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REVIEW

Estimating the numbers of aquatic birds affected by oil spills: pre-planning, response, and post-incident considerations

G.S. Fraser, G.J. Robertson, I.J. Stenhouse, and J.I. Ellis

Abstract: Oil spills most visibly affect waterbirds and often the number of birds affected, a key measure of environmental damage from an incident, is required for public communication, population management, and legal reasons. We review and outline steps that can be taken to improve accuracy in the estimation of the number of birds affected in each of three phases: (1) pre-planning; (2) during a response; and (3) post-response. The more pre-planning undertaken, the more robust the estimates will be. Personnel involved in damage assessment efforts must have training in quantitative biology and need support during all three phases. The main approaches currently used to estimate the number of birds affected include probability exposure models and carcass sampling — both onshore and on the water. Probability exposure models can be used in the post-incident phase, particularly in offshore scenarios where beached bird surveys are not possible, and requires three datasets: (1) at-sea bird densities; (2) bird mortality; and (3) the spill trajectory. Carcass sampling using beached bird surveys is appropriate if trajectories indicate affected birds will reach shore. Carcass sampling can also occur via on-water transects and may overlap with risk assessment efforts. Damage assessment efforts should include a measure of sublethal effects following the post-acute phase of spills, yet this area has significant knowledge gaps. We urge jurisdictions worldwide to improve pre-incident planning. We provide guidance on how, in the absence of pre-incident data, quality data can be obtained during or after an incident. These recommendations are relevant for areas with aquatic-based industrial activities which can result in a spill of substances that could injure or kill waterbirds.

Key words: exposure probability model, population density estimation, trajectory modeling, carcass (density) sampling, sublethal effects.

Résumé : Les déversements d'hydrocarbures affectent de façon manifeste les oiseaux aquatiques et souvent, le nombre d'oiseaux touchés, une mesure clé des dommages environnementaux provoqués par un incident, est nécessaire pour la communication publique, la gestion de la population et les raisons légales. Les auteurs passent en revue et décrivent les étapes qui peuvent être suivies pour améliorer la précision de l'estimation du nombre d'oiseaux touchés dans chacune des trois phases : (1) la préplanification; (2) pendant l'intervention; et (3) après l'intervention. Plus la préplanification est importante, plus les estimations seront solides. Le personnel impliqué dans les efforts d'évaluation des dommages doit avoir une formation en biologie quantitative et a besoin de soutien pendant les trois phases. Les principales approches actuellement utilisées pour estimer le nombre d'oiseaux touchés comprennent les modèles probabilistes d'exposition et l'échantillonnage des carcasses – sur terre et sur l'eau. Les modèles probabilistes d'exposition peuvent être utilisés dans la phase post-incident, en particulier dans les scénarios au large des côtes, où les enquêtes sur les oiseaux échoués ne sont pas possibles, et nécessitent trois ensembles de données : (1) les densités d'oiseaux en mer; (2) la mortalité des oiseaux; et (3) la trajectoire du déversement. L'échantillonnage des carcasses à l'aide d'enquêtes sur les oiseaux échoués est approprié si les trajectoires indiquent que les oiseaux touchés atteindront le rivage. L'échantillonnage des carcasses peut également se réaliser par des transects sur l'eau et peut chevaucher les efforts d'évaluation des risques. Les efforts d'évaluation des dommages devraient inclure une mesure des effets sublétaux après la phase post-aiguë des déversements, mais ce domaine présente des lacunes importantes en matière de connaissances. Les auteurs exhortent les juridictions du monde entier à améliorer la planification pré-incident. Ils offrent des conseils sur la façon dont, en l'absence de données pré-incident, des données de qualité peuvent être obtenues pendant ou après un incident. Ces recommandations sont pertinentes pour les zones où se déroulent des activités industrielles aquatiques pouvant entraîner le déversement de substances susceptibles de blesser ou de tuer des oiseaux aquatiques. [Traduit par la Rédaction]

Mots-clés : modèle probabiliste d'exposition, estimation de la densité de la population, modélisation de la trajectoire, échantillonnage de la carcasse (densité), effets sublétaux.

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Introduction

Almost 900 thousand tonnes of oil is released into aquatic environments annually (Natural Research Council 2003). Birds are the most visibly affected organisms (Hunt 1987; Tsurumi et al. 1999) through mortality (Leighton 1993) and sublethal effects (Alonso-Alvarez et al. 2007; Morandin and O'Hara 2016; Esler et al. 2018). Impacts to wildlife are not fully accounted for in spills (Chilvers et al. 2021). We need to know the number of birds affected because: (1) natural resource managers need the data to aid population management; (2) environmental damage assessments are often required for mitigation; and (3) the public wants this information.

Owing to the complexity of the issue, there are significant challenges in providing a scientifically defensible estimate of the number of birds affected (Castege et al. 2007; Piatt et al. 1990; Wilhelm et al. 2007; Haney et al. 2014*a*, 2014*b*). Most estimates are obtained during or after a spill. One commonly used method is carcass sampling models, whereby counts of affected carcasses are extrapolated by some method (van Pelt and Piatt 1995; Wiese and Robertson 2004; Byrd et al. 2009; Munilla et al. 2011; Haney et al. 2014*b*). More recently, probability exposure models have provided another approach, by overlaying the affected area on bird density and assuming some level of exposure to the contaminant (Wilhelm et al. 2007; Haney et al. 2014*a*). This requires baseline data that are usually lacking (Haney et al. 2014*a*; Wilhelm et al. 2007). Obtaining or collecting timely data to inform one, or both, of these approaches, is the main constraint, especially in the larger context of an oil spill response.

A number of steps must be taken to obtain a scientifically robust estimate, including: (1) pre-planning; (2) identifying priorities during a response; and (3) post-response follow-up. Here, we review statistical and data collection methods, science gaps, and sublethal effects, and provide recommendations to the research community, regulatory agencies, and other stakeholders to be better positioned to provide credible estimates in future incidents. Specifically, we focus on estimating the number of affected birds — a critical variable in determining broader environmental impact.

Estimating the number of affected birds

Data relevant to estimating the number of affected birds can be secondary to other priorities during an incident response. Even within the wildlife response, there is difficulty balancing the need for information for immediate risk assessment and data that can eventually be used in damage assessment. Risk assessment aims to prioritize habitats or species immediately at risk, so wildlife response resources can be deployed to minimize further impacts. Damage assessment is different because it measures the number of birds that have succumbed to the risk. Thus, the data needs for risk assessment and for damage assessment are not identical. Because damage assessment is concerned with already-oiled wildlife, it may seem to be less urgent for informing and directing the wildlife response. However, data needs for damage assessment often cannot be collected later.

Damage assessment is a statistical estimation exercise and should be directed by quantitative wildlife biologists. Its goal is to estimate the number of birds affected. This requires a variety of approaches (Fig. 1; Table 1). Familiarity with survey design, implementation, and analyses are important skills, as is knowledge of methods for estimating a range of probabilities that lead to estimating the number of affected birds. A scientifically defensible estimate requires rigorously collected data on each key component.

Carcass sampling: on shore and on water components

Striking images of oiled birds on shorelines are often the focus of wildlife rehabilitation responses, but they also permit assessment of the total number of individuals potentially affected by an on-water spill. The basic premise is simple: if the probability of an affected bird reaching shore is estimated, counts of oiled wildlife can then be extrapolated to the total number of birds affected. This approach is well developed and has been in use for decades (e.g., Newman et al. 2006; Haney et al. 2014*a*). Although the premise is simple, determining how many birds were affected offshore for every affected bird found onshore is challenging because it involves both onshore and on-water processes (Fig. 2).

Onshore processes

A range of estimates are needed to calculate the total number of birds (alive or dead) that reached all potential shorelines where they could be found (e.g., Piatt and Ford 1996; Newman et al. 2006). First, the geographic scope of shorelines that may receive affected oiled wildlife must be considered. For nearshore and small spills, carcasses may be narrowly geographically constrained. For larger, chronic, and distant spills, the geographic scope may be extensive. Early exploratory surveys help ensure the full extent of the spill is encapsulated and appropriate shoreline surveys implemented. Newman et al. (2006) recommend extending coverage whenever possible. Longer-lasting spills may require increasing the scope to assess any change in extent of the spill. Oil spill trajectory modeling is used to inform which coastlines may have received affected wildlife, and when the effects may occur (e.g., Haney et al. 2014*b*; French-McCay 2009; Grubesic et al. 2017).

