ABSTRACT

Plastics in the environment are of increasing concern for many organisms including seabirds. In this study, I examined the nests of four seabird species – northern gannets, black-legged kittiwakes, great cormorants, and gulls (herring and lesser black-backed gulls) – on two small islands in the North Sea. I quantified the proportion of plastic in each nest following methods described by Thompson et al. (2020), and compared the types and colors of plastics in their nests to those found in the environment. I examined the proportion of nests of each species that contained plastic, and found that northern gannets (98%) and great cormorants (95%) were both more likely to include plastic in their nests than kittiwakes (44%) and gulls (28%). I also found that the average amount of plastic in nests differed across species (northern gannets 36%, great cormorants 9%, black-legged kittiwakes 2%, gulls 1%). These differences in proportions of nests containing plastic and average amount of plastic in nests are likely due to differences in materials used in nests and whether a species reuses nests each year. In comparing plastics in the environment to that in nests, I found that fibrous plastic, in particular dolly rope, a type of sacrificial chafing material used in commercial bottom trawling fishing, was highly preferred by all the studied seabird species. Orange dolly rope was also favored over other colors of dolly rope. Chemical testing of dolly rope pieces found that it was polyethylene, which is consistent with previous reports for the North Sea, and mechanical testing of dolly rope strands highlighted the dangers of entanglement posed by the material. There is a strong preference for orange dolly rope by nesting birds that may be due to morphological similarities to natural nesting material and an ease in locating the brightly colored material in the water. While seabird deaths by entanglement alone are not likely to lead to a population decrease, these deaths are often slow and painful and should be prevented if only for humanitarian reasons. I explore different methods of mitigating deaths by entanglement and reducing plastics in the marine environment, as well as ways in which plastic monitoring in seabird nests can provide information regarding the levels and types of pollution in the marine environment.

Quantifying and Analyzing Plastic in Seabird Nests in the North Sea

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INTRODUCTION

Heligoland is a small island in the North Sea, where thousands of seabirds come to raise their chicks each summer (Dierschke et al., 2011). The nesting cliffs on Heligoland are liberally draped in matted snarls of plastic ropes and lines, and the remains of dead seabirds, often no more than a sun-bleached sternum or desiccated mass of feathers, are interspersed between the colorful plastic. When I worked as a tour guide and environmental educator on Heligoland, some of the most common questions I received regarding the birds on Heligoland were about the plastic in the cliffs and the birds that it killed. While these conversations provided an opportunity to speak to tourists about the problems that plastic pollution posed to wildlife, the unfortunate fact remained that seabirds were incorporating large quantities of plastic into their nests, and dying painfully because of it.

Seabirds can be very effective ambassadors for raising awareness of plastic pollution. While they spend much of their lives at sea, they come ashore to breed, where they are observed by humans. The effects of plastic interactions, such as deaths or injuries due to entanglement or ingestion are directly visible to humans there, and can lead to increased interest in and concern for seabirds and the reduction of plastic pollution.

The negative impacts of plastics in the environment were first and very prominently seen in the 1960s, when ornithologists Kenyon and Kridler discovered that many of the Laysan albatross chicks they found dead in the Pacific Ocean had died with plastic in their stomachs (1969). Since then, many studies have examined interactions between wildlife and plastics in the environment (Kühn et al., 2015; Law 2017; Podolsky and Kress, 1989; Norman, 1995; Montevecchi, 1991; Schrey and Vauk, 1987; Hartwig et al., 2007). During my time working on Heligoland (2018-19, and 2021), I became interested in quantifying the amount of plastic in nests. I was curious as to why seabirds include plastic in their nests, where it comes from, and whether the plastic in their nests could be used as a proxy for plastic pollution in the environment.

In this study, I use the nest plastic quantification methods described by Thompson et al. (2020) to examine the nests of four different species of seabirds: northern gannets, great cormorants, black-legged kittiwakes, and gulls (lesser black-backed and herring gulls). Using quantitative data regarding the plastic composition of their nests, I look at other aspects of nest composition, including color and plastic types, comparing these to plastics in the environment. I also examine potential applications of ongoing nest plastic monitoring, and ways to mitigate deaths and injuries caused by entanglement in plastics.

BACKGROUND

Study Sites

This study evaluates the amount and types of plastic in seabird nests on the North Sea islands of Heligoland and Niegehörn. This part of the North Sea is relatively shallow, with productive fisheries and major shipping routes, and is heavily used by both people and wildlife (Quante et al., 2016).

Heligoland

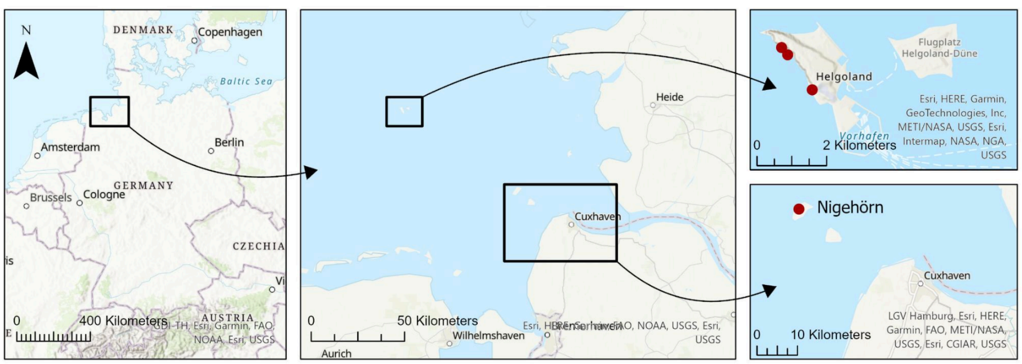


Figure 1: Location of the islands Heligoland and Niegehörn. Locations of sampled seabird colonies (gannets, kittiwakes, and gulls on Heligoland and cormorants on Niegehörn) are marked with red dots.

