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Seabirds & marine plastic debris in Ireland
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Seabirds and marine plastic debris in Ireland:

A synthesis and recommendations for monitoring

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In pursuit of innovative and sustainable solutions for marine plastic waste, the Circular Ocean project seeks to inspire enterprises and entrepreneurs to realise the hidden opportunities of discarded fishing nets and ropes in the Northern Periphery & Arctic (NPA) region.

As increasing levels of marine litter is particularly pertinent to the NPA region, the Circular Ocean project will act as a catalyst to motivate and empower remote communities to develop sustainable and green business opportunities that will enhance income generation and retention within local regions.

Through transnational collaboration and eco-innovation, Circular Ocean will develop, share and test new sustainable solutions to incentivise the collection and reprocessing of discarded fishing nets and assist the movement towards a more circular economy.

Circular Ocean is led by the Environmental Research Institute, www.eri.ac.uk (Scotland), and is funded under the European Regional Development Fund (ERDF) Interreg VB Northern Periphery and Arctic (NPA) Programme http://www.interreg-npa.eu. It has partners in Ireland (Macroom E www.macroom-e.com), England (The Centre for Sustainable Design www.cfsd.org.uk), Greenland (Arctic Technology Centre www.artek.byg.dtu.dk), and Norway (Norwegian University of Science and Technology www.ntnu.edu).

Summary

The presence of plastic in the marine environment is a globally recognised issue, with far-reaching economic, aesthetic, and environmental consequences. Numerous marine species interact with plastic debris through entanglement, nest incorporation, and ingestion, which can lead to negative impacts. However, in Ireland, an area of international importance for seabirds, to date there has been little effort to assess plastic wildlife studies to better understand the spatiotemporal variation of how marine plastic affects different seabird species. To improve our understanding of seabirds and marine plastic in this region, we completed a synthesis of the literature to obtain information on all known documented cases of plastic ingestion and nest incorporation by this group. We found that of 69 seabird species that commonly occur in Ireland, 13 (19%) had evidence of ingesting plastic. However, information from multiple countries and years was only available for four species (6%). No published information was found on nest incorporation. In terms of ingestion, for many species, sample sizes were small or not reported, from only four studies, indicating that we actually know very little about the current prevalence of plastic ingestion and nest incorporation for most species. This synthesis highlights important gaps in our current knowledge, and we recommend co-ordinated collaboration to obtain a more comprehensive and current understanding of how marine plastic is affecting seabirds in Ireland.

- Plastic ingestion was recorded in 19% of seabird species that occur in Irish waters.
- For 75% of species we do not know the extent of plastic ingestion or nest incorporation in Ireland, as they have not been examined in this region.
- We therefore know very little about current levels of plastic ingestion and nest incorporation of seabirds in Ireland for the majority of species.

Background

Plastic pollution in the marine environment

The presence of plastic in the marine environment is a globally recognised environmental issue, with far reaching economic, aesthetic, and environmental consequences (UNEP 2016). Plastic production continues to rise with large quantities, estimated at 4.8 to 12.7 million metric tons, entering our oceans annually. This includes industrial plastic, such as virgin hard plastic pellets used in manufacturing, and user plastic from consumer and commercial sources. User plastic comes in a wide range of forms from hard plastic (polyethylene) to softer plastics such as Styrofoam (polystyrene), both of which can consist of fibres, film, foam and fragments.

The increase in marine plastic debris has led to a multitude of international and regional agreements aimed at reducing the impacts of marine plastic, including the International Convention for the Prevention of Pollution From Ships (MARPOL); the Convention on Biological Diversity (CBD); and the European Unions (EU) Marine Strategy Framework Directive (MSFD). Furthermore, the United Nations (UN) Sustainable Development Goals (SDG), a wide-ranging series of internationally-agreed ambitious goals with associated targets and indicators, includes SDG 14, which seeks to “conserve and sustainably use the oceans, seas and marine resources for sustainable development”. This includes a target of significantly reducing marine pollution, including from plastics, by 2025 (UNDP 2015). SDG 14 incorporates the UN’s #CleanSeas Initiative, and therefore requires robust quantitative data at the national and international level to measure success.

Being a European member state, Ireland is required to comply with the MSFD, which states that all European marine waters should be in 'Good Environmental Status' by 2020. AS part of this is the implementation of a monitoring programme under the MSFD-Descriptor 10 relating to Marine Litter. Furthermore, the Irish Government needs to comply with the Oslo/Paris Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR). To that end, an understanding of the extent and nature of plastics’ impacts on marine life is essential.

Impact of plastic on marine biodiversity

Plastic pollution is a major threat to marine biodiversity. The desirable properties of plastics (low-cost, light-weight, and durable) are those that contribute to it being problematic in the marine environment. For example, due to its low cost, approximately half of all plastic items are produced for single-use, resulting in plastic contributing to 10% of all waste globally (Barnes *et al*. 2009). Owing to its low density a large proportion of plastic floats, increasing the number of species that may interact with it, with potentially negative consequences. Furthermore, it does not biodegrade, but instead breaks up into smaller fragments that remain in the environment and a threat to organisms. In addition to these fragments, there is an increase in micro-plastic entering our oceans from terrestrial sources (UNEP 2016). Micro-plastic is generally defined as small particles of plastic < 5 mm in size. Micro-plastics are frequently used in the cosmetic industry and for air-blast cleaning, and include nurdles - the raw material in the manufacturing process. As micro-plastic is largely not collected during waste-water processing, along with, for example, synthetic fibres from washing clothing, large quantities end up in our oceans (Derraik 2002, Gregory 2013).

“Plastic pollution is a major threat to marine biodiversity. The desirable properties of plastics (low-cost, light-weight, and durable) are those that contribute to it being problematic in the marine environment.”

There are two main ways that plastic pollution affects marine species, through entanglement and ingestion (Laist 1987). Entanglement is generally passive, with individuals becoming entangled in discarded or lost fishing nets, as well as with user plastic such as plastic bags (Derraik 2002). Seabirds can also actively collect plastic as nesting material and incorporate it into their nests where it can cause entanglement of chicks and adults, resulting in direct injury or death (Votier *et al*. 2011). Ingestion of marine plastic is also of particular concern, where individuals either mistakenly consume plastic while foraging on other prey items, or purposefully ingest it by mistaking it for food (Laist 1997). Ingested plastic can have lethal and sub-lethal impacts on a wide range of marine organisms (Browne *et al*. 2015; Rochman *et al*. 2016). Furthermore, plastic fragments can absorb and/or adsorb contaminants, both organic compounds like polychlorinated biphenyls and polybrominated compounds, and inorganic metals, which may interfere with an individual's physiology and therefore have negative consequences on reproduction and survival (Holmes *et al*. 2012; Tanaka *et al*. 2013).