Once the appropriate search area is determined, shoreline deposition models can be applied (Ford et al. 1987; Page 1990; Wiese and Robertson 2004; Amend et al. 2020). These are needed because birds may be overlooked by searchers (detection) or removed from the shoreline before detection (persistence; Fowler and Flint 1997). Most spill response protocols assess detection and persistence probability estimates (Byrd et al. 2009). Numerous factors influence detection and persistence rates, including local environments and weather, size of search area, predators and scavengers, and species-specific variables (Fowler and Flint 1997; Varela and Zimmerman 2020). To be useful for estimating total numbers affected birds, carcasses and live oiled birds must be tallied rigorously. This requires close collaboration among wildlife response organizations (e.g., wildlife rehabilitation). Survey frequency is important and should increase when persistence is low (Ford 2006; Amend et al. 2020). Seys et al. (2002) and Newman et al. (2006) recommend using a standardized approach for beached bird surveys.

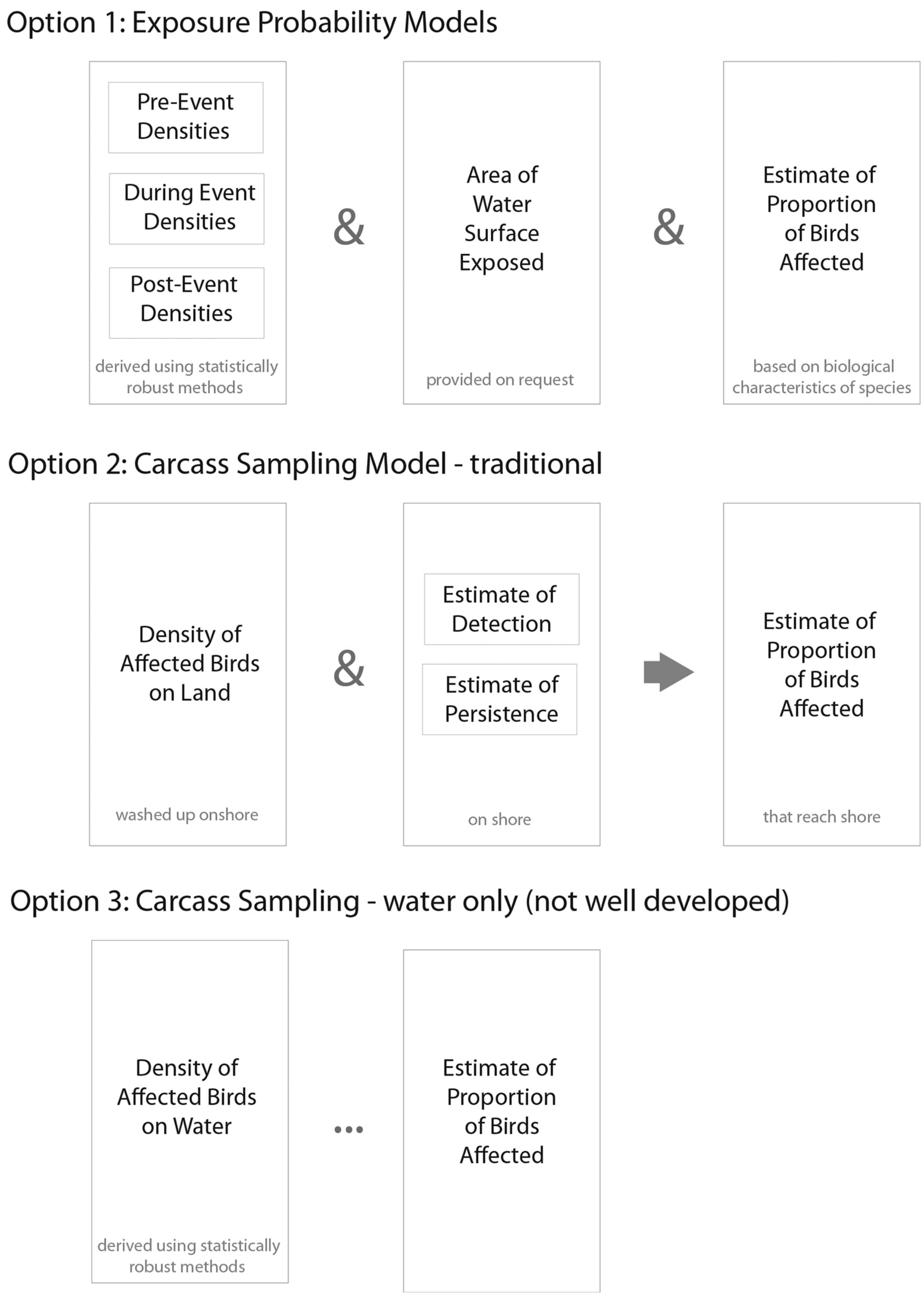
On-water processes

These are more challenging to estimate, and involve more complex logistics, such as requiring assets (e.g., vessels) that may have other pressing duties. However, on-water processes are likely to have the largest effect on the estimate of the number of birds affected, so resources need to be devoted to this aspect of the assessment to provide credible estimates.

The key datum from on-water assessment is modeling the probability that an oiled bird ends up on a beach where it could be detected (Fig. 2). The most common method is to deploy drift blocks/drifters at the spill site. The proportion of drifters deployed that are subsequently found on surveyed beaches provides an estimate of the proportion of all carcasses that could be found. Drifters must be constructed to replicate the drift dynamics of oiled bird carcasses. Wiese et al. (2001*a*) design (9 cm $\times$ 9 cm wooden drift block) appear to match the drift properties of species, such as medium-sized auks (Munilla et al. 2011), and had very similar drift trajectories as carcasses, even over several days (Fifield et al. 2017).

For large spills, drift patterns may vary across the extent of the slick and change with weather conditions (Flint and Fowler 1998), thus deployment of drifters spatially and temporally are usually needed (Wiese and Robertson 2004; Munilla et al. 2011). If few to no drifters reach shore from some positions within the spill area, Hlady and Burger (1993), Wiese and Robertson (2004),

Fig. 1. Higher level flow chart options for data collection.



and Martin et al. (2020) suggest that other approaches are also required. Unlike birds, drift blocks do not eventually sink and are not scavenged by predators. Thus, buoyancy and sinking rates of carcasses must also be assessed, so that drifters found after a carcass would have sunk can be removed from the final tally (Wiese 2003; Castege et al. 2007; Martin et al. 2020). Deployment of marked carcasses can provide more accurate estimates of deposition (Munilla et al. 2011; Himes Boor and Ford 2020). A simultaneous deployment of drifters and carcasses, especially drifters with telemetry, can be particularly useful in modelling (Martin et al. 2020). Drift models that include modules that track potentially oiled carcasses could be used in understanding the extent of shorelines that may receive oiled carcasses, and the modules could supplement drift studies to simulate what proportion of drifting carcasses potentially reach surveyed coastlines.

Birds that are exposed to oil, but not killed, provide a challenge in total impact estimation (Fig. 2). Even more challenging are birds that are affected, but end up perishing on their way to shore, or those that make their way to the beach and then are found dead by searchers. Deposition probabilities from drifters are less relevant in these instances. If larger numbers of live oiled birds are found on shorelines, or birds are suspected to perish after travelling away from the spill site, additional considerations on how to estimate those numbers are needed.

Table 1. Summary of approaches and applications in pre-response planning, during an event and post-response.

Type	Approach	Pre-response planning	During incident	Post-incident	Application	How to obtain information/data
Oil trajectory	Use oil trajectory models to identify areas most likely affected by oil spill by season	Yes	Yes	—	Oil trajectory models inform: where to focus beached bird surveys and (or) at-sea density sampling in the event of a spill	Hydrodynamic model: input includes bathymetry, bed roughness, model grid set-up, model boundary conditions; should include calibration
	Ensure trajectory data formats are accessible and compatible for exposure probability models	Yes	—	—	Use trajectory model data with exposure probability model in mock exercises	
	Calculate area (A) covered by spill event	—	Yes	Yes	Data required for exposure probability estimates	Combine hydrodynamic model with on-site spill observations
At-sea bird density estimates	Identify species most at risk	Yes	—	—	Informs: exposure probability models; the number of highly vulnerable to oil species, rare species or species of concern in an area prior to an incident	Bird counts using standardized monitoring protocols on dedicated surveys trips or vessels of opportunity
	Use spill trajectory data to inform where to survey	Yes	Yes	—	Ongoing surveys of priority species or priority habitats	
	Determine temporal and spatial scales for at-sea surveys	Yes	—	—		
	Develop incremental survey plan	Yes	—	—		
	Conduct at-sea bird surveys for on-going monitoring or using vessels of opportunity	Yes	Yes	If necessary		
	Use density data for exposure probability estimates	—	—	Yes		
On-water carcass density estimates	Determine which methods (e.g., boat-based surveys; visual aerial) may be used for on-water carcass density estimates	Yes	Yes	—	Informs: whether on-water carcasses will be sampled; which approach will be used to sample on-water carcasses	On-water carcass density surveys
	Trial main approach to test feasibility	Yes	Yes	—		
	Conduct sampling surveys during event	—	Yes	—		
Beached bird surveys	Determine whether beached bird surveys will be used in damage assessment	Yes	Yes	—	Informs: whether beached bird surveys will be part of damage assessment; background metrics (e.g., deposition rates; carcass detection) for focal beaches important for calculating damage; permits communication with industry partners about the need to use drifters	Drifter experiments using blocks or carcasses under varying seasonal conditions. Conduct carcass detection surveys

Table 1 (*concluded*).