Heligoland is a small German island in the southern North Sea, roughly 50 km (31 miles) from the German mainland (Figure 1). Heligoland is only about 1 km^2 (1.7 km^2 including its "daughter island", the Dune), and the natural perimeter of the island consists of 60 meter tall, sub-horizontally layered sandstone cliffs that offer excellent nesting habitat for a variety of seabirds. The rock is lower Triassic sandstone that was locally uplifted by a "halite bubble" (diapir). The island has been reduced to its current footprint by wind and wave action, and its top smoothed and leveled by Quaternary glacial erosion (Schmidt and Thome, 1987). The generally slightly angled orientation of the sedimentary rocks that make up Heligoland is readily visible, as the red sandstone (iron oxide hydrates lending the rock its characteristic color) is interrupted at irregular intervals by layers of off-white sandstone (which lack iron oxide hydrates) (Figure 2). These lighter layers are more erosion-prone than the red sandstone, and wear away more easily to create "shelves," or long, cave-like bands in the cliff face that seabirds nest in (Schmidt and Thome, 1987).

Figure 2: The Northwest Heligoland cliffs, showing both the angled orientation of the sandstone and the bands of erosion that are home to nesting seabird colonies.

While human activity and creation of land at the foot of Heligoland's cliffs along the South and East sides of the island has limited erosion and allowed for dense human settlement of those areas, the West and North sides of the island remain largely undeveloped, save for concrete seawalls at the foot of the cliffs on the West of the island (Schmidt and Thome, 1987; personal observation, June 2021). A section of the northwest cliff, which is home to the majority of the breeding seabird colonies on Heligoland, is also a designated nature preserve (Wolf, 2021).

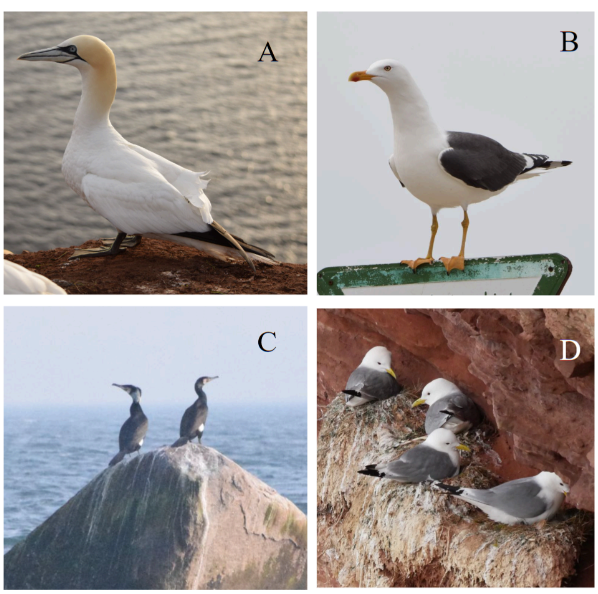


Figure 3: The seabird species studied: northern gannets (A), lesser black-backed and herring gulls (B), great cormorants (C), and black-legged kittiwakes (D).

Two of the seabird species examined in this study have nesting colonies in the northwestern Heligoland cliffs: northern gannets (*Morus bassanus*), hereafter "gannets," (Figure 3a) and black-legged kittiwakes (*Rissa tridactyla*), hereafter "kittiwakes" (Figure 3d). Other seabirds that nest alongside these species on Heligoland, such as razorbills (*Alca torda*), common murres (*Uria aalge*), and northern fulmars (*Fulmarus glacialis*) were not included in this study as they do not build nests.

The colony of lesser black-backed gulls (*Larus fuscus*), and European herring gulls (*Larus argentatus*) that was examined in this study is located at the foot of the southwestern cliffs on Heligoland. As the colony of lesser black-backed gulls and herring gulls was mixed, and it was not possible to differentiate the nests of each species when gathering data from them, lesser black-backed gulls and European herring gulls are hereafter summarily described as “gulls.” However, the colony consisted primarily of lesser black-backed gulls (Figure 3b).

Niegehörn

Cormorants (*Phalacrocorax carbo*), hereafter “cormorants” (Figure 3c) do not nest or breed on Heligoland, but images of cormorant nests included in this study were taken on the German island Niegehörn, located roughly 43 km southeast of Heligoland in the North Sea and approximately 14 km northwest the German mainland coast (Figure 1).

Niegehörn is a small, uninhabited, artificial island that is home to a variety of shorebird, duck, and seabird colonies (Rothfuß, 2022). As of 2017, the cormorant colony on Niegehörn consisted of 203 nests (Grave, 2018).

Plastics in the Environment

Plastics from a variety of sources are entering the marine environment and are of increasing concern for many organisms, including seabirds (Paleczny et al., 2015). Plastics are a relatively new material, and their commercial use is a product of the 20th century. With their many useful qualities and vast range of applications, plastics slowly rose in popularity following World War I and became a staple of everyday life after World War II. What we commonly refer to as plastics are generally synthetic materials made up of many large, intertwined molecules called polymers. We can shape them and add chemicals (additives) to them to give plastics almost any shape or texture, from soft and flexible to sturdy and rigid, and serve almost any purpose, be it cling film for keeping food fresh, or bumpers on a car (Hahladakis et al., 2018). Since plastic is so lightweight, it can improve fuel efficiency in vehicles and transport of goods. Finally, plastic is inexpensive, making it an appealing material to make disposable objects out of, from to-go containers to medical equipment (Tullo, 2013).

Unfortunately, the very qualities that make plastics so desirable for packaging, furniture, outdoor structures, electronics, and soft fabrics, etc., make them particularly hazardous in the environment. Plastic objects, from sheet-like objects (e.g., plastic bags), to hard disposable knives and forks, to soft polyester shirts or blankets, or lightweight Styrofoam, all have negative impacts on the environment – many before, and all after, we dispose of them. Their waterproof, rot-proof properties prevent them from being quickly broken down and biodegraded. Their light weight and low density make them more likely to be blown from landfills, and allow them to float at the surface of rivers and oceans. The many additives we incorporate into plastics in order to imbue them with useful properties leave the plastic and enter the environment around them.

The low cost of plastics means that their material loss to the environment is no financial hardship to humans. Unfortunately, efforts to keep plastics out of the environment consist of a patchwork of regulations and policies that are often ineffective at containing plastic waste (Freinkel, 2011).