The first documentation of encounters between marine species and plastic was in the 1960s, with the first recorded case of plastic ingestion in seabirds in Ireland recorded in the 1980s (Buckley 1990). Since then the issue has escalated and several reviews have documented species' ingestion of and entanglement with marine debris (Laist 1987; Gall & Thompson 2015; Kühn *et al*. 2015). Recent estimates indicate that over 690 marine species globally have been affected by marine debris, includes cetaceans, pinnipeds, seabirds, turtles, fish, and crustaceans, with the majority involving plastic (Gall & Thompson 2015). However, these reviews do not provide quantitative information that can be used to identify spatial and temporal patterns.

Many of the studies within these reviews focus on seabirds. However, despite knowing that many seabird species ingest or become entangled with marine plastic, generally we understand very little about the extent of these interactions at most locations and how this changes over time. There is an understanding of marine plastic debris and seabirds in Canadian waters due to a recent comprehensive review in the region (Provencher *et al*. 2015), which highlighted knowledge gaps and how these should be addressed. This level of understanding in other regions, such as Ireland, is vital to highlight local knowledge gaps, direct the focus of future monitoring, and make linkages for coordinated efforts.

"Despite knowing that many seabird species ingest or become entangled with marine plastic, generally we understand very little about the extent of these interactions at most locations and how this changes over time."

Atlantic Puffin © Chris Cachia Zammit

Marine plastic debris and seabirds

Ireland is an important region for seabirds, incorporating 29 Important Bird and Biodiversity Area (IBAs, Figure 1; Birdlife 2017) in marine habitats and supporting internationally important numbers of 25 species. These include breeding populations of Atlantic Puffin (*Fratercula arctica*), as well as passage and wintering numbers of Leach's Storm-petrel (*Hydrobates leucorhous*), Long-tailed Duck (*Clangula hyemalis*) and Velvet Scoter (*Melanitta fusca*), all of which are classified as vulnerable, by the International Union for Conservation of Nature (IUCN 2016).

The presence of plastic, particularly micro-plastic (< 5 mm), is widespread in the northeastern Atlantic with a mean of 2.46 particles m^{-3} (Lusher *et al.* 2014). There are no baseline data for levels of marine plastic in the seas around Ireland. However, recent monitoring in the Celtic Sea revealed that 57% of trawl samples contained litter, with 84% of this comprising of plastic (Moriarty *et al.* 2016).

> *"Ireland is an important region for seabirds, incorporating 29 Important Bird and Biodiversity Area (IBAs) in marine habitats and supporting internationally important numbers of 25 species."*

Incorporating the seas around Ireland, OSPAR contains targets to prevent and eliminate pollution including plastic, from land-based sources and by dumping, and mandates regular assessments of the quality of the marine environment. Importantly, OSPAR has developed a system of Ecological Quality Objectives (EcoQOs) with fixed monitoring approaches and associated targets for acceptable ecological quality, including those for marine plastics (OSPAR 2008). This includes the Northern Fulmar (*Fulmarus glacialis*) as an EcoQO indicator species for monitoring plastic debris in the North Sea (van Franeker & Meijboom 2002). The EcoQO indicator states that for acceptable ecological quality no more than 10% of Northern Fulmars should exceed a critical level of 0.1 g of ingested plastic within their stomach. Plastic ingestion by Northern Fulmars has been investigated in the Netherlands since the 1980s, with widespread sampling efforts in multiple countries since 2002 via the North Sea Northern Fulmar project, although this does not include Ireland. Between 2012 and 2016, 93% of 14 beached fulmars collected from Ireland were found to contain ingested plastic, all exceeding the 0.1g EcoQo level (van Franeker *et al.* 2011).