Type	Approach	Pre-response planning	During incident	Post-incident	Application	How to obtain information/data
	Calculate detection and persistence rates of carcasses	Yes	Yes – if no pre-planning data	—		
	Experiment with drifters if possible	Yes	Yes	—		
	Beached bird surveys during event	—	Yes – ideally within 24 h	Use in mortality estimate		
	Deploy drifters	—	Yes – ideally be within 24 h	Probability of proportion of birds arriving to shore		
Species distribution models	Bird density surveys and associated physical and oceanographic data to inform Species Distribution Models (SDMs)	Yes	—		SDMs and density data can be used to inform habitat vulnerability models for spill planning	Bird density data and environmental data
Oil spill response plan	Review spill response plan. Codify key elements into the plan Incorporate damage assessment into the plan if possible Identify roles and responsibilities	Yes			Identifies assets required for damage assessment with key response partners and that damage assessment is an essential element of the response Permits opportunities for mock exercises and (or) the need to improve spill response plans	
Sublethal exposure	Conduct surveys/studies for the sublethal exposure	—	Yes	Use in mortality estimate	Provides a more complete picture of the effect of a spill beyond birds that die	Range of methods to detect sublethal oiling, including documenting behavioural changes and visible oiling, and for birds in the hand, using spectroscopy and physiological parameters to detect impairment
Development of decision support tools	Build a conceptual model to delineate data inputs for final mortality estimate For example, development of Bayesian Networks (BN) utilising empirical data and (or) expert opinion	Yes	—	Yes	Provides information to support spill response efforts including final estimate of the total number of birds affected; BN can also explicitly state the uncertainty associated with estimates	

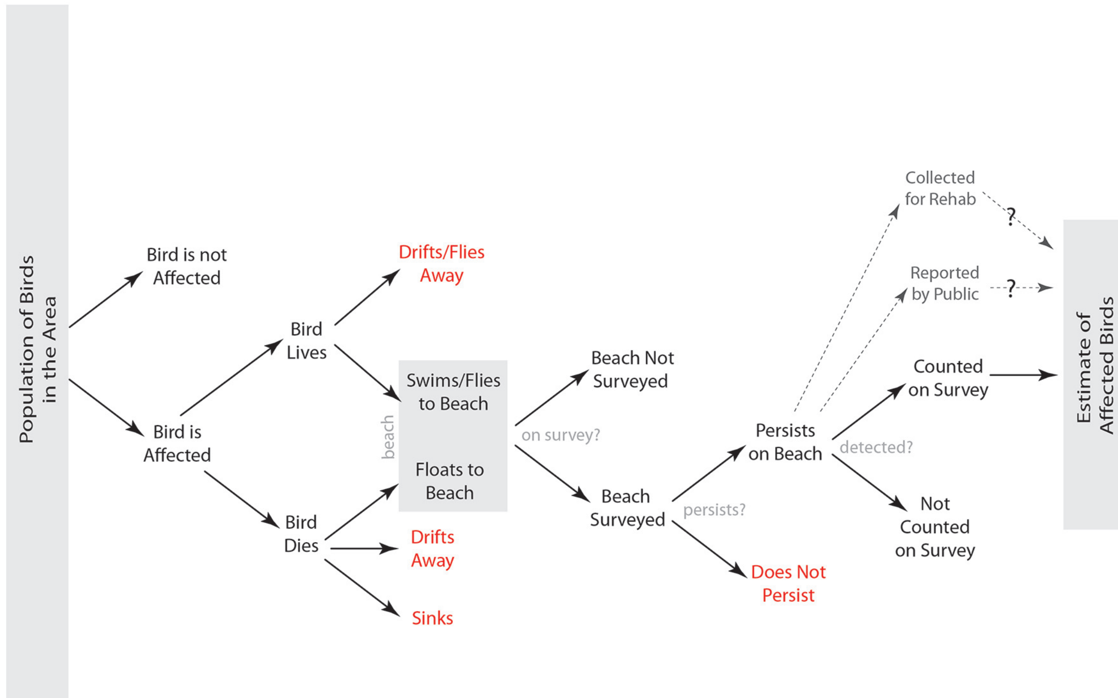
Probability exposure models

Probability exposure models permit quantification of the number of birds affected, especially where beached bird surveys are not possible (Wilhelm et al. 2007; Haney et al. 2014*a*, 2017). The models require three estimates: (1) at-sea bird densities (*D*); (2) bird mortality (*M*); and (3) the spill trajectory or area (*A*). Wilhelm et al. (2007) initially developed and applied the concept of a "risk model" to a discrete spill. Haney et al. (2014*a*) described the overall model as $N = ADM$, and binned the estimates using exposure periods to account for temporal variation from a lengthy blowout (i.e., *Deepwater Horizon*, 103 days) and spatial variation in oil coverage. Conceptually, these approaches follow French-McCay (2009), who developed a biological risk model for a range of biota, including wildlife, that is linked to oil spill fate and effects. Here, we summarize the methods employed to obtain data to develop an estimate of the number of birds killed using the probability exposure model.

At-sea bird densities (D)

D (birds/km^2) can be obtained via ship-based or aerial surveys using linear transects, and provide a measure of abundance (Camphuysen et al. 2004). Decisions on when and where to conduct surveys are addressed below (see Pre-incident planning). Ship-based and aerial surveys both require dedicated personnel trained in bird identification (Camphuysen et al. 2004). Waterbird

Fig. 2. Carcass sampling model for onshore and offshore environments.



abundance is often related to environmental data, such as primary productivity, zooplankton abundance, and hydrographic metrics (e.g., Hunt et al. 1999; Louzao et al. 2006, 2009; Gjerdrum et al. 2008; Garthe et al. 2009; Tremblay et al. 2009; Renner et al. 2013; Wong et al. 2018*a*). Wind and current data are also used in spill trajectory models (see Hou et al. 2017). For both survey platforms, additional information beyond bird presence and numbers could be gathered (Camphuysen et al. 2004). For example, in ship-based surveys, additional behaviours (e.g., foraging, species associations) can be recorded to provide greater insight into at-sea species ecology (Camphuysen and Garthe 2004; see also Fifield et al. 2009*b*). During aerial surveys, marine mammal and other wildlife observations can also be recorded (Camphuysen et al. 2004).

Ship-based surveys use fixed time periods (e.g., 5 min) and transect width (e.g., maximum distance of 300 m), and record the number and species on the water in a 90° arc on either side, depending on glare or other visibility factors (e.g., Tasker et al. 1984; Gjerdrum et al. 2012; Camphuysen et al. 2004). Camphuysen et al. (2004) reviews platform type, vessel speed, and sea-state considerations when sampling waterbird densities. Because smaller birds are less likely to be detected further from the vessel, and species' behaviour influences detection, the distance birds are observed from a vessel is recorded (e.g., Tasker et al. 1984; Buckland et al. 2001; Camphuysen and Garthe 2004; Camphuysen et al. 2004; Marques et al. 2007; Gjerdrum et al. 2008; Ronconi and Burger 2009; Bolduc and Desbiens 2011). Distance can be recorded in bins or exact distance, and the distance package in R is available to account for the decline in detectability with distance from the vessel (Miller et al. 2019). Flying birds are recorded separately; e.g., the "snapshot" method counts them every 10 min (van Franeker 1994; Spear et al. 2004; Camphuysen et al. 2004; Barbraud and Thiebot 2009; Fifield et al. 2009*a*).

There are several options for continuous data entry. For example, voice-activated recorders are used in the Eastern Canadian Seabirds at Sea program to ease observer data entry and reduce errors (Fifield et al. 2009*a*). In the USA, the Bureau of Ocean Energy Management (BOEM) uses SeaScribe (https://briwildlife.org/seascribe/; freely available on Google Play and the App Store), and the National Oceanographic and Atmospheric Administration uses SeeBird (Ballance and Force 2016; see also Jodice et al. 2019), to standardize offshore bird survey data entry and output. Also, we recommend the Seabird Information Network as a valuable and wide-ranging resource on seabirds (https://www.seabirds.net/seabird_information_network/).