It is difficult to calculate how much plastic enters the oceans every year. Jambeck et al. (2015) calculated that in 2010, anywhere between 4.8 and 12.7 million metric tons entered the oceans annually. This number is only set to increase, and Jambeck et al. (2015) estimates that by 2025, these numbers will increase tenfold. Plastics enter the oceans mainly via rivers, with some direct sources from vessels at sea and from the fishing industry. While some plastic enters the oceans due to accidents in shipping, from coasts due to natural disasters, and from losses in fishing industries, these sources are not well recorded, so most of the plastic pollution we are able to trace is improperly discarded or mismanaged trash (Jambeck et al., 2015).

Because so much plastic ends up in the world's oceans, a wide variety of marine organisms interact with plastic and are negatively affected by it. Entanglement, ingestion, and obstruction are main ways in which organisms interact with plastics. Entanglement in old fishing gear or sheet-like plastic often leads to injury or death in marine mammals, birds, turtles, and sometimes even fish. Pieces of plastic that are small enough to swallow are ingested by a wide range of species, including marine mammals, birds, turtles, fish, and invertebrates that are unable to distinguish them from natural food sources. Ingestion can lead to reduced fitness or death, through blockage of the digestive tract or filling the stomach with indigestible material. Even sessile organisms like corals are negatively impacted by plastics, when debris covers them, blocking water flow and light penetration (Law, 2017). Of 693 species examined in one study, 17% of species that interacted with plastic were considered threatened or near threatened (Gall and Thompson, 2015), indicating a potentially significant population-level impact. Additionally, the threat of plastics in the environment is increasing, as plastic continues to accumulate in the environment. Kühn et al. (2015) found that the number of species for which plastic entanglement or ingestion has been recorded doubled between 1997 and 2015.

Plastics and Seabirds

There are multiple ways in which plastic in the environment can negatively impact birds.

Ingestion: Plastics may be ingested by birds because they confuse them with food items (Cadee, 2002; Ibanez et al., 2020). Plastic that is small enough to be ingested can cause death by blocking parts of the digestive system. This is a significant threat as in one study, a single piece of ingested plastic resulted in an estimated 20% mortality rate in birds (Roman et al., 2019). When not blocking the digestive tract, plastic can physically fill up the stomachs of birds. While some birds naturally regurgitate indigestible material and can expel plastics in that manner, those that do not, such northern fulmars, can die of starvation if plastic fills their stomachs (van Franeker et al., 2011). Even when plastic doesn't lead to death by starvation, its presence is still linked to a reduction in fitness (Spear et al., 1994). Wilcox et al. (2015) estimates that by 2050, 99% of seabird species will include individuals that have ingested plastic. Ingested plastics also have the potential to release harmful additives contained in the plastic or chemicals sorbed from other plastics and reabsorbed by plastic fragments, although the extent to which plastics contribute to the uptake of these chemicals is not clear (Tanaka et al., 2020; Hahladakis et al., 2018; Herzke et al., 2015).

Entanglement: There are also many recorded instances of birds becoming entangled in plastic, leading to injury or death (Votier et al., 2011; Thompson et al., 2020; Ryan, 2020; Garcia-Cegarra et al., 2020; Hartwig et al., 2007; de Souza Petersen et al., 2016; Witteveen et al., 2017; Tavares et al., 2016; O'Hanlon et al., 2019; O'Hanlon et al., 2021; Antczak et al., 2010; Heimstra et al., 2021; Henderson et al., 2022; Schrey and Vauk, 1987), although comprehensive data regarding the extent of entanglement-related mortalities does not currently exist, making the extent of this threat unclear (O'Hanlon et al., 2019).

Entanglement can occur at sea during foraging or in nests (Figure 4). Entanglement is often deadly, as entangled birds are hindered in their ability to fly and forage (Schrey and Vauk, 1987). In nests, chicks are often victims of entanglement as they grow into snares and loops of plastic that tether them to their nests, preventing chicks from leaving once they are old enough to fly and seek food for themselves. While the recorded number of deaths by entanglement is currently not high enough to be responsible for a decline in population size, deaths by entanglement are often slow and painful, and for humanitarian reasons, should be avoided when possible (Votier et al., 2011).

The plastics primarily responsible for this entanglement are frequently fibrous, fisheries-related debris. As commercial fishing is prevalent in the North Sea, there is significant overlap between the nesting and foraging grounds of many seabirds and fibrous fisheries debris in the environment (O'Hanlon et al., 2021; Montevecchi, 1991).

Figure 4: Seabird deaths by entanglement on Heligoland. Arrows indicate dead murres and gannets.

Commercial Fishing in the North Sea and Plastic Pollution

Commercial fishing by the inhabitants of Heligoland itself was important to the Heligoland economy until the end of the Second World War. After heavy bombing necessitated the evacuation of the island in 1945, Heligolanders returning to the island in 1952 found that fishing was no longer profitable. The previously economically important lobstering industry was also almost entirely lost due to the collapse of the lobster population around Heligoland in the mid-1950s (Klimpel, 1965).

However, the North Sea, overall, remains one of the most important fishing grounds worldwide, and approximately 3.5 million tons of fish and shellfish were caught in there in 2013 (Pinnegar et al., 2016). Not only do nations bordering the North Sea have large commercial fishing fleets (Schacht et al., 2008), but it is also one of the most heavily bottom trawled regions in the world (Amoroso et al., 2018; Kroodsma et al., 2018).

Bottom Trawling

Bottom trawling, which includes beam and otter trawling, involves pulling one or more large nets behind one or more fishing vessels. These nets drag along the seabed, scooping up fish and marine organisms residing near or at the bottom of the seabed. Bottom fish and other organisms that are at or near the bottom are swept into a funnel-shaped net, where they collect in the pear-shaped end, called the cod-end. When the nets are hauled aboard, fish are removed by unlacing part of the cod-end (Stepputtis et al., 2022).