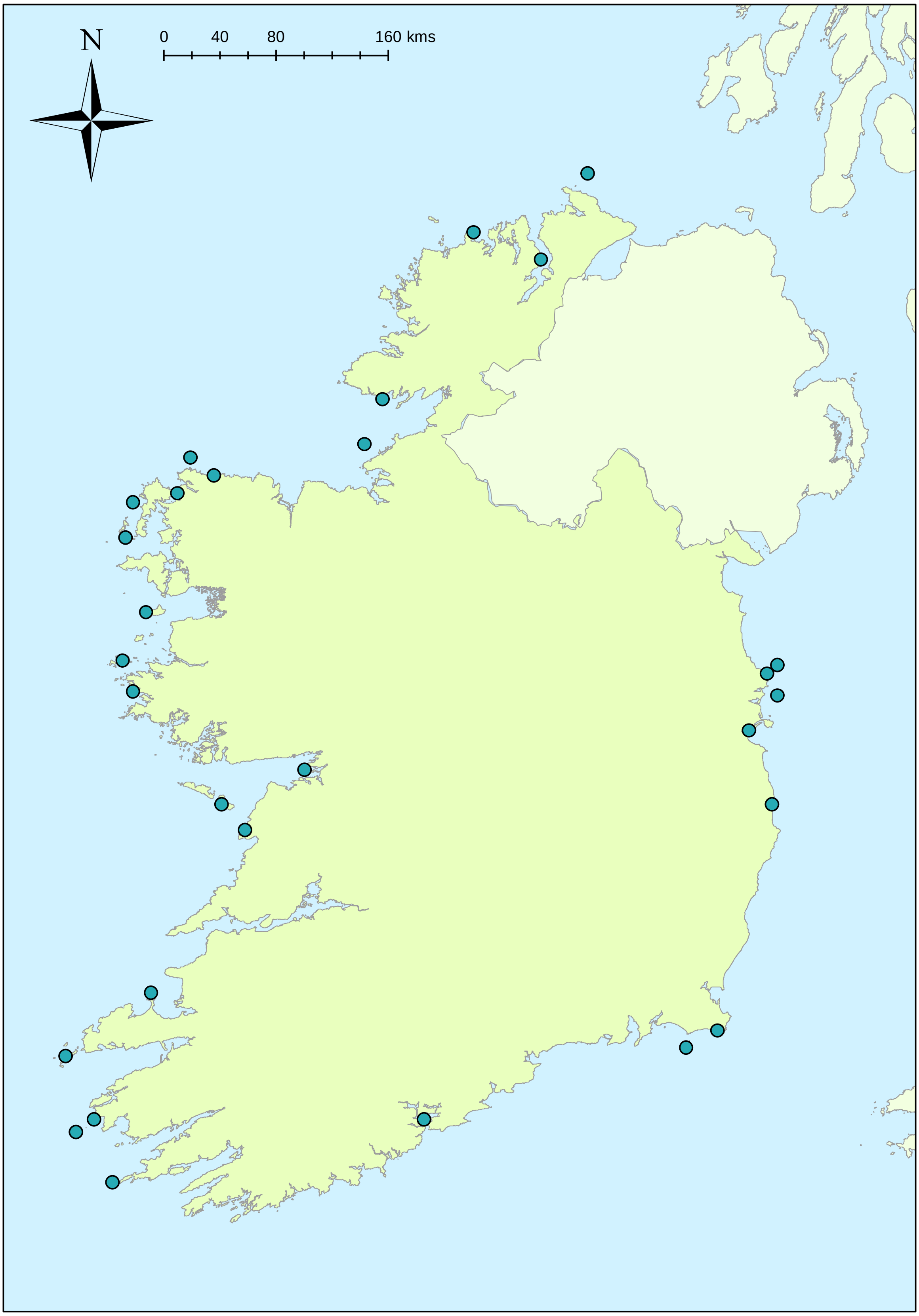


Figure 1: Location of the 29 marine Important Bird Areas (IBAs) across Ireland obtained from Birdlife 2017.

The Northern Fulmar project has allowed spatial and temporal patterns to be examined in relation to how effective policies are, how methodologies may influence results, and how marine plastic pollution is changing in the region over time. However, we know very little about the prevalence and spatiotemporal scale of plastic ingestion, or nest incorporation, of Irish seabirds outside this indicator (van Franeker *et al*. 2011). Although a number of studies have identified the prevalence of plastic ingestion in a variety of seabird species, the majority of information currently collected is ad hoc and opportunistic, with the North Sea Northern Fulmar project the only example of a coordinated effort to monitor marine plastic in seabirds in the region.

In this synthesis, we aim to determine the level of knowledge of how seabirds actively interact with marine plastic, focusing on nest incorporation and ingestion. We then identify knowledge gaps and make recommendations for future monitoring to address them, to improve our understanding of how marine plastic affects seabirds in Ireland.

Northern Fulmar © Nina O'Hanlon

Approach

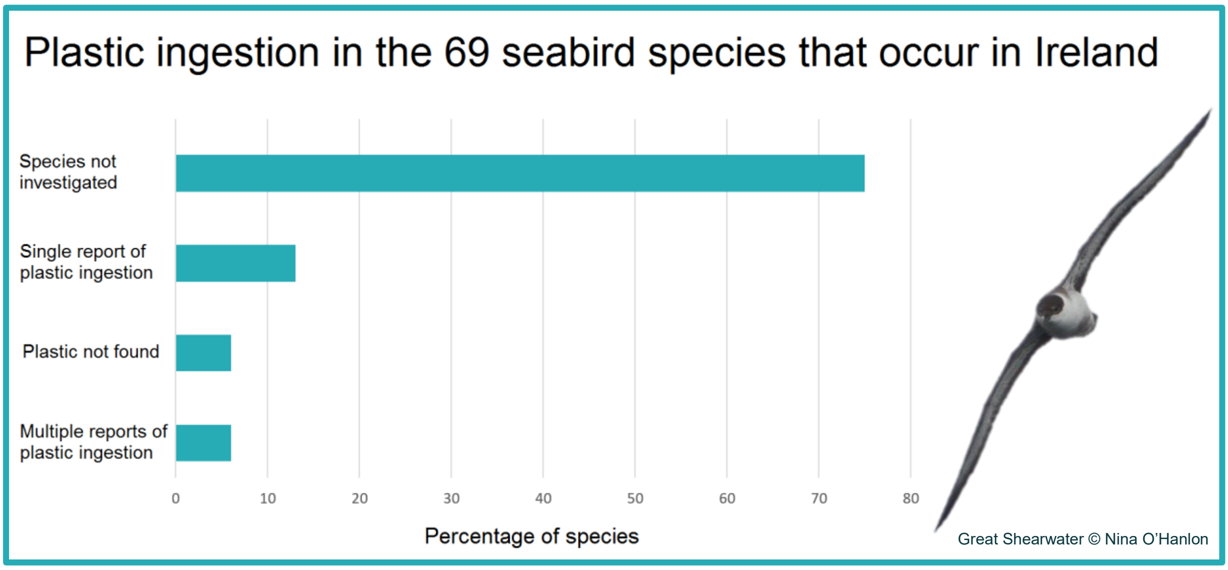
We focused on birds sampled within Ireland. We included species categorised as seabirds following Gaston (2004), namely the tubenoses (Procellariidae, Hydrobatidae), cormorants (Phalacrocoracidae), gannets (Sulidae), phalaropes (Charadriidae: *Phalaropus* spp.), skuas, gulls, and, terns (Laridae), and auks (Alcidae). We also included loons (Gaviidae), sea ducks and mergansers (Anatidae: Mergini), as these species spend the majority of the year at sea (Gaston 2004). All seabird species known to breed within Ireland, as well as regular non-breeding migrants, were included (del Hoyo et al. 2016). We did not include vagrants, as they do not provide useful information on systematic monitoring in our study area. Throughout, we followed the taxonomic treatment of The Handbook of the Birds of the World (HBW) and BirdLife International (Del Hoyo & Collar 2014).

To obtain information on plastic ingestion and nest incorporation of plastic by seabirds within Scotland we carried out an extensive review of the literature. Key word searches were performed on Web of Science, Google Scholar and Google including the English and scientific names of the selected seabird species or groups. Key words relating to plastic interactions included: plastic (as well as elastic, polythene and cellophane), diet, plastic ingestion, nest, nest incorporation, nest material and marine debris. The reference lists of previous marine plastic review papers (Laist 1997; Gall & Thompson 2015; Kühn *et al*. 2015) and the references of relevant papers were also examined. We also contacted known researchers working on plastic ingestion and/or diet in seabirds, to obtain relevant unpublished data. In all cases, we restricted our data collection to articles or reports published, or data collected, up to 30 April 2017.