Aerial surveys are less commonly used than ship-based (Carter et al. 2003; Tremblay et al. 2009), but can provide broader spatial coverage (Pettex et al. 2017). Pettex et al. (2017) used zig-zag transects to allow for unforeseen events in the Mediterranean Sea. Wong et al. (2018*b*) used Distance (Thomas et al. 2010) to design their survey in the Bay of Fundy, Canada. Traditional visual aerial surveys are flown at low enough altitudes that observers can detect and identify birds on the water perhaps to higher taxonomic levels, but not always or even usually to species. Digital aerial surveys, using ultra-high resolution cameras, are increasingly used to assess distribution and abundances of wildlife from much greater altitudes, reducing safety hazards and wildlife disturbance (Žydelis et al. 2019).

Because of seasonal-based species turnover, density estimates should be seasonally specific. Months with higher spill risk should receive more of a focus on gathering at-sea bird density estimates. Longer duration spills require resets of density estimates to account for movement in and out of a spill area, owing to seasonal migration and other factors (Haney et al. 2014*a*).

Waterbird mortality (M)

Bird species differ in risk when exposed to oil, primarily related to differences in behavior, such as foraging strategies and time spent sitting on the water (e.g., divers versus aerial foragers; Williams et al. 1995; Camphuysen and Heubeck 2001; Fifield et al. 2009*b*; Robertson et al. 2012; King et al. 2021; Fig. 3). Yet, our understanding of bird behaviour at sea is limited (Wilhelm et al. 2007; Haney et al. 2014*a*). For example, what proportion of flying birds detected in at-sea surveys would be at risk of exposure, and

Fig. 3. How bird behaviour can influence species specific mortality rates.

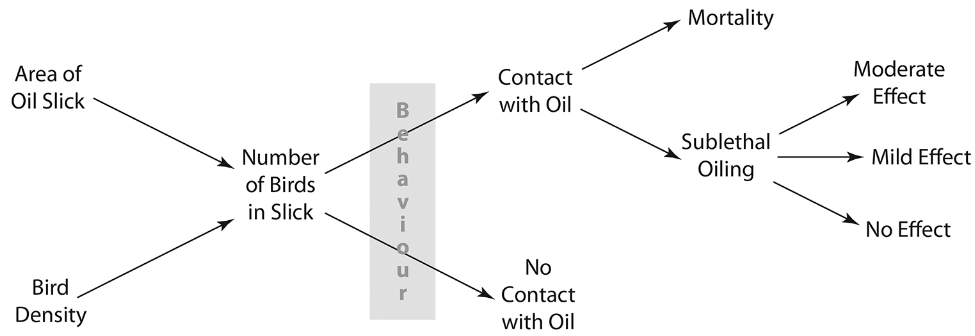


Table 2. Considerations for future research needs.

Approach	Future research needs
Probability exposure model: estimations of mortality	Proportionate mortality based on life histories (e.g., diver vs wader), behaviours (e.g., flying vs on-water) and different types of exposure to hydrocarbons (e.g., inhalation of volatile fumes or ingestion; see King et al. 2021)
	Proportionate mortality in relation to in situ exposure to different hydrocarbon types (e.g., sweet vs. sour crude)
	Proportionate mortality associated with different levels of exposure in relationship to temperature of the environment (King et al. 2021) with a particular focus on warmer climates (Haney et al. 2014*b*)
	How operations (burning in situ; skimming; dispersants) may affect mortality estimates (see Haney et al. 2014*b*)
	Separately estimating risk of exposure and risk of mortality if exposed for a range of species and environmental conditions
Beached-bird surveys: deposition rates	Where data are lacking, focus on geographical regions with seabird breeding colonies (see Tavares et al. 2016)
	Improving range estimates on wind trajectories and deposition rates (see O'Hara and Morgan 2006)
	Improving the range of in situ decomposition rates with varying water temperatures (see Haney et al. 2014*b*)
	Describing and quantifying scavenging rates by at-sea predators (see Haney et al. 2014*b*)
Beached-bird surveys: detection rates	Improving quantification of the variation of the *daily probability of carcass persistence* due to bird scavenging/ predator communities across a range of environments (Haney et al. 2014*b*)
	Studies on how beach material type (e.g., rocky vs sandy), weather conditions, beach width, presence of wrack/debris, observer experience and other factors influences carcass detection. Although site-specific detection rates are preferred, generalizations might be possible from a range of studies over varying conditions
	More metrics/input on accounting for body size in detection (i.e., "the size-group searcher efficiency parameters"; Haney et al. 2014*b*: 245)
	Improving range estimates on how wind or wave action buries or removes carcasses (O'Hara and Morgan 2006; Haney et al. 2014*b*)
Spatial tools: predictive modelling	Improving predictive models by including levels of uncertainty in model estimates (Moilanen et al. 2006)
	Inclusion of behaviour in models such as foraging activities and species associations (see Camphuysen and Garthe 2004)
	Developing fully Bayesian Network approaches that include all model parameters (Kaikkonen et al. 2021) and development of spatial BNs to improve tools available to assess number of birds affected by spills
	Begin by formally including carcass drift trajectories modules into oil spill trajectory models; afterwards, develop methods that directly link exposure models to oil spill trajectory models
	Better integration of species vulnerability and spill trajectory information with Species Distribution Models to identify spatial hotpots for spill recovery response efforts

would that differ with ocean temperature or bird assemblages (Table 2)?

In a cold-water environment, following a discrete oil spill (estimated length, 6 days), Wilhelm et al. (2007) used three different levels of possible exposure, where exposure resulted in 100% mortality: (1) all birds only detected on the water; (2) 50% of all birds detected on water and flying; and (3) all birds on water and flying, for species with high vulnerability to small quantities of oil (diving birds; murres, *Alca* spp. and dovekies *Alle alle*). The mortality estimates for murres were later improved by incorporating empirical data on bird behaviour into models (Fifield et al. 2009*a*). However, tracking individuals (e.g., Wakefield et al. 2009; Montevecchi et al. 2012*a*; see also King et al. 2021) may be problematic when applied to the probability exposure model (see Lieske et al. 2014).

In a warm water environment, with an extended period of oiling (Gulf of Mexico, *Deepwater Horizon* blowout), Haney et al. (2014*a*) estimated proportionate mortality for an assemblage of birds which were primarily aerial foragers. Given the warm water environment, they assumed that mortality due to thermal stress would be lower, compared with the values used by Wilhelm et al. (2007). French-McCay (2009) provided a range of values of combined probability of oil encounter and mortality once oiled for different wildlife species and groups; and were directly related to *M* estimates used by Haney et al. (2014*a*). Values ranged from 0.1% for terrestrial raptors to 99% of surface divers, with 35% assigned to aerial divers and shorebirds.

Future research also needs to consider how the inhalation of volatile components may be incorporated into *M* estimates (Haney et al. 2014*a*; see also King et al. 2021; Table 2). For example, after the Montara well release in the Timor Sea, off the north coast of Australia, a dead Common Noddy (*Anous stolidus*) was found with only hydrocarbons in the lungs (Gagnon and Rawson 2010).

Spill area (A)

Area can be determined by several approaches, including trajectory models, satellite imagery, trackers deployed at spill occurrences, and aerial surveillance (Özgökmen et al. 2016; see also Wilhelm et al. 2007). They may also aid in calculating hydrocarbon residence time (see Garcia-Pineda et al. 2020). Haney et al. (2014*a*) averaged a spill area over the length of time of the *Deepwater Horizon* blowout. French-McCay (2009) included spill area in an oil spill fate and effects model which links with a range of biological endpoints.

Other approaches

There may be other approaches to be developed or considered aside from carcass sampling and probability exposure models. The latter was first applied because of a paucity of data during an offshore spill (Wilhelm et al. 2007). We encourage continued research on how best to quantify waterbird mortality from spill incidents particularly as technologies improve.

On-water direct estimation of affected birds

Fifield et al. (2017) experimentally assessed whether numbers of dead birds (carcasses), could be directly estimated from vessel-based surveys using Distance methods. They developed a protocol based on the location and spread of deposited carcasses that were tracked through telemetry, so the location of most carcasses was known. They found that they could detect carcasses on the sea surface under reasonable survey conditions, and could estimate carcass densities that reflected the number of carcasses deployed better when the birds were large (gulls) but that estimates for smaller birds (dovekies) were somewhat low. Further experiments like these would be beneficial and may provide another means of estimating the number of affected birds by directly surveying them on the sea surface.

Pre-incident planning (with a focus on logistics/planning)

Pre-incident planning and data collection is *critical*, especially in areas with industrial activities that involve large volumes of hydrocarbons, and particularly in operationally challenging environments that may preclude data collection during the response phase (Fifield et al. 2009*a*, 2016). Even in low-risk areas, aquatic bird data collection is important, and in the case of abundance and density information, can also inform environmental assessments and coastal and marine spatial planning (McGowan et al. 2013). Almost all elements of a damage assessment previously discussed can be considered in the pre-incident planning phase.