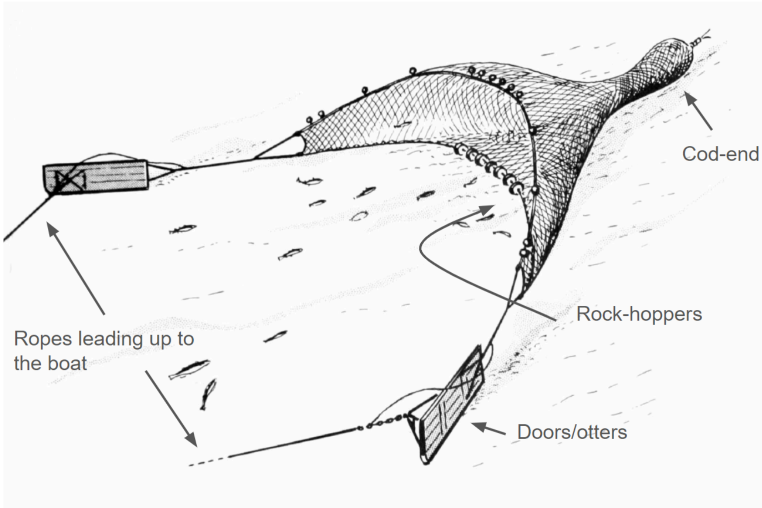


Figure 5: Diagram of an otter trawl, a type of bottom trawling net. Illustration from Knake, 1956.

Nets differ in the hardware elements they include (Figure 5). Some have large metal or wood panels (called doors or otters) attached to the cables that connect the ship to the net. These serve dual purposes: they stir up sediment, herding fish towards the mouth of the net, and utilize water pressure to keep the mouth of the net open. Others have a large rigid beam that spans the width of the mouth of the net to keep it open. Many nets also have metal and rubber spools or wheels along the bottom edge of the net, called “rock-hoppers”, allowing the net to move more freely over rocks and obstacles on which the net would otherwise get caught. Additionally, metal chains along the bottom edge of the front of the net (called tickler chains) stir up sediment and dislodge organisms hiding close to the bottom (Stepputtis et al., 2022).

In addition to the hoppers and ticklers, many trawling nets also include protective material fastened to the underside of the cod-end of the net (Figure 6). When the cod-end fills and becomes heavy with fish and other marine organisms, it drags along the seabed. As the seabed is often rocky or uneven, nets can easily be damaged. To avoid repairing or replacing expensive nets, trawlers often fasten so-called “chafing material” to the underside of the cod-end. This chafing material bears the brunt of abrasion and snaring, acting as a sacrificial buffer between the seabed and the trawling net (Stepputtis et al., 2022).

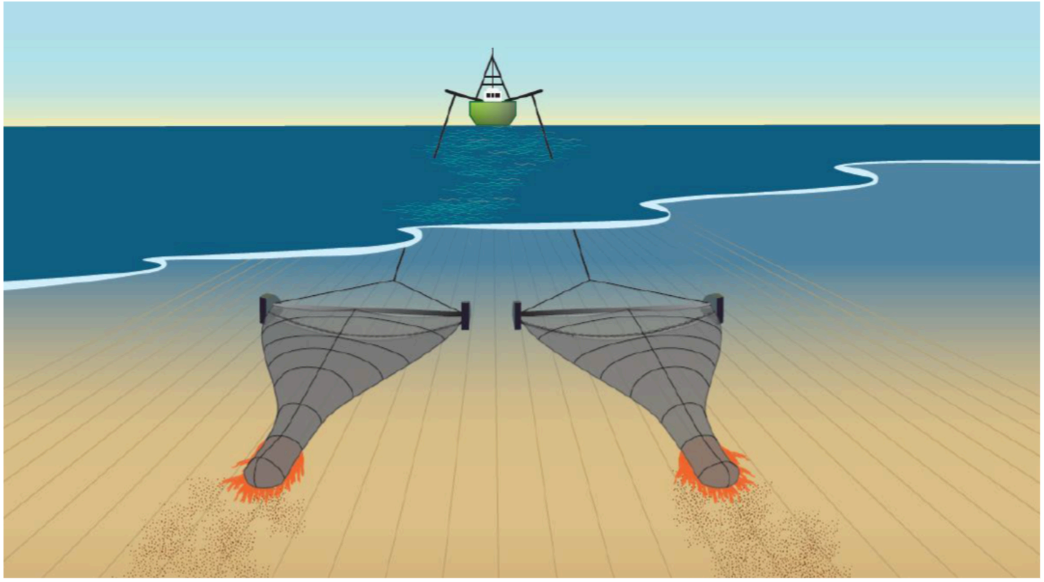


Figure 6: Dolly ropes, shown here in orange, are fastened to the cod end of trawling nets to protect them from wear. Image credit: Annemarie Schütz in Sepputtis et al., 2022.

Before the widespread availability of inexpensive polymers, chafing material on trawl nets consisted of cow hides treated with an algaecide. Old bicycle tires and pieces of worn out rope were also used in some cases. As plastics became available and inexpensive, however, they have completely replaced cow hides (Demetri, 2016; Bekaert et al., 2015; OSPAR, 2020b). Today, chafing material is generally sacrificial, and made up of inexpensive polyethylene or polypropylene monofilament bundles (OSPAR, 2020a; OSPAR, 2020b).

Environmental Impacts of Bottom Trawling

Bottom trawling has a notorious reputation for causing environmental damage. As the mouth of the net (often weighted down with chains to stir up sediment and organisms) drags along the seabed, it can dig up to 8 cm deep into the sediment, destroying marine habitats and ecosystems, especially fragile ones such as coral assemblages. As trawling nets indiscriminately collect all marine life they encounter, trawling also results in significant bycatch. Depending on the target species, bottom trawling can result in as much as 95% bycatch (Schacht and Bongert, 2008). While many negative aspects of trawling have been documented and some are being monitored, the impacts of trawling are complex and current monitoring criteria may be underestimating its impacts (McLaverty et al., 2023).

Another environmental impact of bottom trawling includes lost or abandoned gear (Buhl-Mortensen and Buhl-Mortensen, 2018). In fact, a Belgian fisheries research group estimates that between 2,000 and 12,000 tonnes of commercial fishing gear is lost in the North Sea each year (OSPAR, 2020b; Bekaert et al., 2015). This lost gear often resurfaces on beaches or floats at the surface of the sea. In regularly conducted beach litter monitoring on North Sea beaches, 13% of all beach litter was fishing gear (OSPAR, 2020b), a percentage that increased to 62% when examining litter collected at sea (Bekaert et al., 2015).