For each study, we recorded the species examined, the location and year of sampling, the sampling method, and the frequency of occurrence (%) of plastic ingestion or nest incorporation. The frequency of occurrence of plastic ingestion was recorded following van Franeker & Meijboom (2002), presented as the number of birds within a sample that contained evidence of plastic, including samples that were examined but were not found to contain plastic (van Franeker & Meijboom 2002). For nest incorporation, we recorded the frequency of occurrence as the number of nests within a sample that contained plastic. Where provided, we also recorded all metrics referring to the number, mass, size, type, and colour of plastics identified. For plastic ingestion, we then determined how many studies achieved the standardised metric recommendations outlined by Provencher *et al*. (2017), and which of these recommendations were most widely documented.

Results

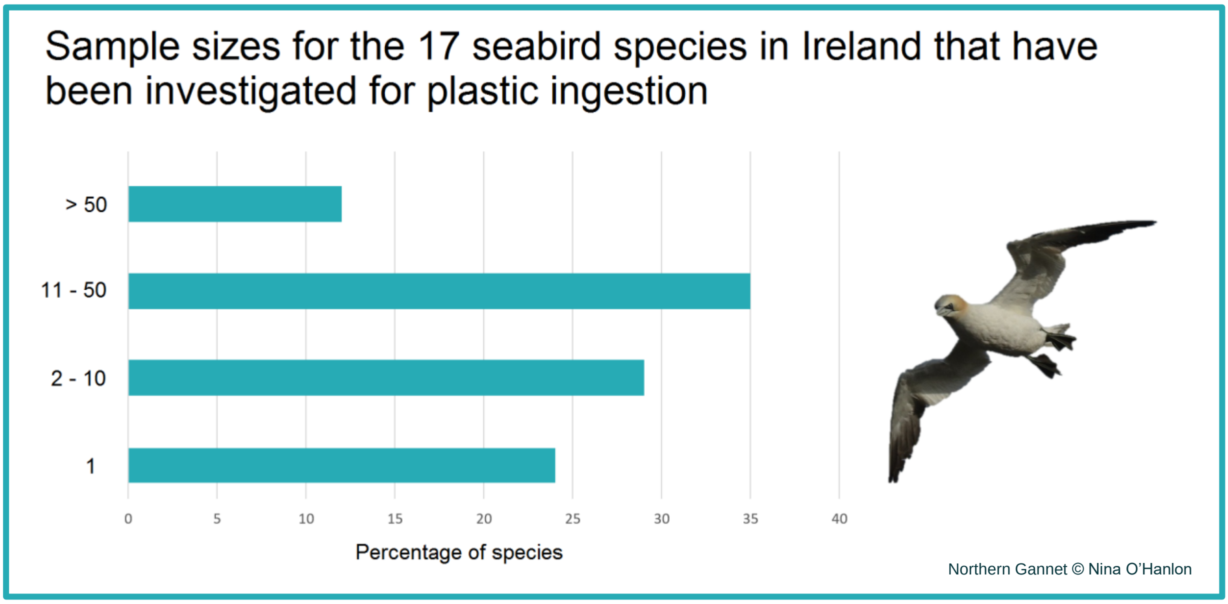
We identified 69 seabird species that commonly occur as breeding species or migrants within Ireland (Table 1), with four studies reporting on plastic interactions by these species. Of these, 17 species (25%) had been examined for plastic ingestion (Table 1). For four species (6%), there was no evidence of plastic ingestion. Therefore, of the 69 seabird species reviewed, plastic ingestion was recorded in 13 species (19%), however only four of these species had data from multiple studies. This means that 52 species (75%), which can occur within Irish waters, have not been examined for plastic ingestion, although it has been documented in 25 of these species (48%) outside of Ireland. Furthermore, in all four of the species within this synthesis where no evidence of plastic ingestion was documented, plastic ingestion has been recorded elsewhere. For the seabird species that build visible, surface nests (n = 50), data on nest incorporation of plastic was not documented.



Of the species with recorded incidences of plastic ingestion, three species had frequency of occurrence > 50% (Table 2). However, all sample sizes were relatively low, with the 100% frequency of occurrence recorded in Arctic Jaeger (*Stercorarius parasiticus*) and Lesser black-backed gull (*Larus fuscus*) both referring to one and two individuals respectively. The three species examined for plastic ingestion with no evidence detected also had small sample sizes (n < 15), with three species referring to only single individuals.

For this synthesis, there were only four published studies covering Ireland. Three directly investigated plastic ingestion, and were by the same authors, with the fourth investigating diet. Of the standardised metric recommendations outlined by Provencher *et al.* (2017), none of the studies met them all (Table 4). However, all recorded location, year and sampling method, sample size (94%) and frequency of occurrence (69%). In addition to frequency of occurrence, the mass of ingested plastic fragments is the most biologically important metric (van Franeker & Meijboom 2002) and the three studies focusing on plastic ingestion did record this metric (Acampora *et al.* 2016, 2017a, b).

The information in Table 2 highlights the temporal coverage of published studies that have documented plastic ingestion in seabirds across Ireland, with the spatial distribution displayed in Figure 2. Temporally, the studies sampled seabirds over multiple years between 2011 and 2016, as well as one study, that focused on diet, from 1986.



