food may cause shorebirds to move and forage in other—potentially lower-quality—habitats. Following the 2003 *Prestige* oil spill off of the northwest coast of Spain, the reproductive performance of European shag (*Phalacrocorax aristotelis*) declined, their chick condition worsened, and the number of breeding adults decreased significantly (Velando et al. 2005). These changes were attributed to an indirect negative impact mediated by a more-than-25% reduction in the consumption of sandeel (family Ammodytidae), the preferred fish prey of European shag (Velando et al. 2005). Prey switching has not been documented in shorebirds following an oil spill. However, shorebirds will feed in alternative habitats when the intertidal zone alone cannot fulfill their energy requirements. For example, ruddy turnstones (*Arenaria interpres*) wintering in England switched from feeding on intertidal cockles to feeding on human-spilled wheat grain and fishmeal during periods of decreased cockle abundance (Smart and Gill 2003). Nonbreeding shorebirds along the GOM coast will forage in agricultural fields during migration and throughout winter when the conditions are suitable (Vermillion 2011). A reduction in habitat quality and resource abundance in the intertidal zone by the DWH spill may increase the importance of agricultural fields as buffer habitats. This change could result in decreased fitness during the nonbreeding season and could also result in carryover effects, such as decreased breeding success. Gunnarsson and colleagues (2005) used carbon stable isotope ratios ($^{13}\text{C}/^{12}\text{C}$ expressed as delta ^{13}C ($\delta^{13}\text{C}$)) of feathers grown on the wintering grounds by black-tailed godwits (*Limosa limosa*) to measure the habitat quality of the wintering grounds. They found that individuals wintering in high-quality coastal habitats, characterized by high

$\delta^{13}\text{C}$ ratios, had greater reproductive success than those wintering in poorer-quality inland habitats, characterized by low $\delta^{13}\text{C}$ ratios.

Diminished plumage quality. Birds wintering or stopping over in oiled habitats may show poor feather condition and dulled plumage before spring departure as a result of decreased health or diminished energy accumulation. The completeness and color of breeding plumage is a direct indication of physical condition (i.e., an honest signal of quality) in some birds (Piersma and Jukema 1993). Many shorebird species begin molting into breeding plumage before spring migration, which means that the quality of their breeding plumage can be influenced by the quality of their wintering or stopover habitats. Piersma and Jukema (1993) found a positive correlation between the completeness of breeding plumage and body mass in bar-tailed godwits (*Limosa lapponica*) during spring migration. Germain and colleagues (2010) measured the amount of breeding plumage in American redstarts (*Setophaga ruticilla*) and found a significant positive correlation between the amount of black breast plumage and birds wintering in high-quality habitat and a negative correlation between the amount of black breast plumage area and arrival time on the breeding grounds, both of which are indications of increased breeding success. Similar to redstarts, many shorebirds have melanic breeding-plumage coloration. A decrease in plumage quality or brightness could result in decreased breeding success for oil-affected birds and warrants further investigation.

Delayed migration. A bird's inability to obtain adequate resources delays its premigratory fattening and can delay the departure for its breeding grounds. Birds arriving on their breeding grounds earlier realize higher reproductive success through increased clutch size and offspring survival (for a review, see Harrison et al. 2011). If GOM coast habitats are sufficiently degraded by oil that premigratory fattening is slowed and birds delay departure for their breeding grounds, the individual effects could carry over into the breeding season and into distant breeding habitats.

Long-term impacts. Evidence from previous oil spills suggests that the impacts of the DWH incident are not likely to be limited to immediate or short-term effects (Peterson et al. 2003, Short et al. 2007). Oil contaminants, including polycyclic aromatic hydrocarbons (PAHs), which are some of the most harmful components of oil, can remain in the environment for decades. Sixteen years after the *Exxon Valdez* oil spill in Prince William Sound, Alaska, Short and colleagues (2007) identified slightly weathered oiled from the spill in subsurface sediments. Long-term exposure and ingestion of PAHs is carcinogenic, and there is evidence that PAHs may be incorporated into the food chain, although they do not biomagnify at higher trophic levels (NRC 2003, Peterson et al. 2003). Weathered oil has been shown to reduce

hatching success in exposed mallard eggs (Finch et al. 2011), and adverse effects from the leaching of PAHs from weathered oil have been observed years after the *Exxon Valdez* oil spill (Esler et al. 2002, 2010). Documentation of the long-term effects of residual oil, however, is difficult and requires many years of research. For example, PAHs were found in yellow-legged gull (*Larus michahellis*) chicks 17 months following the *Prestige* spill (Alonso-Alvarez et al. 2007). These chicks were never directly exposed to spilled crude oil, and their parents showed no evidence of external oiling, which suggests that the contamination had been incorporated into the food chain. Given the warm climate of the northern GOM and some evidence of increased microbial respiration (e.g., Edwards et al. 2011), it has been suggested that the persistent effects of oil observed following other large spills will not be as severe following the DWH spill. However, almost 500 miles of coastline remained contaminated by weathered oil a year after the oil stopped leaking (as was reported by Polson 2011).