A major category of lost fishing gear is chafing material. Chafing material is designed to tear or wear out in place of the net, and often ends up in the marine environment. In one OSPAR beach litter monitoring report, 67% of fishing litter found was classified as “lines,” a category including and largely consisting of chafing material (OSPAR, 2020b). A Norwegian beach litter monitoring report found that of all “lines” collected, 99% were chafing material (Bråte et al., 2019). The amount of chafing material found in the environment may also be underreported, as some papers identify plastics found in fish or nests only as commercial fisheries debris, but images of those fibers strongly resemble chafing material (Rummel et al., 2015).

Spekvis, a Belgian research group with the aim of reducing chafing material input into the environment worked together with local fishermen that used chafing material. Spekvis reports that fishermen estimate that 25% of the chafing material that is torn out in the course of normal, intentional wear is lost within the first two weeks of use (Bekaert et al., 2015; OSPAR, 2020a). Remaining chafing material becomes matted and heavy with debris over time and must be replaced regularly. The frequency of replacement depends on a variety of factors, such as how rocky the seafloor is, and can range from daily replacement to replacement only a few times a year (Bekaert et al., 2015). Overall, however, it is estimated that every year approximately 25,000 kg of chafing material is lost to the North Sea through normal wear, and as chafing gear is often lost overboard during maintenance, another 25,000 kg accidentally or intentionally ends up in the North Sea during repair or replacement of chafing material (OSPAR, 2020a; Bekaert et al., 2015).

When these filaments end up in the ocean, they tend to float or remain relatively high in the water column, where pelagic birds or fish encounter them (Rummel et al., 2015). In a sample of fish caught around Heligoland, 10% were shown to contain thick orange monofilament fragments in their stomachs (Rummel et al., 2015). While this monofilament was not identified by the authors as chafing material, the description of thick colored monofilament fibers made of polyethylene and polypropylene is very much in agreement with the physical and chemical properties of chafing rope. Rummel et al. (2015) speculated that the fibers likely originated from commercial fishing gear, and photos of the fibers appeared very similar to chafing material fragments seen on Heligoland’s beaches (personal observation, June 2021).

Seabirds encounter chafing material in the water, and gannets have been observed carrying strands or whole bundles back to their nests along with seaweed (a preferred, natural nesting material). The very distinctive orange and blue colors of the chafing material used in the North Sea can also be seen in large quantities in gannet nests in the Heligoland breeding colony, and found washed up on beaches on Heligoland (personal observation, June 2021).

Dolly Ropes as Chafing Material

In the North Sea, these plastic chafing fibers are most commonly known as "dolly ropes" (OSPAR, 2020a; OSPAR 2020b). They are also known by regional names such as "spekken" or "spekmat" ("bacon," in Frisian), or "Snører" ("[shoe]laces" in Norwegian) (Bekaert et al., 2015; Bråte et al., 2019). Dolly ropes are inexpensive polyethylene monofilaments that are typically twisted into smaller bunches of 25 strands, which are then again loosely twisted together with 30 other bunches to form a flexible, unconsolidated rope. This is then cut into 1-2 m lengths, folded in half, and fastened to the cod end of trawling nets. Because the monofilaments aren't tightly twisted together, they hang from the net as tassels, creating a large surface area of buffering material between the net and the seabed (Figure 7). Dolly ropes are typically bright orange, blue, or black (Bekaert et al., 2015; OSPAR, 2020a).

Figure 7: Orange dolly rope bundles fastened to the cod ends of trawl nets on fishing vessels in the German harbor Cuxhaven.

The color of dolly rope is an important element to some fishermen, but largely irrelevant to others (Bekaert et al., 2015). Some fishermen claim that orange is a better color, as it is easier to see at night, but others say black dolly ropes are preferred as they are cheaper from one company, and more durable from another, making them a more appealing product. Unfortunately, accurate counts of the amount of each color of dolly rope sold is not available to the public. The chemical composition of dolly ropes is not uniform, and is often proprietary information that companies are unwilling to disclose (Bekaert et al., 2015). Dolly rope properties differ between manufacturers, and many sellers do not disclose many specifications for their dolly ropes. While one company reported that their dolly ropes were low density polyethylene and gave measures of thickness, tensile strength, and specific weight (Bekaert et al., 2015), other sellers provided no information beyond price, weight, color, and length of the spool of uncut dolly rope.

Dolly rope samples found in the environment were analyzed following a marine cleanup initiative, "fishing for litter." These samples showed a 75% decrease in tensile strength between the reference material (new, unused dolly rope) and the dolly ropes found at sea. This analysis also determined that the dolly ropes were made of polyethylene, and each fiber was approximately 1 mm in diameter (Gerke et al., 2016).

Plastic in Seabird Nests

In the nests of the seabirds studied, plastics are often very noticeable and present in large quantities (Figure 8). It is not clear exactly why birds include plastic in their nests. They may include plastics simply because they share structural or color similarities with natural nesting material, or even because the structure or color of a type of plastic has social or mechanical advantages. Other cases suggest that plastics may be collected due to similarities to food or other valuable non-nest material, or that certain colors are simply easier to locate in the environment.

Figure 8: Large quantities of brightly colored plastic in nests on Heligoland.

Votier et al. (2011), Bond et al. (2012), and Massetti et al. (2021) observed that northern gannets incorporate ropes and lines into their nests, which often have a structure similar to the algae and seaweed otherwise used by northern gannets as a nest-building material in the region. Other seabirds that use seaweed or fibrous natural nest material including gulls, cormorants, kittiwakes, and noddies have also been observed incorporating plastic fibrous material such as fishing gear and ropes into their nests (Tavares et al. 2016; Garcia-Ceguarra et al. 2020; Ryan 2020; O'Hanlon et al., 2021; Hartwig et al., 2007). Inclusion of artificial material that closely resembles typically-used, natural material has also been observed in coots and shrikes, which are freshwater birds and passerines, respectively (Heimstra et al., 2022; Antczak et al., 2010), suggesting that many birds will readily incorporate plastic into their nests if it shares characteristics (often shape and color) with natural nest material.

In a study conducted on black kites (a raptor species), white plastic was used to decorate nests and potentially indicate status (Sergio et al. 2011). In shrikes (a passerine species), plastic string may be used because it is widely available and easier to manipulate during nest building than natural material (Antczak et al., 2010).