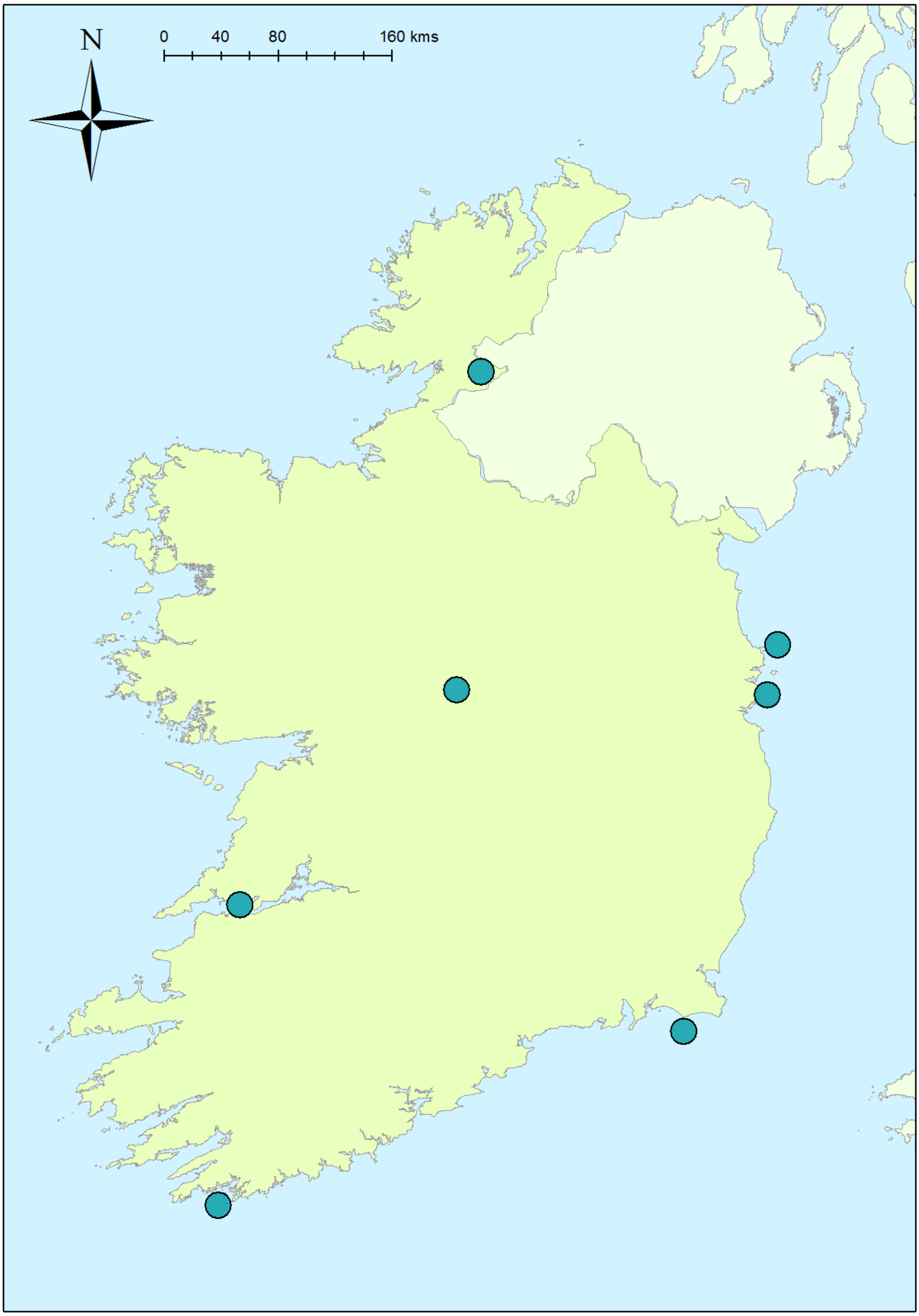


Figure 2: Spatial distribution of documented plastic ingestion by seabirds in Ireland. Blue filled circles show the positive presence of plastic ingestion, in at least one species at that location.

Table 1. Species categorised by the spatial and temporal ingested plastic data available from Ireland.

Species with ingested plastic data reported from multiple studies	Species with single reports of ingested plastic	Species currently with no reports of ingested plastic
Northern fulmar (*Fulmarus glacialis*)	Manx shearwater (*Puffinus puffinus*)	Red-throated loon (*Gavia stellata*)
Great cormorant (*Phalacrocorax carbo*)	Northern gannet (*Morus bassanus*)	Common loon (*Gavia immer*)
Great black-backed gull (*Larus marinus*)	European shag (*Phalacrocorax aristotelis*)	Arctic loon (*Gavia arctica*)
Black-legged kittiwake (*Rissa tridactyla*)	Arctic jaeger (*Stercorarius parasiticus*)	Yellow-billed loon (*Gavia adamsii*)
	Sabine's gull (*Xema sabini*)	Zino's petrel (*Pterodroma madeira*)
	Black-headed gull (*Larus ridibundus*)	Cape Verde petrel (*Pterodroma feae*)
	Lesser black-backed gull (*Larus fuscus*)	Cory's shearwater (*Calonectris borealis*)
	European herring gull (*Larus argentatus*)	Great shearwater (*Ardenna gravis*)
	Iceland gull (*Larus glaucoides*)	Sooty shearwater (*Ardenna grisea*)
	Common murre (*Uria aalge*)	Balearic shearwater (*Puffinus mauretanicus*)
	Razorbill (*Alca torda*)	Wilson's storm-petrel (*Oceanites oceanicus*)
	Black guillemot (*Cepphus grylle*)	European storm-petrel (*Hydrobates pelagicus*)
	Atlantic puffin (*Fratercula arctica*)	Leach's storm-petrel (*Hydrobates leucorhous*)
		Steller's eider (*Polysticta stelleri*)
		Common eider (*Somateria mollissima*)
		King eider (*Somateria spectabilis*)
		Harlequin duck (*Histrionicus histrionicus*)
		Long-tailed duck (*Clangula hyemalis*)
		Common scoter (*Melanitta nigra*)
		Surf scoter (*Melanitta perspicillata*)
		Velvet scoter (*Melanitta fusca*)
		Red-breasted merganser (*Mergus serrator*)
		Common goldeneye (*Bucephala clangula*)
		Red-necked phalarope (*Phalaropus lobatus*)
		Red phalarope (*Phalaropus fulicarius*)
		Pomarine jaeger (*Stercorarius pomarinus*)
		Long-tailed jaeger (*Stercorarius longicaudus*)
		Great skua (*Catharacta skua*)
		Mediterranean gull (*Larus melanocephalus*)
		Laughing gull (*Larus atricilla*)
		Little gull (*Hydrocoloeus minutus*)
		Ross's gull (*Rhodostethia rosea*)
		Bonaparte's gull (*Larus philadelphia*)
		Ring-billed gull (*Larus delawarensis*)
		Mew gull (*Larus canus*)
		Yellow-legged gull (*Larus michahellis*)
		Glaucous gull (*Larus hyperboreus*)
		Caspian gull (*Larus cachinnans*)
		Thayer's gull (*Larus thayeri*)
		Ivory gull (*Pagophila eburnea*)
		Common gull-billed tern (*Gelochelidon nilotica*)
		Caspian tern (*Hydroprogne caspia*)
		Sandwich tern (*Thalasseus sandvicensis*)
		Roseate tern (*Sterna dougallii*)
		Common tern (*Sterna hirundo*)
		Arctic tern (*Sterna paradisaea*)
		Little tern (*Sternula albifrons*)
		Whiskered tern (*Chlidonias hybrida*)
		Black tern (*Chlidonias niger*)
		White-winged tern (*Chlidonias leucopterus*)
		Thick-billed murre (*Uria lomvia*)
		Little auk (*Alle alle*)