The attribution of population-level effects to specific oil spills at longer temporal scales can be difficult and controversial. For example, although early studies suggested that the effects of the *Exxon Valdez* oil spill were short lived for most bird species, such as the harlequin duck (*Histrionicus histrionicus*; for a review, see Wiens et al. 2010), 10 years after the spill, female harlequin ducks that wintered in previously contaminated sites had significantly lower survival rates than those that wintered in uncontaminated sites (Esler et al. 2002). Other researchers, citing evidence that the numbers of harlequin ducks were lower in contaminated regions than in uncontaminated regions before the *Exxon Valdez* oil spill, have suggested that the different survival rates could be explained by differences in the intrinsic habitat quality of the two sites (for a summary, see Wiens et al. 2010). More recently, researchers have refuted this suggestion by demonstrating the return of winter survival rates in oiled sites 11–14 years after the *Exxon Valdez* oil spill to levels observed across the study period in the uncontaminated habitats (Esler and Iverson 2010).

Similarly, attribution to the *Exxon Valdez* oil spill of increased induction of cytochrome P4501A (CYP1A), a biomarker that is a sensitive indicator of exposure to PAHs, in harlequin ducks both a decade and two decades after the *Exxon Valdez* oil spill has been disputed (discussed in Esler et al. 2010). Some researchers have argued that although elevated CYP1A expression can indicate exposure to PAHs, there are many potential sources of PAHs in Prince William Sound that are not related to the *Exxon Valdez* oil spill (for a summary, see Wiens et al. 2010).

The debate about the attribution of effects from the *Exxon Valdez* oil spill appears to be driven, in large part, by a lack of baseline prespill data. The ecological risk-assessment approach used to quantify the intensity and duration of impacts to populations and ecosystems from environmental disasters requires the establishment of recovery endpoints that represent a return of a population or habitat to some

prespill state. Without baseline data, endpoints are difficult to assess and are likely to be highly controversial. As in the case of harlequin ducks (Esler et al. 2002), very little is known about the prespill population densities, habitat use, or age:sex ratios of migratory shorebirds on the northern GOM. If the changes in overwinter survival rates experienced by harlequin duck populations resulted from the *Exxon Valdez* oil spill, the site fidelity to nonbreeding habitats exhibited by shorebirds (Drake et al. 2001) would suggest that shorebird populations will continue to experience effects from the DWH spill for years to come. Attributing population-level effects in shorebirds potentially exposed to DWH oil will be difficult, given the many other threats facing shorebird populations, including climate change, habitat loss, and the background levels of oil present in the GOM as a result of natural oil seeps and an oil industry that has been in place for over half a century. A careful examination of environmental and spatial variation when comparing sites is necessary to assess the long-term effects of oil exposure. Therefore, to link changes in shorebird populations to the DWH spill, it will be essential to implement long-term research plans in which sources of variation other than contamination by DWH oil are accounted for. Unfortunately for shorebirds, no such studies appear to have yet been initiated in the damage-assessment plan (NRDAR 2011).

The ecological communities at risk outside the GOM

Population declines of migratory shorebirds and reduced breeding productivity as a result of the DWH spill may have an impact on ecosystems outside the GOM (figure 1). In this section, we discuss the ecosystems most likely to be affected—those in which GOM shorebirds stop over during migration and spend the breeding season.

Stopover migration. Migrating shorebirds are a major food source for avian predators, including peregrine falcons (*Falco peregrinus*) and merlins (*Falco columbarius*). Although these avian predators are not likely to have direct contact with DWH oil, they may experience indirect impacts by consuming contaminated prey, such as shorebirds. A single merlin has been observed consuming an average of 2 shorebirds per day across the nonbreeding season, or about 295 shorebirds over a five-month period (Page and Whiteacre 1975). Following the 2002 *Prestige* oil spill, Zuberogoitia and colleagues (2006) found PAH concentrations from 21.20 nanograms per gram (ng/g) to 461.08 ng/g in eggs from peregrine falcon nests around the area of the spill. These high concentrations were probably the result of adults feeding on contaminated shorebird prey and passing the contamination on to embryos during egg production. PAH contamination was also observed at inland peregrine falcon nests, far from the spill, which suggests that it was from preying on contaminated shorebirds stopping over during migration at inland rivers (Zuberogoitia et al. 2006). A similar indirect exposure to predators could occur within

ecosystems across the migration pathways of shorebirds in North America.