In some cases, birds have been observed preferentially collecting certain types or colors of plastic, and including them disproportionately in their nests. Cases of "mistaken identity" may explain some of these instances. In Seychelles, sooty terns included disproportionately large quantities of green/blue plastic in their colony compared to the proportion present in the environment, which may be due to a similarity in color to a favored prey species (Van de Crommenacker et al., 2021).

In other cases, certain colors of plastic that do not have a natural counterpart are disproportionately added to nests. Some color preferences may be due to an ease in spotting that particular color in the environment. A more conspicuous color may be easier to locate than other colors of plastic or even natural nest material, making it an easier target when seabirds search for nest material. For example, along the Chilean coast, Hidalgo-Ruz et al. (2020) observed that cormorants that included plastic in their nests added red plastic at a higher frequency than would be expected given the proportion of red plastic available in the environment.

Whether a species finds a color particularly conspicuous in the environment may also depend on whether the color or material reflects or absorbs UV wavelengths. Many birds can see wavelengths in the UV spectrum (Olsson et al., 2021), and so see objects differently than humans do. However, in this study, not all of the studied species are UV-sensitive. While members of the gull family including black-legged kittiwakes, lesser black backed gulls , and herring gulls are UV-sensitive, cormorants and northern gannets likely are not (Machovsky Capuska et al., 2011). While the UV-sensitivity of northern gannets and great cormorants in particular have not been examined in the literature, other members of the Sulidae family, which gannets belong to, and of the Phalacrocoracidae family, which cormorants belong to, are not UV-sensitive (Machovsky Capuska et al., 2011).

The presence of UV-sensitivity in gulls and its presumed absence in gannets and cormorants likely relate to their foraging behaviors. Gulls forage in shallower water and on land, where UV vision capabilities can be very useful in identifying food (Machovsky Capuska et al., 2011). Nutrient-rich plant parts as well as insects often reflect or do not reflect UV light in conspicuous ways (Burkhardt, 1982; Tedore and Nilsson, 2021). However, while UV vision is useful for detecting some food sources, it isn't particularly useful at a distance. As gannets dive for prey from heights greater than the minimum distance needed for UV detection, UV sensitivity likely would not provide a significant advantage to them (Machovsky Capuska et al., 2011). Additionally, UV wavelengths can damage retinal tissue, and in a marine environment with high levels of direct and reflected sunlight, the benefits of UV sensitivity may not outweigh the costs of UV damage (Machovsky Capuska et al., 2011; Olsson et al., 2021).

Quantifying and Analyzing Plastic in Seabird Nests

The presence, prevalence, and composition of plastic in nests can tell us about the impacts of human activity on seabirds, and can also give us insights into the behavior and physiology of seabirds. However, there are different ways to identify, quantify, and analyze the plastic in a given nest, and strengths and weaknesses to each method.

Dissection

Quantifying the amount of plastic in seabird nests is most accurate when the nest is dismantled and the proportion of plastic to natural material can be evaluated completely. This method ensures that no plastic is overlooked, and allows plastic buried in the center of a nest to be recorded (Sugasawa et al., 2021; Henderson et al., 2022). However, removing material is disruptive to actively breeding birds, and sometimes logistically infeasible. Removing plastic from a nest may not be possible at all if the nest is only accessible with special equipment and training (such as nests of cliff-breeders) and may not be possible without detrimentally disturbing the breeding birds, such as in nests where a significant proportion of the nest consists of plastic. Such a collection effort can also be expensive and time-consuming. In light of these challenges and limitations, it is often preferable to use a non-invasive method for quantifying plastic in nests.

Visual Scoring

One option is to assign each nest or parts of each nest a score on a scale of "least contaminated" to "most contaminated" (Ryan, 2020). However, visual scoring can be subjective, and therefore will likely differ between scorers (O'Hanlon et al., 2019). While training of visual scorers and repetition of scoring over time can lead to much more consistent results and less variation between scorers (Thomsen et al. 2008), this means that to get consistent and accurate results, scorers must be trained ahead of time, which is time-consuming and may not always be possible. Additionally, scoring or evaluation in the field often involves spending long periods of time near nests which can be a disturbance to breeding birds.

Another method is to estimate the degree of plastic contamination to a certain percent (O'Hanlon et al., 2019). This method produces a proportion of plastic in each nest, which can easily be compared to other nests, whole colonies, or even other species. However, this method, like the previous "scoring" method is subjective and prone to errors, since two evaluators will frequently assign different estimated plastic percentages to the same nest (O'Hanlon et al., 2019).

Image Analysis

Therefore, in an effort to reduce disturbance to breeding birds and colonies and to create a more objective method for evaluating the plastic content of nests, image analysis of nests has been offered as an alternative (Ryan, 2020; Thompson et al., 2020; Verlis et al., 2014; Sugasawa et al., 2021). Taking photos in the field and evaluating them later minimizes disturbance in the field and maximizes documentation and opportunities for evaluation.

Thompson et al. (2020) used the software Coral Point Count with Excel extensions (Kohler and Gill, 2006), hereafter CPCe, to generate a percentage of the nest composed of plastic. This software, originally developed to evaluate the composition of corals in photos, allows the user to superimpose an array of randomly placed points on an image, and to manually categorize what each of these points lands on. This method allows the user to generate a random sample of the makeup of objects in the image. When applied to photos of bird nests, CPCe allows the user to calculate the proportion of points that mark plastic in the nest relative to total nest material, giving a proportion of plastic present in the nest.

With standardized data on the proportion of nests containing plastic and the proportion of plastic in nests, it is possible to objectively compare different species and to track changes in plastic content of a given seabird species' nests over time. CPCe can also be used to calculate the proportion of other variables of interest in nest material, such as the color or type of plastic (if specific materials or objects can be recognized). This information may allow us to speculate as to which colors or types of material are particularly attractive to birds, information that would allow us to target specific types of plastic pollution and work to reduce them at the source.

Seabirds as Bioindicators

By examining seabird nests, we can also gain information about plastic pollution in the environment. This is useful because in some cases, environmental pollutants are difficult to measure directly, due to logistical or cost constraints. To gain information about an environmental pollutant in a more convenient way, a species can be selected as a bioindicator, and a particular parameter of that species monitored as a proxy for a particular environmental pollutant. Seabirds are well suited for this method of monitoring marine-based pollution (Furness and Camphuysen, 1997).