Seabird species that breed in Ireland (in blue). Species where studies looked for plastic (or noted it in other species within the same study) but no evidence of plastic ingestion recorded (in green – these species also breed in Ireland with the exception of Sabine's and Iceland Gull). Migrant species to Ireland (in black).

Table 2. Publications and unpublished data on plastic interactions and seabirds in Ireland.

Species	Country	Sampling year	Reported frequency of occurrence % (*n*) [b]	Interaction type	Source
Northern fulmar (*Fulmarus glacialis*)	Ireland*	2012 & 2014-2016	93 (14)	Ingested	Acampora et al. 2016
	Great Saltee	2015	28 (14)	Regurgitates	Acampora et al. 2017b
			61 (28)		
Manx shearwater (*Puffinus puffinus*)	Ireland [a]	2014-2016	33 (3)	Ingested	Acampora et al. 2016
Northern gannet (*Morus bassanus*)	Ireland [a]	2014-2016	27 (15)	Ingested	Acampora et al. 2016
Great cormorant (*Phalacrocorax carbo*)	Great Saltee & Money Point	2011 & 2014-2015	3 (92)	Pellets	Acampora et al. 2017a
	St. Patrick's, Great Saltee & Ireland's Eye	2011-2012	7 (28)	Regurgitates	Acampora et al. 2017b
			5 (120)		
European shag (*Phalacrocorax aristotelis*)	Ireland [a]	2014-2016	10 (10)	Ingested	Acampora et al. 2016
Arctic jaeger (*Stercorarius parasiticus*)	Ireland	2014-2016	100 (1)	Ingested	Acampora et al. 2016
Sabine's gull (*Xema sabini*)	Ireland	2014-2016	0 (1)	Ingested	Acampora et al. 2016
Black-headed gull (*Larus ridibundus*)	Ireland [a]	2014-2016	22 (9)	Ingested	Acampora et al. 2016
Lesser black-backed gull (*Larus fuscus*)	Ireland [a]	2014-2016	100 (2)	Ingested	Acampora et al. 2016
European herring gull (*Larus argentatus*)	Ireland [a]	2014-2016	32 (13)	Ingested	Acampora et al. 2016
Iceland gull (*Larus glaucoides*)	Ireland	2014-2016	0 (1)	Ingested	Acampora et al. 2016
Great black-backed gull (*Larus marinus*)	Ireland	1986	2 (52)	Regurgitates	Buckley 1990
	Ireland [a]	2014-2016	25 (4)	Ingested	Acampora et al. 2016
			14 (56)		
Black-legged kittiwake (*Rissa tridactyla*)	Ireland [a]	2014-2016	50 (4)	Ingested	Acampora et al. 2016
	Rockabill	2013 & 2015	8 (38)	Regurgitates	Acampora et al. 2017b
			29 (42)		
Common murre (*Uria aalge*)	Ireland [a]	2014-2016	12 (25)	Ingested	Acampora et al. 2016
Razorbill (*Alca torda*)	Ireland [a]	2014-2016	0 (15)	Ingested	Acampora et al. 2016
Black guillemot (*Cepphus grylle*)	Ireland	2014-2016	0 (1)	Ingested	Acampora et al. 2016
Atlantic puffin (Fratercula arctica)	Ireland [a]	2014-2016	33 (3)	Ingested	Acampora et al. 2016

[a] Indicates plastic interaction investigated for multiple locations within the country, which were not provided in the publication. [b] Where more than one study is listed, the average frequency of occurrence and total sample size, in parenthesis, is also provided in bold. Although, it should be noted that in all four cases this involves combining frequency of occurrence values from necropsied beached birds to values from regurgitates, with this later method likely to under-estimate the occurrence of ingested plastic.

Discussion

We found evidence for seabirds ingesting marine plastic from multiple locations across Ireland. Of the 69 seabird species commonly found across the region, 13 had evidence of plastic ingestion, with a further four species examined but with no evidence recorded. For the remaining 52 species, there was no empirical evidence of how, or even if, they interact with marine plastic debris in Ireland. Only four studies were found that had reported plastic ingestion and no studies were found that provided quantified information about nest incorporation. Therefore, although active interactions with marine plastic occurred across the region, information on the extent of these interactions for specific species and locations is limited. This synthesis reveals several key knowledge gaps, which we highlight below, along with recommendations for how to target future monitoring and research to obtain a better understanding on the impact of marine plastic and seabirds in Ireland.

> *"No studies were found that provided quantified information about nest incorporation."*

Plastic ingestion

For species where multiple samples were available, the highest prevalence of plastic ingestion occurred in the Northern Fulmar, consistent with other studies, which highlight that as surface-feeders Procellariiformes are highly susceptible to plastic ingestion (Day *et al.* 1985; Provencher *et al.* 2014). The other Procellariiforme species included within this synthesis, the Manx Shearwater (*Puffinus puffinus*), also had a relatively high frequency of occurrence at 33%, although this was based on only three samples. The other group with relatively high frequency of occurrence, and which are also surface foragers, were the gulls. The prevalence of plastic ingested by gulls is likely to depend on their foraging habitats. Black-headed (*Larus ridibundus*), Herring (*L. argentatus*), Lesser Black-backed (*L. fuscus*) and Great Black-backed Gulls (*L. marinus*) are all known to forage on terrestrial, anthropogenic resources, specifically landfill sites (Kubetzki & Garthe 2003). Species that regurgitate the hard parts of their diet, such as the gulls and also cormorants, are less at risk than species that cannot, as plastic does not accumulate as much within their gastro-intestinal tract compared with other species (Ryan 1987). However, we need to understand the proportion of ingested plastic that is expelled in pellets, as it is likely that some will remain in the birds' gastro-intestinal tract (Ryan 1987; Ryan & Fraser 1988). Nonetheless, monitoring plastic ingestion in these species can still be useful to investigate relative spatiotemporal trends.