Trajectory models

Information on the pattern and likelihood of where hydrocarbons drift (Price et al. 2006) should cover different weather conditions. If data are lacking, simulations or drifter deployment is needed (see Price et al. 2006). Trajectory data are typically presented in environmental assessments or scenario analysis documents (Hou et al. 2017; Price et al. 2006) and can predict areas of high risk (Barker et al. 2020) and inform beached-bird surveys and at-sea bird density sampling. The pre-incident phase is a time when trajectory models can be validated for use in exposure probability models. If the trajectory models indicate minimal probability of oil reaching the shoreline, then onshore carcass sampling methods are not likely to be useful to estimate the number of affected birds.

Tracking data

Tracking data can be used to identify priority areas (Camphuysen et al. 2012; Montevecchi et al. 2012*a*) and should be considered in risk assessment responses. It may also inform the selection of survey areas for density estimates, or be used along with surveys to identify important bird use areas (Louzao et al. 2009). However, variation in spatial scale must be considered when pairing tracking data with broad scale survey density estimates (see Lieske et al. 2014).

Choosing density (*D*) estimate locations

Prioritizing species for monitoring can occur in the pre-incident phase (e.g., Skov et al. 2021); with a focus on those highly vulnerable to oil (i.e., oil vulnerability index; see review in Camphuysen 2007), rare species, species of conservation concern, and those that are challenging to monitor (Camphuysen et al. 2007). Romero et al. (2018) provided a simple sensitivity index for poorly known species; and Reich et al. (2013) described a habitat vulnerability model approach for oil spill planning. Trajectory models can inform priority survey locations, and an incremental survey plan, starting with transects in high-risk areas, can be rolled out. With resources and time, monitoring beyond high-risk areas provide data useful for species distribution models (see Appendix A), and for risk assessment during an incident.

Once it is determined when, where, and how to survey priority species (Camphuysen et al. 2007), then survey as much as resources will allow. Supply vessels to oil operations (e.g., Burke et al. 2012; Wiese et al. 2001*b*; Kuletz et al. 2014), ferries, or research cruises, provide cost-effective platforms for at-sea bird density estimation. Camphuysen et al. (2004) provided details on suitability of different types of vessels for ship-based surveys. If spill trajectories have a coastal component, transects should include the coast because use of these habitats is particularly dynamic and reflects a different assemblage of bird species.

Carcass sampling

If onshore recovery of carcasses is possible, information can be collected in the pre-or post-incident phases (Amend et al. 2020). This includes data on detection and persistence rates of carcasses on beaches (Varela and Zimmerman 2020; Zimmerman et al. 2020), and the probability of carcasses reaching the shore (buoyancy, simulation or trajectory modeling; see Camphuysen and Heubeck 2001 for review; Martin et al. 2020). Many of these probabilities are locally specific, and some vary seasonally, so should be generated for each area at risk at relevant times of year (Piatt and Ford 1996; O'Hara and Morgan 2006; Sackmann and Becker 2015). On-the-water carcass density estimation methods (digital aerial, visual aerial, and boat-based surveys) need to be trialed locally. The feasibility of these methods can be assessed by determining if enough detections can be obtained to generate meaningful estimates (Fifield et al. 2017).

Drifters can also be deployed to measure onshore deposition rates in different seasons and weather conditions, and these experiments may assist in understanding local currents and the specific factors that influence deposition (e.g., Hlady and Burger 1993; Martin et al. 2020). Drifters may be deployed differently depending on whether point source (e.g., platform) versus a broader risk (e.g., tanker traffic) dominates a region; if the risk is too broad, drifters may not be appropriate. But, if drifters will be used, they must be prepared to deploy *immediately* after an incident occurs.

Background oiling rates could confound the estimate of affected birds of a specific incident. Systematic beached bird surveys are commonly used to measure chronic oiling rates (Henkel et al. 2014; Tavares et al. 2016). Local communities could be mobilized to implement regular beached bird surveys on target beaches (McKinley et al. 2017).

Oil spill response plan (OSRP)

Most constituencies with hydrocarbon activities have an OSRP, written either by government agencies (for mystery or tanker spills) or industry (e.g., CAPP 2009; Camphuysen et al. 2007). However, damage assessment is not necessarily covered just because an OSRP is in place. In general, these plans fail to include the steps required to estimate the number of birds affected. Key elements, such as the commitment of assets and personnel to collect data for a damage assessment during a response, should be codified in OSRPs. In situations where the pre-incident beach carcass studies indicate very low deposition and (or) detection rates, onshore damage assessment may not be possible. Damage assessment will therefore have to be done entirely with on-water components, and assets (e.g., boats) must be made available to undertake the assessment. When possible, permitting agencies should both review and approve any damage assessment requirements incorporated into OSRPs.

Damage assessment should be embedded into a wildlife response unit. Ideally, personnel undertaking a damage assessment and a risk assessment should be separate people, particularly if the incident is a lengthy one (e.g., a blowout that will continue for an unknown length of time), and both individuals/teams should be included in incident command decisions. One person could fulfill both roles for small spills, but any significant spill requires separate personnel; the damage assessment person/team has the long-term responsibility of obtaining a defensible estimate of the number of birds affected, while the risk assessor(s) would minimize the incident's impact on wildlife in real time. These individuals should be specifically dedicated to the tasks at hand, and retained throughout the damage assessment exercise.

Mock exercises, either on paper or on site, provide excellent opportunities to consider damage assessment. A paper exercise could identify obstacles or constraints in generating required data, such as available assets, site access, inappropriate data formats or applicable correction factors. On site mock exercises may permit an opportunity to collect useful data, such as deploying drifters. Finally, mock exercises allow risk and damage assessors to practice coordination during a response (see Chilvers et al. 2021).

Incident response

Depending on the type of spill, the chemical makeup of the substance spilled, and the receiving environment, responses vary in length. Here, we divide this phase into immediate, 24–48 h, and ongoing [until the spill dissipates and (or) is cleaned up].

Immediate

In the first 24 h of an incident, damage assessment is typically not a priority. However, if beached bird surveys and drifters have been identified as useful damage assessment inputs in the pre-incident phase, then drifters should be deployed from the source of the spill immediately. Available regionally specific spill trajectory models inform the risk assessor on where and which birds are at risk and suggest mitigation actions, such as deterrence. If the spill is close to shore, and oiled birds are detected on beaches, then beached bird surveys should be implemented immediately. The urgency of these surveys will depend on carcass persistence rates obtained during the pre-incident phase.

24–48 h

The risk to wildlife may be better understood 1 or 2 days into the incident and risk assessment personnel will have implemented wildlife protection actions. Assets may be freed up for damage assessment at this point. The needs and actions for risk and damage assessment may converge, both may benefit from bird density data from transects through and near a spill. Damage assessment personnel should begin receiving information from the wildlife response unit at this point. There are several considerations at this stage:

1. Flexibility. Pre-incident planning should have provided feasibility assessments for damage assessment. If it is clear the incident is large and lengthy, prioritization among metrics may be needed. For example, if there are many people from a range of agencies on beaches collecting dead and live birds, it may be hard to maintain quality control on the beached bird survey data, and a focus on other approaches to assess damage might be more productive.
2. Quality control. Data may come from the wildlife rehabilitation team, the wildlife response unit, and the public (Fig. 2). Wildlife rehabilitation teams will be both collecting live birds and recording data on birds that are cleaned. It is critical that the damage assessor obtain these data, thus, coordination with the rehabilitation team is paramount. We recommend that the damage assessor copy rehabilitation data daily; redundancy at this juncture is good, and data should be examined in depth to ensure that the information required is being recorded.
3. Be aware of the possibility of double-counting carcasses. Because reports can come in from a variety of sources, be cautious about how birds are tallied. For example, if a member of the public calls in a dead bird and that bird is also retrieved via a beached bird survey, it has the possibility of being counted twice.
4. Ensure auxiliary data on carcasses are collected. For example, natural resource managers could find information on the sex, age (juvenile vs. adult), and whether birds are banded very useful. Camphuysen et al. (2007) provides an excellent guide on the types of data and tissues that should be collected from carcasses.

Ongoing

The issues that may arise will depend on whether an incident continues (e.g., blowout) or is a discrete spill.

Maintaining continuity in quality data collection

Continuity in data collection is essential for scientifically defensible assessments. Oil spills are stressful for all responders (Kwok et al. 2017), and the longer the incident lasts, the greater the importance of providing support to responders and assessors to maintain the quality of information collected. Any additional personnel must understand the data needs for damage assessment, understand the ecosystem and existing data, and know the priorities identified and decisions made during the response, all prior to their deployment. There is minimal time for documenting this information during an incident response, which stresses the importance of a pre-incident planning report for reference and guidance.