An example of a seabird bioindicator species is the northern fulmar, which is used as a bioindicator for an aspect of marine plastic pollution in a legislative framework set up the Convention for the Protection of the Marine Environment of the North-East Atlantic, more commonly known as OSPAR[1]. The convention has been signed by fifteen countries in Europe as

[1] The name OSPAR is a combination of "Oslo" and "Paris," as the Convention for the Protection of the Marine Environment of the North-East Atlantic replaced the previous Oslo and Paris Conventions.

well as the European Union, and it monitors and implements legislation to reduce anthropogenic impacts on marine environments. As northern fulmars are prone to ingesting (and do not regurgitate) plastic from the surface of the ocean, plastic that they ingest is used as a proxy for the amount and type of plastic floating at the surface of the North Sea. Northern fulmars that are found dead in and around the North Sea are collected, their stomach contents weighed, and the quantity and type of plastic found is recorded (van Franeker et al., 2011).

Monitoring a bioindicator species illustrates how parameters change over time, and can also be used to evaluate the efficacy of efforts to address certain pollution sources. For example, while no significant trend in the overall amount of plastic found in fulmar stomachs was seen between 1979 and 2007, an analysis of the types of plastics found in stomachs showed that industrial plastic (such as pre-production plastic pellets or nurdles) had decreased over time and that consumer plastics had increased at a similar rate (van Franeker et al. 2011). Therefore, while efforts to reduce nurdle pollution had actually been successful, that success had been hidden by an increase in other pollution sources.

Data collected from bioindicators is also frequently coupled with regulatory or legislative targets and efforts. In 2005, when oil spills and oil-contaminated birds were of concern in the North Sea, OSPAR used common murres as a bioindicator for oil spills. They set a target that, at most, 10% of common murres that were found dead should be contaminated with oil. As the percentage of oiled birds could not realistically be expected to be zero, a percentage of oiled birds below that 10% threshold was considered acceptable. A similar approach was taken with the implementation of northern fulmars as bioindicators. As it was deemed unrealistic to expect a complete elimination of all plastic pollution in the North Sea, OSPAR set a target level of plastic contamination: at most, 10% of northern fulmars found may have > 0.1 g plastic in their stomachs (van Franeker et al., 2021).

While these thresholds are largely arbitrary, they provide legislative bodies with targets to aim for. Ideally such thresholds are determined by the degree of pollution that begins to impact a species' fitness, but this cannot always be accomplished while still establishing targets that feel attainable for legislators (van Franeker et al., 2021).

Given the information that such bioindicator species can provide, and the demand for methods to quantify the presence and impact of plastics in the marine environment, many studies have highlighted the possibility of using the nest plastic content of various seabirds as bioindicators (Tavares et al., 2016; Grant et al., 2021; O'Hanlon et al., 2019; Ryan 2020; Bond et al., 2012).

However, species under consideration for use as indicators of environmental plastic pollution need to be selected carefully. O'Hanlon et al. suggest that a bioindicator species must meet four criteria: the species must be "abundant, widely distributed, affected by the pollutant of concern, and reflect the levels of this pollutant in the environment" (O'Hanlon et al., 2019, p. 8).

Furness and Camphuysen (1997) also stipulate that bioindicators noticeably respond to changes in a timely manner. These criteria are logical: the population from which data is being collected needs to be large enough so that it is practical to collect data (and so that data collected from the population is statistically useful). The more widely distributed a species is, the more useful it is for evaluating larger trends. The species needs to interact with the pollutant in some measurable way, and that way must represent environmental pollution levels. Lastly, changes in pollution levels must be noticeable relatively quickly, ideally in a matter of years, not many decades (Furness and Camphuysen, 1997).

As O'Hanlon et al. (2019) point out, northern gannets meet the first three requirements of a bioindicator listed above, but fall short of the fourth. As gannets have, in other studies, shown that they have a preference for fibrous plastic, their nests do not accurately reflect the plastic found in the environment around them (Votier et al., 2011; Bond et al., 2012; O'Hanlon et al., 2019). Bond et al. (2012) also argues that northern gannets are not particularly well suited to be bioindicators as they reuse nests over many years, and changes in nest material may only become apparent over multiple decades.

However, even if some species aren't well-suited to be an indicator species for a broad category of pollutants, or if there are not any other species that are better suited, they can still be valuable in more specific ways. Given their preference for fibrous plastics, gannets are well-suited for monitoring the presence or absence of certain specific types of fisheries equipment, or how marine fisheries pollution changes over time (O'Hanlon et al., 2019).

Another important consideration when choosing an indicator species is developing and agreeing on a consistent and standardized method of quantifying the pollutant of interest. For northern fulmars, the grams of plastic in a bird's stomach are weighed (van Franeker et al. 2011). When using the nests of a seabird species as an indicator, a method of quantifying plastic also needs to be agreed upon.

Study Species

Northern Gannets

Northern Gannets (*Sula bassanica)* are a part of the family Sulidae, which includes other gannets and boobies, and are present in marine environments around the globe. Northern gannets (Figure 9) are accomplished fliers, with wingspans of up to 1.8 m (Cramp and Simmons, 1977). They often forage 300 km away from their colonies in search of food, although they stray less far once they have chicks to feed, generally flying only 200 km away at that point (Lane et al., 2020). Northern gannets eat a variety of fish, including cod, mackerel, haddock, and others. They hunt by plunge diving, or diving into the water from a height of 10 to 40 m, and capturing fish underwater, usually in depths of 10-15 m (Cramp and Simmons, 1977). This method of hunting requires gannets to visually locate fish first above water, but then also actively pursue individual fish underwater, which is done by sight (Machovsky-Capuska et al., 2012; Cramp and Simmons, 1977). Gannets will also duck their heads underwater and dive from the surface, similar to cormorants (Cramp and Simmons, 1977). Gannets prefer to hunt schooling fish, and often identify new feeding opportunities by joining or following conspecifics that are also foraging (Machovsky-Capuska et al., 2014).