“For species where multiple samples were available, the highest prevalence of plastic ingestion occurred in the Northern Fulmar.”

It is more difficult to establish which species might be at lowest risk of plastic ingestion, largely because of inadequate sampling. Given the abundance of floating marine plastic (Cozar *et al*. 2014), diving species are likely less susceptible, though not completely immune, to ingesting plastic (Tavares *et al.* 2017). Furthermore, where plastic does sink there is potential for ingestion by benthic foraging seabirds.

Within Ireland, no information was available on the potential plastic ingestion of storm-petrels, loons or sea-ducks, the majority of skuas or terns. Limited information is available for some species in these groups outside of Ireland. In Scotland, a study in the 1980s found that 59% of Leach’s Storm-petrels (*Hydrobates leucorhous*) contained ingested plastic (Furness 1995). Skuas may be susceptible to plastic ingestion, directly and through secondary ingestion. In the Faroe Islands, plastic has been found in Great Skua (*Stercorarius skua*) pellets, with the highest frequency of occurrence from individuals that had depredated Northern Fulmars (Hammer *et al.* 2016). The frequency of occurrence of ingested plastic in terns is thought to be low, however for many species in this group we have very little information (Day *et al.* 1985; Provencher *et al.* 2015). Outside of Scotland, plastic ingestion has been recorded in the Common Tern (*S. hirundo*) and Black Tern (*Chlidonias niger*), including within regurgitated pellets, although sample sizes were small (Hays & Cormons 1974; Braune & Gaskin 1982; Moser & Lee 1992). Therefore, collecting tern pellets may also be an option for monitoring plastic ingestion in this group.

Aside from the Sooty and Great Shearwater, and the Iceland Gull (*Larus glaucoides*), we found no studies that had looked for plastic ingestion in the other migrant seabird species regularly occurring within Irish waters. For these species, it may be more appropriate to investigate interactions with marine plastic in their breeding grounds. However, sampling all species in both their breeding and non-breeding areas may help determine where they are most likely to encounter marine plastic, if large enough sample sizes can be collected. Furthermore, examining these species in breeding and non-breeding regions may allow for insights into how seabird may be differentially vulnerable by marine plastic pollution throughout the annual cycle, and therefore have potentially different effects on different life history traits.

The spatial and temporal coverage of plastic ingestion studies of seabirds in Ireland, and the sample sizes involved, were low. This is also the case across the wider northeastern Atlantic region, with the exception of the Northern Fulmar. The good representation for the Northern Fulmar is largely due to the North Sea Northern Fulmar monitoring project, which is incorporated into the Ecological Quality Objectives (EcoQOs) set by OSPAR for the North Sea (OSPAR 2008; van Franeker *et al.* 2011; van Franeker & the SNS Fulmar Study Group 2013). Although this monitoring project is focused on the North Sea region, Northern Fulmar samples have also been opportunistically collected, following the same standardised methodology, from the Faroe Islands (van Franeker & the SNS Fulmar Study Group 2013), Svalbard (Trevail *et al.* 2015) and Iceland (Kühn & van Franeker 2012), as well as elsewhere throughout the northern hemisphere, allowing for comparisons across their entire range (Provencher *et al.* 2017). This wide geographical coverage has increased our understanding of plastic ingestion in the Northern Fulmar revealing decreased frequency of occurrence with latitude, and separate processes occurring in the Atlantic and Pacific basins (Provencher et al. 2017). It would therefore be beneficial to carry out this level of monitoring across Ireland for the Northern Fulmar and other species.

"The majority of samples were collected between 2014 and 2016, highlighting that in Ireland we do not know anything about previous levels of plastic ingestion."

There was temporal and spatial bias in where samples were collected based largely on where specific studies occurred. For example, with pellet and regurgitate samples being collected opportunistically whilst visiting colonies for ringing (Acampora *et al.* 2017b). The majority of samples were collected between 2014 and 2016, highlighting that in Ireland we do not know anything about previous levels of plastic ingestion. However the three recent studies do therefore provide a baseline of current plastic ingestion levels in Irish seabirds (Acampora *et al.* 2016, 2017a, b). For the majority of species, samples were collected from multiple locations, however the sample sizes for each location were generally small due to taking advantages of beached birds (Acampora *et al.* 2016). Given the importance of seabirds in Ireland, and the number of researchers and organisations that do work at seabird colonies across the country, a coordinated approach, particularly around widely distributed species, would ensure the greatest value of systematic standardised sampling.

Opportunistic studies are useful to compare current frequency of occurrence levels and provide a point of comparison to determine how plastic ingestion may change over time. However, systematically monitoring species, preferably annually, is a more robust way of detecting spatiotemporal trends (van Franeker & Meijboom 2002).In addition to frequent monitoring, adequate sample sizes are also required. For the Northern Fulmar in the North Sea, to detect a reliable change in the frequency of occurrence or quantity of plastic ingested, a sample size of at least 40 birds was required annually over a period of 4-8 years, to detect a 25% change in the mass of ingested plastic. The annual sample size required to detect a change will vary depending on the species, location, and the level of detectable change required (Provencher *et al.* 2015). No species in this synthesis had annual sample sizes > 40 in > 4 years, which limited our ability to assess the statistical power associated with proposed sampling regimes. Ideally, to detect spatial variation among taxonomic groups and age classes (Provencher *et al.* 2015), this level of monitoring would occur for all species across Ireland. However, this effort is likely impractical, therefore it is important to identify which species are of highest priority, and where they occur, to target future coordinated monitoring.