Species turn-over

Bird species turn-over is more likely the longer the spill. As migratory birds enter or exit seasonally, sublethally affected individuals could depart prior to being sampled, or new birds could enter the system and become exposed to lingering or new oil (e.g., Franci et al. 2014).

Rare species challenges

Good survey data prior to an incident informs species distribution models for common species, and permits the damage assessor to devote more resources to data collection on rare species, or

Table 3. Examples of studies on sublethal or long-term effects of hydrocarbon spills on seabirds.

Species	Key methods	Main variable(s)	Key effect(s)	Other	Spill, location	Reference
European Shag (*Phalacrocorax aristotelis*)	Before – after – control – impact design	Population size; reproductive success	One-year post spill, population size and reproductive success at breeding colonies lower in oiled areas		*Prestige*, Galicia, Spain	Velando et al. (2005)
European Shag	Before – after – control – impact design	Annual reproductive success	A reduction of reproductive success by 45% through a reduction in the number of chicks fledged per pair in oiled sites compared to non-oiled sites for 10 years	[Residual oil observed for 9 years]	*Prestige*, Spain	Barros et al. (2014) [Bernabeu 2013]
Common Guillemots, (*Uria aalge*)	Capture – mark – recapture at breeding colony	Population size; population growth; over-winter adult survival; environmental variables	Adult over-winter mortality from oil spills was offset by recruitment into the breeding population ("compensatory recruitment")		Four spills: *Aegean* – Spain, *Sea Empress* – Wales, *Erika* – France, *Prestige* –Spain, *Tricolor* – English Channel Colony - Skomer Island, Wales	Votier et al. (2008) (See also Votier et al. 2005)
Yellow legged Gull (*Larus michahellis*)	Before – after – control – impact design	Adult body condition; chick size; various markers in blood	17 months post spill: no difference in adult body condition between oiled and non-oiled sites; chicks had elevated PAH through diet, but no resulting difference in body condition between oiled and non-oiled sites		*Prestige*, Spain	Alonso-Alvarez et al. (2007)
Black-legged Kittiwake (*Rissa tridactyla*)	Before-after comparison; Control colony used for comparison in molecular marker (haematological)	Breeding parameters; foraging behaviour; adult attendance at nest site; site fidelity; survivorship	No before-after differences in breeding parameters, foraging behaviour or attendance However, low post-spill return rates to breeding site and birds that did return had significantly different haematological markers compared to control	Main forage fish not impacted by spill; birds may have been exposed to oil via nest material	*Braer*, South Shetland Island, Scotland	Walton et al. (1997)
South Polar Skua (*Catharacta maccormicki*)	Before and during comparisons	Reproductive metrics	Indirect effects from spill suggested to be the cause of reproductive failure (parental attendance modified resulting in intraspecific attacks on unattended chicks)	Brief description of primary, secondary, and tertiary effects from oil spills	*Bahia Paraiso*, Antarctica (near Palmer Station)	Eppley and Rubega (1990)

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Table 3 (*continued*).

Species	Key methods	Main variable(s)	Key effect(s)	Other	Spill, location	Reference
Black Oystercatcher (*Haematopus bachmani*)	Compared birds breeding on oiled to non-oiled shoreline; study complicated by extended disturbance by cleanup efforts	Number of breeding pairs; nest success; clutch size	Disturbance from cleanup operations lowered nest success at oiled site in 1990 (one-year post spill) Two-year post spill comparison (with no disturbance via cleanup): increase in breeding pairs at oiled site (indicative of immigration into area); no difference in nest success or clutch size		*Exxon Valdez*, Valdez, Alaska	Andres (1997)
Multiple species (34)	Oil treated as gradient, bays in spill area were selected along this gradient (oiled to non-oiled); oil index for each bay was calculated (described as "single-time gradient analysis"; Wiens and Parker 1995); physical features quantified	Habitat use (abundance of 34 species) for the year of the spill and two years post-spill	Twelve out of 34 species showed a negative effect; of those, 50% had recovered after two post-spill years		*Exxon Valdez*, Alaska	Day et al. (1997) (see also Murphy et al. 1997)
Multiple species (12 taxa)	Before–after–control–impact; paired sites; oiling index used to categorize areas; summer transects	Abundance and distribution	Changes in abundance observed from 1 to 3 years post spill: 7 taxa – no changes; 2 taxa – positive changes; 3 taxa – negative changes		*Exxon Valdez*, Alaska	Murphy et al. (1997)
Multiple species (14 taxa)	Before – after – control – impact	Bird densities (summer)	Nine taxa – negative impact, impact for some groups evident nine years post-spill (mostly for diving birds); Three taxa – no impact; Two taxa – positive impact	Habitat measured (shoreline type), but not incorporated into analyses (see Wiens et al. 2004); useful discussion on the issue of scale	*Exxon Valdez*, Alaska	Irons et al. (2000)
Black Oystercatcher	Oiled vs non-oiled sites nine years post spill	Various reproductive parameters (e.g., phenology, clutch size, chick growth, nest success)	No main effects; authors conclude species recovered		*Exxon Valdez*, Alaska	Murphy and Mabee (2000)
Multiple species	Oiled areas only; oiled areas compared to non-oiled areas; transect areas divided into different habitats (coastal,	Population trends, for nine years post spill (winter and summer surveys)	Winter taxa (14) Summer taxa (15) In oiled areas in total: five populations increased; eight decreasing trends; 16 no trend (of recovery)		*Exxon Valdez*, Alaska	Lance et al. (2001)

Table 3 (*concluded*).

Species	Key methods	Main variable(s)	Key effect(s)	Other	Spill, location	Reference
	nearshore, offshore) and stratified sampling applied		nearshore and diving taxa more affected			
Pigeon Guillemot (*Cepphus columba*)	Before – after comparison; oiled – unoiled site comparison	Adult body condition; prey availability various chick metrics (diet, growth); nest productivity	Adult body condition was lower post spill, but no difference was observed comparing non-oiled with oiled sites Adults likely re-exposed to residual oil via foraging Changes in forage fish in oiled sites likely explains differences in productivity for pre- and post-spill comparisons	Recovery not fully evident 10 years post spill	*Exxon Valdez*, Alaska	Golet et al. 2002 (see also Esler et al. 2018)
Harlequin Duck (*Histrionicus histrionicus*)	Oiled vs no-oiled areas, while factoring in habitat features	Population density with habitat characteristics; female survivorship; abundance	Oiled areas had lower densities (1995–1997); oiled areas had lower female survivorship (1995–1998); population in oiled areas not recovered 6–9 years post-spill	Residual oil resulted in prolonged re-exposure which may have population level effects; exposure quantified through molecular markers	*Exxon Valdez*, Alaska (1989)	Esler et al. (2002)
25 species (includes some terrestrial species)	Oiling treated as gradient (an oiling index) for within year analyses; oiling treated as categorical variable between yearsBiotic and abiotic habitat variables where available incorporated into the analyses	Compared oiled with non-oiled areas; 12 years post-spill for changes in habitat use and habitat occupancy	12 species – no impacts observed; ten species – negative impacts (up to seven years post spill); three species – positive impacts	Useful discussion on defining recovery	*Exxon Valdez*, Alaska	Wiens et al. (2004) (see also Wiens et al. 2001)
Harlequin Duck	Radio-tracked individuals in oiled vs no-oiled areas; molecular markers for exposure	Female survivorship	Oiled and un-oiled areas had similar female survivorship 11–14 years post spill	Molecular evidence that exposure to hydrocarbons was still occurring, but not resulting in population-level impact	*Exxon Valdez*, Alaska	Esler and Iverson (2010) (see also Iverson and Esler 2010; Wiens et al. 2004; Wiens 2007)
Multiple (eight species: waders, gulls, skimmer)	Examined multiple colonies and used a categorial designation of oiling (none, little, medium/ heavy) of nesting habitat for comparison	Breeding phenology; number of species at each colony; reproductive success and related metrics at 30 different colonies	One-year post-spill no differences were observed for breeding phenology or reproductive metrics	Individuals not marked because attempts were made to minimize investigator disturbance to nesting birds	*Deepwater Horizon* blowout, Louisiana	Burger (2018)

those of conservation concern; particularly those with a high vulnerability to oil.

Detection of lightly oiled birds

As oil disperses or is contained, oiled birds may be more difficult to detect. In cold water environments, species highly vulnerable to oil can perish from hypothermia, even from minor exposure to oil (Jenssen et al. 1985; Jenssen 1994; Wiese and Ryan 2003; O'Hara and Morandin 2010; Morandin and O'Hara 2016), and should be considered in mortality estimates and modeling efforts (see section on *Post-incident phase*). However, lightly oiled birds in warmer waters should be considered under sublethal impacts, although studies on the effects of light oil and hyperthermia in a range of environments are lacking (Table 2).