Upland prairie. Several species of shorebirds that overwinter and stop over along the GOM coast breed in the mixed-grass prairie habitats of North America (Gratto-Trevor 2006), which are threatened by conversion to agriculture. Prairie food webs are complex, and therefore, the effects of declines in shorebird abundance are difficult to predict. Shorebird and waterfowl nests are important food resources for predators in prairie ecosystems, and a decline in shorebird abundance can increase predation pressure on waterfowl that nest in the same region (Gratto-Trevor 2006). Such effects may be exacerbated by the extensive habitat loss and degradation that has already occurred in the prairie pothole regions of central North America, which has led to waterfowl population declines (Gratto-Trevor 2006).

Arctic and subarctic regions. An estimated 30 million shorebirds breed in the high Arctic (Lanctot 2004), and another 7 million breed in the boreal forests of North America (Wells and Blancher 2011). The yearly influx of shorebirds into these ecosystems provides a vital food source for predators such as the snowy owl (*Bubo scandiacus*) and the arctic fox (*Alopex lagopus*). This is particularly true during low phases of the lemming (*Lemmus sibiricus* and *Dicrostonyx groenlandicus*) abundance cycles, when shorebirds and waterfowl are the primary alternative prey for these predators (Gilg and Yoccoz 2010). Shorebird nest success can increase as much as 75% between high- and low-lemming-abundance years (McKinnon 2011), which indicates the potential importance of shorebirds as a buffer for Arctic predator populations. For example, the estimated home range of a male arctic fox is 10.22 square kilometers (km²) (standard deviation = 6.18) (Anthony 1997). Using an upper limit of observed shorebird nest densities (80 per km²; Cotter and Andres 2000) and an average of four eggs per nest, approximately 3270 shorebird eggs may be found in the territory of an arctic fox family. Careau and colleagues (2008) calculated the metabolized energy value of greater snow geese (*Chen caerulescens atlantica*) to the arctic fox's daily survival. Adjusting for shorebird egg size (one seventeenth the size of a snow goose egg; McKinnon 2011), we calculate that if every shorebird egg within a territory were consumed, this would be the caloric equivalent of 141 arctic fox pup rearing days (1112 kilojoules per day; Careau et al. 2008), or 1.48 additional pups. This suggests that any significant decrease in shorebird productivity could have a significant impact on arctic foxes, especially during low-lemming-abundance years. Because of the relatively low diversity of Arctic terrestrial vertebrate communities, any changes in community structure can quickly cascade through trophic levels (Gilg and Yoccoz 2010). Therefore, the diminished availability and productivity of breeding shorebirds resulting from the degradation of their non-breeding habitat has the potential to have a drastic impact on

Arctic predators, and these impacts could cascade through Arctic food webs.

Conclusions

Shorebird populations of the GOM coast are likely to experience both direct and indirect effects from the DWH oil. Shorebirds that use the northern GOM are already facing a diverse array of threats, including habitat loss caused by wetland erosion from shipping, sea level rise, and human development. The DWH oil spill, occurring as it has in the context of these multiple other stressors, has likely added an additional burden to an already stressed system.

To monitor the impacts of the DWH disaster, it is important not only that researchers measure acute mortality in these species but also that they look for evidence of long-term, sublethal effects. Measuring these effects throughout the annual cycle in migratory species will be challenging, because migratory connectivity is difficult to discern and not well understood in many GOM coast species. Emerging technologies, such as stable isotope analysis, genetic markers, geolocators (global location sensors), and satellite telemetry, provide researchers with tools to uncover the connectivity of migratory populations (Robinson et al. 2010) and should be employed in efforts to quantify the effects of the DWH spill and other future environmental disasters. For example, Montevecchi and colleagues (2011) used geolocators to estimate the population size of adult northern gannets wintering in areas on which the DWH spill has had an impact. In comparison with band recoveries, their estimate increased by over 50,000 (53.7%) when they used information retrieved from geolocators.

As our knowledge of migratory connectivity grows, so does our understanding that ecosystem dynamics are not driven entirely by local events but, through migratory animals, can be influenced by events taking place in distant locations. The DWH oil spill is one such event that, through migratory shorebirds and other highly mobile species, may affect ecosystems far distant from the coastline along which the spill occurred. An increased awareness of the large temporal and spatial scales at which local habitat degradation can have measurable impacts on populations and ecosystems should be an important component of monitoring and planning for the effects of this and other future challenges, such as those presented by climate change, on migratory species.

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