The majority of studies within this synthesis did not specify the minimum size of the plastic recorded, and given that the focus of most studies was not specifically for ingested debris, it is likely that they overlooked the presence of micro-plastic, and also ultrafine- and nano-plastic (items < 1 mm). While seabirds can be used to monitor relative levels of plastic debris in the marine environment, it is difficult to detect the presence of all plastics smaller than 1 mm in seabirds. Therefore, when examining seabirds it is important to report the minimum size threshold of plastic detected, or at least a recognized size category, so that the scale of plastic detected is known in order to improve our overall understanding on how plastic affects species (Provencher *et al.* 2017). This is particularly important in advancing our understanding of how seabirds may acquire plastic indirectly, through secondary ingestion of contaminated marine invertebrates (Van Cauwenberghe & Janssen 2014) and vertebrates such as fish (Boerger *et al.* 2010; Foekema *et al.* 2013).

> *“When examining seabirds it is important to report the minimum size threshold of plastic detected, or at least a recognized size category, so that the scale of plastic detected is known.”*

Nest incorporation

The lack of quantitative information highlights how little we know about nest incorporation of plastic by seabirds in Ireland. Of the species included within our synthesis, nest building, surface nesters include the Northern Gannet, Great Cormorant and European Shag as well as the gulls, skuas, loons and sea ducks (n = 50). Outside of Ireland, incorporation of plastic into nests has been reported in Northern Gannets, Black-legged Kittiwakes (*Rissa tridactyla*) (Hartwig *et al.* 2007), cormorants (Podolsky & Kress 1989) and gulls (Witteveen *et al.* 2016). In order to obtain systematic, quantified data on nest incorporation it would be valuable to establish a monitoring scheme for multiple species across the country to provide a better understanding on which species are the most affected.

Recommendations

To increase our knowledge of marine plastic pollution in Ireland, and how this affects the seabird species in this region, further monitoring is required to address current species, spatial, and temporal knowledge gaps.

1. **Future studies that report plastic metrics should follow the standardised recommendations made by Provencher *et al.* (2017).** The most important of these are mass and frequency of occurrence of ingested plastics, as the most biologically relevant. Furthermore, studies should report the minimum plastic size threshold detected so that when comparing between studies the scale of plastic recorded is known. These suggestions also pertain to studies where the focus is not ingested plastic, to ensure that the presence and quantity of plastic, and other marine debris, that might be found for example in diet studies is documented adequately to further address the knowledge gaps associated with plastic ingestion in seabirds.

2. At present, monitoring seabirds for plastic ingestion is largely opportunistic with limited, if any, co-ordination. This makes identifying spatial and temporal trends among and between species challenging. **Coordinated, collaborative effort is therefore necessary to obtain samples required to monitor the temporal and spatial variation in plastic ingestion among seabird species in Ireland.** As has been demonstrated by Acampora *et al.* (2017a, b), advantage should be made of existing trips to seabird colonies by scientists and management agencies. Those visiting seabird colonies should be actively approached to establish whether they can collect samples following a standardised protocol, especially if the method of obtaining samples is straightforward such as collecting pellets. Seabird wrecks should be exploited to examine beached birds for plastic ingestion by necropsy. Although taking advantage of current diet monitoring or ringing activities may seem opportunistic however, if carried out in a standardised manner, and the information reported adequately, then this information can still be extremely useful. Opportunities should be exploited across Ireland, and for all species, however particular emphasis should be on those species for which we have very little current information for (based on table 1), especially those which may be at higher risk, i.e. the Procellariiformes, and in locations that are currently under represented.

3. From the data collated within this synthesis it was not possible to determine the sample sizes required to detect significant changes in ingestion trends over time. When collecting samples, the number required to provide a large enough sample to detect potential changes needs to be considered, and so that adequate samples sizes can be determined for future monitoring. **Methods that allow for frequent collection of a large number of samples from multiple species and locations may therefore be necessary, for example endoscopy or pellets.** For species that regurgitate or produce pellets, these can provide a non-invasive means of examining for ingested plastic, as already demonstrated in Ireland for the Great Cormorant (Acampora *et al.* 2017a). **As stated above, this requires coordinated effort to regularly collect large sample sizes from multiple colonies by, for example, visiting researchers and ringing groups.** The non-invasive collection of pellets from Great Cormorants, and from European Herring Gull as this species is also widely distributed across Ireland, may be useful in monitoring trends in plastic ingestion from coastal and inland locations across this region.

4. **To document nest incorporation of nest building, surface nesters across Ireland, a standardised, repeatable protocol should be established.** Coordinated monitoring, as described for plastic ingestion, can then be carried out at colonies that are repeatedly visited by researchers, ringers, and tourists (through photographs where feasible) in order that spatiotemporal changes for different species can be detected.

In terms of future research priorities, the proportion of plastic that remains in the gastro-intestinal tract of different pellet producing species is unknown. This could be investigated further through comparing the quantities of plastic detected in pellets to that detected through lavage or necropsy on the same species at a similar time and location. Furthermore, we know little on how long plastic remains in the gastro-intestinal tracts of different seabird species, or how contaminants that come from the plastics, or adhere to it, impact seabirds (Ryan 2015). In terms of nest incorporation, much research is required to establish the extent of plastic incorporation in to the nests of different species and what affect this may have on both the chicks and adults of these species.

There is wide scope for the use of citizen scientists for documenting the location and extent of plastic incorporation in nests through photographs. In addition, as has been highlighted elsewhere, we still do not fully understand the impacts plastic has on seabirds (Provencher *et al.* 2015, 2017). Plastic can have a negative impact on species at the sub-organismal level, however, very little is known about the impact of plastic at the organismal and ecological level, especially that has been demonstrated rather than simply inferred (Rochman *et al.* 2016). Therefore, investigations into these aspects of marine plastic and seabirds should also be a priority for future research.

"To establish a better understanding of the growing issue of plastic marine debris in the marine environment, we require a region wide, coordinated effort to collect information on both plastic ingestion and nest incorporation, collected and reported in a standardised manner."

Here we focused on knowledge gaps associated with monitoring the interactions between plastic and seabirds in Ireland. Our synthesis highlights that our knowledge about the incorporation of plastic into the nests of those species that build them is very poor. We also know very little about the frequency of occurrence of plastic species in the majority of seabird species, at many locations across the region, especially the current state of occurrence. To establish a better understanding of the growing issue of plastic marine debris in the marine environment, we require a region wide, coordinated effort to collect information on both plastic ingestion and nest incorporation, collected and reported in a standardised manner. This is vital to meet national and international targets, and more importantly understand the impacts of marine plastic debris on seabirds and other marine organisms.

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