The methods used to detect lightly oiled migratory birds include capture or visual assessment. For both categories, the damage assessor will need to consider where birds are going, and where they can be accessed. Captured birds can be assessed through a variety of blood markers that indicate exposure to oil (e.g., Heinz bodies; see Leighton et al. 1985; Fallon et al. 2013). These approaches are particularly useful in sampling migratory species that leave the oiled area. For example, Northern Gannets (*Morus bassanus*) breeding in Quebec, and migratory Common Loons (*Gavia immer*) in the Gulf of Mexico were both sampled for exposure to oil after the *Deepwater Horizon* blowout (Franci et al. 2014; Paruk et al. 2014). Exposure markers can be used in comparing non-oiled to oiled sites (Alonso-Alvarez et al. 2007). Such studies (e.g., Franci et al. 2014) should be paired with others (e.g., reproductive success, survivorship) because significant gaps remain in understanding how exposure affects individuals and populations (Velando et al. 2005; Iverson and Esler 2010; Fallon et al. 2018; King et al. 2021). The ecotoxicology literature on oil and birds is extensive and will not be reviewed here, instead we refer readers to a few avian toxicology reviews (Briggs et al. 1996; Albers 2006; Bursian et al. 2017; King et al. 2021).

Captured wildlife can be sampled for hydrocarbon exposure using external swabbing. Fritcher et al. (2002) suggested the use of a rapid immunoassay to detect polycyclic aromatic hydrocarbons on captive birds. Haney et al. (2017) noted the application of UV fluorescence to detect trace oiling of in-hand birds during the *Deepwater Horizon*. Paruk et al. (2019) used digital photographs to categorize the degree of oiling for three species (Common Loons, American White Pelicans [*Pelecanus erythrorhynchos*], and Northern Gannets) post *Deepwater Horizon* and extrapolated impacts to populations.

Sublethal

Sublethal effects bridge Ongoing and Post-Incident Phases because birds can experience effects when incident responses are over (see Peterson et al. 2003; Esler et al. 2018). Sublethal effects following the post-acute phase of spills should be included in a damage assessment.

Funds for bird damage assessment cease when an incident is considered over (e.g., spill dispersed). We urge people to not rush to a settlement, if one is offered, or include a re-open clause that would permit seeking further funds for damages not assessed at the time of settlement (see Rice 2009). Time should be taken to consider sublethal effects despite natural environmental variation that complicate determining longer-term effects (Wiens et al. 2004). If resources for sublethal studies are scarce, we suggest forming partnerships with researchers, or in the case of migratory species, involve other nations that host the species during their annual cycle (e.g., Montevecchi et al. 2012*b*).

Sublethal assessments increase the accuracy of impacts

They also inform the management of harvested populations or species at risk; and assist in setting precedents for use in future damage assessments, if necessary. Here, the focus is on damage assessment and we do not review the topic of population recovery (see Skalski et al. 2001; Lance et al. 2001; Wiens et al. 2004; Harwell et al. 2013), although the two concepts can overlap, depending on statistical approaches utilized (see Lance et al. 2001). We reiterate that robust statistical approaches in study design are of utmost importance for a scientifically defensible damage assessment.

Quantifying sublethal impacts on waterbird populations remains a challenge as multiple pathways of impact (e.g., direct vs indirect; see Henkel et al. 2012; Wiens et al. 2013; Saaristo et al. 2018), hydrocarbon persistence re-exposing wildlife, and species life- and natural-histories, all influence impacts and require post-acute phase studies (see Piatt et al. 1991; Burger and Fry 1993; Peterson and Holland-Bartels 2002; Peterson et al. 2003; Albers 2006; Franci et al. 2014; Heubeck et al. 2003; Wiens et al. 2013; Esler et al. 2018). Two incidents are particularly informative in understanding sublethal effects in waterbirds: the *Exxon Valdez* tanker spill in Alaska (1989; see Peterson et al. 2003; Wiens et al. 2013; Esler et al. 2018 for reviews; Barron et al. 2020); and the *Prestige* tanker spill in Spain (2002; Barros et al. 2014). All spills have site-specific habitat characteristics (e.g., water temperature, shoreline complexity), variation in pre-incident data on bird populations, and variation in responses (e.g., use of dispersants; Michel et al. 2013) that require consideration.

Here, we summarize the main approaches and findings from field-based studies on wild waterbird populations that examined sublethal effects of exposure to hydrocarbons. We do not include studies that: (1) undertook experimental dosing (e.g., Ainley et al. 1981; Butler et al. 1988; Prichard et al. 1997; Dorr et al. 2019); (2) focused only on expression of molecular markers associated with hydrocarbon exposure (e.g., Trust et al. 2000; Pérez et al. 2008, 2010; Franci et al. 2014; Paruk et al. 2014; Nisbet et al. 2015; Fallon et al. 2018); or (3) examined rehabilitated individuals released back into the wild (e.g., Fowler et al. 1995; Chilvers et al. 2015; Jaques et al. 2019).

Before-after-control-impact approaches are common when pre-incident data are available; where pre-incident data did not exist, oiled to non-oiled areas were compared (Table 3). The variables assessed and their potential effects are listed in Table 3. The length of impact varies considerably among species but can extend to 10 years following exposure (Golet et al. 2002; Esler et al. 2002; Table 3). Barros et al. (2014) found a decrease in reproductive success in European Shags (*Phalacrocorax aristotelis*) through a reduction or change in prey exposed to oil and from direct exposure to oil for 10 years following the *Prestige* tanker spill. In the *Exxon Valdez* spill, nearshore species were more exposed to persisting oil, and took longer to recover compared to pelagic species (Esler et al. 2018). For example, Pigeon Guillemots (*Cepphus columba*) and Harlequin Ducks (*Histrionicus histrionicus*) showed signs of impact 10 years after the spill through exposure to residual oil (Golet et al. 2002; Esler et al. 2002; Table 3). Species consuming benthic invertebrates were more impacted by hydrocarbons through sediment disturbance and (or) through the accumulation of hydrocarbons from filter-feeding prey (Esler et al. 2018).

Post-incident

After an incident, experiments or field work started during the incident (e.g., carcass persistence) should be completed or undertaken if they are not yet done. Data collation can also begin. In the post-incident phase, the decision of what kind of analyses can be done to estimate the number of affected birds is made.

For relatively acute and short-lived incidents, opportunities remain to collect bird density data that reflect conditions during and just after incident resolution. Post-incident data on bird densities may have considerable value in assessing the population level effect of the incident (see above), but this method should not be the sole approach as many factors influence bird densities, especially for mobile and highly migratory species. The examples described above with Harlequin Ducks and Pigeon Guillemots in the aftermath of the *Exxon Valdez* spill are ideal scenarios, as both species are remarkably site-faithful to their non-breeding areas (Esler et al. 2018).

Data collation, curation, and maintenance occur in the post-incident phase. Data may also be considered legal evidence and need very careful curation and possibly "chain of custody" documentation. Analysis is the main task during the post-incident phase, and may include determining which approach to use with inadequate pre-incident planning.

Once model(s) are chosen, which may be a set of candidate models, the work of coding them begins. The complexity of the model and the data available will dictate, to some degree, the computational processes used. The use of coding or scripting language used to construct the models has a number of advantages, the main one being that the entire analytical pipeline is transparent and reproducible (Lewis et al. 2018). Estimates of the total number of birds affected may be challenged from a variety of quarters, including through legal proceedings, and transparent and reproducible code allows full disclosure. We recommend use of open-source programming languages to increase accessibility of the pipeline, which also facilitates collaboration among researchers (Mislan et al. 2016). R (R Core Team 2021) is a popular programming language in the ecological sciences community, with other languages, such as Python, also being used (Mislan et al. 2016). The level of interoperability among open-source programming languages is growing, so the choice of language should not constrain future comparative analyses (Ushey et al. 2021).

The resources required for modeling and analysis should not be underestimated. At a bare minimum, for a simple model with limited data and parameters, weeks of dedicated time are needed. Sophisticated modeling efforts will likely take months because model testing, data quality assurance and quality control, debugging, and troubleshooting are notoriously slow, but essential for ensuring robust results (Brown et al. 2018).

The exact statistical methods used to estimate the number of birds affected is a choice of the analyst, but we recommend that modern statistical methods be employed. This can be challenging without access to statistical expertise; the statistical approaches available today are more powerful, but also more complex, than those taught to undergraduates. In general, and in theory, obtaining a point estimate of the number of birds affected can be relatively straight forward. The real work comes when generating metrics of statistical confidence in the result(s). Bayesian approaches (Appendix B) are a natural fit for estimation (e.g., for assessing the birds affected by an oil spill), and are amenable to a range of inputs beyond raw data. Further, powerful approaches to construct statistical models of bird distribution, such as species distribution models (Appendix A), are increasingly used. Their output may provide much better input (or the only suitable input) to the exposure model than raw bird density data. The level of expertise required to combine spatial distribution modeling into a Bayesian assessment of number of birds affected is not trivial. The addition of an oil spill trajectory model increases the complexity further.

Small teams function more efficiently than individuals working in isolation (Shade and Teal 2015). Someone familiar with the overall goal of assessment, and knowledge of the ecosystem and birds affected, should provide a reality check on the modeling efforts. All complex models require decisions on how to approach a problem (e.g., selecting an appropriate distribution for a parameter) and a statistical perspective (e.g., computationally efficient) versus a biologically informed perspective (e.g., more birds should be in left part of that distribution) may result in a different solution that may affect model output.

Once model-based estimates are produced, peer-review and other opportunities for feedback should occur, as is common for fishery stock assessments (Brown et al. 2020). The opportunity for review may be limited where legal proceedings are underway, but, when possible, it should be encouraged. Interactive visualization tools (Chang et al. 2018) can increase the quality of feedback from review. These tools allow reviewers to explore key model inputs and outputs without requiring the resources for complete re-runs of models (Regular et al. 2020).

Discussion

In this review, we described the various approaches used to estimate the number of birds affected in a hydrocarbon incident. We made recommendations on which data should be collected before, during, and after the incident.

A key feature in these recommendations is that most of the data needed (trajectory models, density estimates, persistence rates from beached bird surveys, and species turn-over) are all regionally specific, hence our call to action for pre-incident planning. However, the methods used to gather these data can be applied in most marine or freshwater systems. Some species-specific data may be transferable across systems. For example, behavioural responses to spills may be used to estimate the vulnerability of species across regions: on the water, diving species have higher oiling rates compared to primarily aerial species (e.g., King and Sanger 1979; Speich et al. 1991; Williams et al. 1995; Camphuysen 1998, 2007).

We identified research gaps that require attention to increase the accuracy of estimates of the number birds affected (Table 2). While physiological measurements of exposure are improving (King et al. 2021), there are few data linking exposure with population level effects. Thus, sublethal effects are rarely included in damage assessments. Methodological developments are needed to identify birds with light oiling, and then to ascertain its possible impacts, especially in warm water environments.

More estimates on waterbird mortality to inform probability exposure models are needed. Especially data on the proportion of flying birds detected in at-sea surveys that should be counted in risk assessments for exposure (Wilhelm et al. 2007; Haney et al. 2014*a*). Bird mortality (*M*) as defined by Haney et al. (2014*a*; or P_w in French-McCay 2009) is a combined probability of risk of encountering oil, and the risk of mortality on exposure; uncoupling this composite into its two underlying probabilities will improve future assessments and help clarify the underlying assumptions used in the modeling. Quantifying these two probabilities in wild pelagic birds is very challenging, but telemetry-based behavior studies (Robertson et al. 2012) and formalized expert opinion solicitation (Lieske et al. 2019) are two possible means of obtaining defensible estimates. Data are required for a wide range of regions with differing ocean temperature and bird assemblages.

Conclusions

We conclude by summarizing some of the key take away messages of this review.

Pre-incident planning is critical for efficient collection of pre-spill data, and in formulating response plans. The end goal is a statistically robust number of affected birds, although pre-incident data has other uses (e.g., establishment of marine reserves). We encourage jurisdictions to obtain pre-incident density data and generate spill trajectory models to determine which approaches should be used. When onshore metrics are used, drift blocks should be readily available should an incident occur.

Even if no pre-incident data are obtained, various agencies should coordinate, formulate a response plan, and undertake mock exercises. The tension between risk assessment and damage assessment data should be recognized, but the key goal for the latter is statistically quantifiable estimates. In regions where multiple spill risks exist (e.g., shipping and oil production platforms), discussions among different agencies may be more complicated, but coordination, cooperation, and flexibility are paramount to ensure full cost accounting of the specific sectors with the eventual end goal of fully understanding the cumulative effects.

If an incident occurs before quality data are obtained, we have identified approaches that can be used during or after an incident. In some cases, data from other regions may be applied to regions where data are lacking. However, even with robust pre-incident data, considerable work is required during and post incident. No matter how good the data are, the confidence intervals will be large, and ensuring approaches and data collection are transparent and systematically implemented is important. Finally, we encourage the community to publish their results, even failures.

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Appendix A. SDMs

Species distribution models (SDMs) are widely used in conservation and biodiversity studies to predict distributions extrapolated through space and time (Elith and Leathwick 2009). SDMs predict a species' probability of occurrence, based on data on species distributions and relevant environmental predictors, and offer a recognized correlative method of predicting species' probability of occurrence (Guisan and Thuiller 2005; Elith et al. 2006). Species observational data inputs to model a species' ecological niche are based on the assumption that the distribution of known encounters reflects the species' environmental preferences. Well-designed survey data can provide useful insight into current species range, and have strong predictive capability. But they may not perform well with deficient input data (e.g., limited numbers of sightings for offshore or rare species; Ferrer-Sánchez and Rodríguez-Estrella 2016), or when they are used to extrapolate beyond the modelled environmental range (Elith and Leathwick 2009; Guisan and Zimmermann 2000).

SDMs are increasingly used in studies of waterbirds (Melo-Merino et al. 2020; Myers et al. 2000), and commonly used to inform marine protected area planning, detection of areas important for migratory species, and for risk assessment (Fauchald et al. 2002; Fifield et al. 2017). A simple risk assessment procedure typically combines spatial distribution data with indices of species-specific vulnerability (Williams et al. 1995). While the spatial distribution of pelagic birds is generally highly patchy (Schneider and Duffy 1985), they frequently forage in areas with specific oceanographic features, which are more spatially and temporally predictable areas (Hunt et al. 1998; Russell et al. 1999). This clustering of birds in specific marine habitats, for example, with distinctive oceanographic features, underpins the potential strength of correlative analysis used in SDMs. With good spatial and temporal data sets, SDMs can predict areas of highest bird density. This can then be combined with species vulnerability and spill trajectory information. Hotspots of bird density that overlap with the largest spill areas, volumes, or trajectories, represent areas to focus spill recovery response efforts. SDMs have also been used retrospectively to assess impacts of historical spill events from a recovery perspective (Le Rest et al. 2016).

Varying levels of uncertainty in predictions of the occurrence layers can be modelled, which can affect the interpretation of bird hotspots and their efficacy for informing spill response efforts. Inclusion of uncertainty in estimates, and (or) accounting for data availability, is rarely considered, however, and represents an area for model improvement (Moilanen et al. 2006; Rowden et al. 2019).

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Appendix B. Bayesian

For individuals with limited or traditional statistical training, Bayesian approaches can be daunting (Kurt 2019; Donovan and Mickey 2019). Further, how Bayesian thinking can help assess the number of animals affected by an oil spill may not be readily apparent. However, these approaches offer an analytical framework that can directly estimate, with appropriate credibility intervals, the numbers of animals affected. Bayesian statistics premised on Bayes Theorem, boils down to the notion that our "belief" or inference is based on what we previously believed, updated by additional observations. Conversely, traditional statistics, is based on assessing the results of experiments, and less well suited for calculating estimates derived from equations and parameters. Combining data with summary statistics extracted from a variety of sources is something not well handled by traditional statistics.

The data and estimates used in a damage assessment are almost always going to range widely in quantity, quality, and potential relevance to the incident at hand. Consider the following pieces of information available for a damage assessment: (1) two published estimates of carcass persistence on similar beaches in the general area (raw data not available, only mean ± SE); (2) a solid data set of persistence rates collected locally before the incident; (3) another limited dataset collected on persistence rates during the spill; and (4) an expert opinion that persistence rates seemed unusually low during the incident. All of these sources are potentially informative, but there is no obvious way to use these sources in a traditional statistical analysis.

In contrast, Bayesian statistics can include all the diverse data, previous estimates, and even expert opinion (Kuhnert et al. 2010; Fisher et al. 2012) to obtain a final estimate. It also provides a statistically defensible estimate of the confidence limits around the final estimates. Including statisticians who understand these approaches in spill response analysis teams is highly desirable. By using randomization and extensive use of distributions (as opposed to point estimates), Haney et al. (2014*a*, 2014*b*) employed a Bayesian style approach in their assessment of the number of birds affected by the *Deepwater Horizon* spill, projecting uncertainties around the final estimate with assumptions clearly stated, which allowed for further discussion of the estimates (Sackmann and Becker 2015; Haney et al. 2015). A fully Bayesian approach, such as constructing a Bayesian Network that includes all model parameters (Kaikkonen et al. 2021), and development of spatial Bayesian Networks in time, would be next logical steps to improve methods in assessing the number of birds affected by spills. We recommend Pourret et al. (2008) to learn more about Bayesian statistics.

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