Figure 9: A northern gannet sits on its nest in the Heligoland cliffs.

While they spend most of their lives at sea, in waters on the coastal shelves of Europe, North America, and North Africa, northern gannets come ashore to breed and raise their young. Preferring to nest in colonies in large cliffs, northern gannet breeding colonies are long-established and well known in Britain and Ireland, Iceland, France, and Norway (Cramp and Simmons, 1977). On Heligoland, however, northern gannets did not establish a breeding colony until 1991 (Dierschke et al., 2011). The colony has been growing since then, and in 2021, consisted of 1458 breeding pairs (NABU, 2022).

Northern gannets pair for life, and return to the same nest year after year. Nests are normally constructed from natural materials including seaweed, grasses, mud, feathers, and guano. While male gannets collect the bulk of nest material, females also contribute once the egg has been laid and incubation has begun (Cramp and Simmons, 1977; Gurney, 1913). Nest material is generally collected close to the colony, with grasses often pulled from the tops of the cliffs that colonies reside in, and mud frequently scraped from areas immediately surrounding the nest (Gurney, 1913). Other material such as seaweed is also collected close to the breeding colony (Tavares et al., 2016). Seaweed is a particularly advantageous nesting material due to its mechanical and insulative properties. Seaweed is flexible and heavy when wet, and can be positioned in the nest without flying away in gusts of coastal wind. When it dries, it contracts somewhat, becoming rigid and keeping its shape in the nest. This not only helps protect nests from wind damage (Gurney, 1913), but it also acts as an insulating material. Australasian gannet nests containing seaweed remained warmer overnight than nests constructed of other natural material such as grass (Matthews et al., 2008).

Nest sites and existing nests are reused each year. Depending on the site, only a small proportion of nests are lost entirely to wind or overwash by waves each winter. Nests that survive with any amount of material are built upon the next breeding season (Montevecchi, 1991). Since most nests accumulate material over time, northern gannet nests can reach impressive sizes, standing as tall as 2 meters (Gurney, 1913; Cramp and Simmons, 1977).

Unfortunately, northern gannets' choice of nest material and reuse of nests has resulted in many interactions with man-made material, especially plastics and fishing gear. Human artifacts have been reported in the nests of northern gannets as far back as 1913, when Gurney noted that gannet nests on Bass Rock, Scotland, contained a range of objects including rubber shoes, a golf ball, and perfume bottles (Gurney, 1913). While these objects are unlikely to have caused much damage to the inhabitants of those nests, more recent studies have found man-made debris in nests that are less benign.

As the field of plastics in the environment has gained relevance, many studies have documented interactions between Sulidae and plastic (Massetti et al. 2021; Merlino et al. 2018; Votier et al. 2011; Schrey and Vauk, 1987; Montevecchi, 1991; Norman, 1995; Lavers et al., 2013; Tavares et al., 2016; Bond et al., 2012; Verlis et al., 2014). While most studies focus on the use and dangers of plastic in the nests of Sulidae, gannets can also become entangled in plastic outside of the nesting season. On Heligoland in 1987, 29% of northern gannets found dead or immobile on beaches were entangled in plastic fishing gear (Schery and Vauk, 1987). As there was no breeding colony on Heligoland at this time, these birds became entangled during their migration South at the end of the breeding season.

Plastic in nests remains a much larger concern for Sulidae, however. In 1991, when the first northern gannet pair bred and raised a chick on Heligoland, the chick died after becoming entangled in plastic in the nest (Dierschke et al., 2011). At that same time, across the Atlantic, northern gannet colonies in Canada reported that plastic was present in 97% of nests (Montevecchi, 1991). A decade and a half later, 100% of gannet nests that were examined on Heligoland contained some amount of plastic (Hartwig et al., 2007). Since then, plastic in gannet nests has been reported in the Mediterranean (Massetti et al., 2021), Canada (Bond et al., 2012), Wales (Voter et al., 2011), and in the nests of boobies and Australasian gannets, other members of the family Sulidae (Verlis et al., 2014; Merlino et al. 2018; Norman, 1995; Lavers et al., 2013; Tavares et al., 2016). While there is some difference in the proportion of nests containing plastic across these species, this is likely due to differences in local pollution sources, type and structure of that pollution, and similarities to natural nest materials that may differ between species.

Among the types of plastic found in seabird nests, fibrous material such as fishing gear is of particular concern. While ingestion of plastic fragments can be very dangerous for seabirds (Cartraud et al., 2019; Roman et. al., 2019; Pierce et al., 2004), fisheries-related plastic is most likely to result in death in seabirds, due to the threat of entanglement that nets, ropes, and lines pose (Costa et al., 2020). As seabirds often nest in areas with active fisheries, studies of plastic in the nests of Sulidae have focused primarily on the dangers of entanglement (Votier et al., 2011; Lavers et al., 2013; Norman, 1995; Montevecchi, 1991).

Furthermore, seabirds, and northern gannets in particular, show preferences for certain types of plastic. Gannets prefer to include fisheries-related material in their nests (Votier et al. 2011; Bond et al., 2012), which poses a higher risk of entanglement than plastic or rubber fragments. This preference has been attributed to the fact that ropes, lines, and net fragments are morphologically similar to seaweed that gannets normally collect and utilize in nest building (Votier et al., 2011; Bond et al., 2016; Tavares et al., 2016).

Northern gannets have been nesting on Heligoland since 1991. The colony has been growing since then, and in 2021, consisted of 1,458 nesting pairs (NABU, 2022). This colony growth is faster than can be explained by offspring returning to nest, as gannets only raise one chick each year, and offspring mature only after four years (Cramp and Simmons, 1977). Therefore, immigration from other gannet colonies in the North Sea is likely responsible for much of the colony growth of the last 30 years. This is supported by band resights, which indicate that some adult individuals were banded in Scotland and immigrated to Heligoland later (Dierschke et al., 2011).

Great Cormorants

Great cormorants (*Phalacrocorax carbo*) are relatively large, mostly black seabirds (Figure 10). Cormorants and shags (a close relative) are found all over the world, and are skilled at catching fish by diving and swimming underwater. They locate prey by sticking their heads underwater, looking around, and diving from the surface to pursue prey (Cramp and Simmons, 1977).

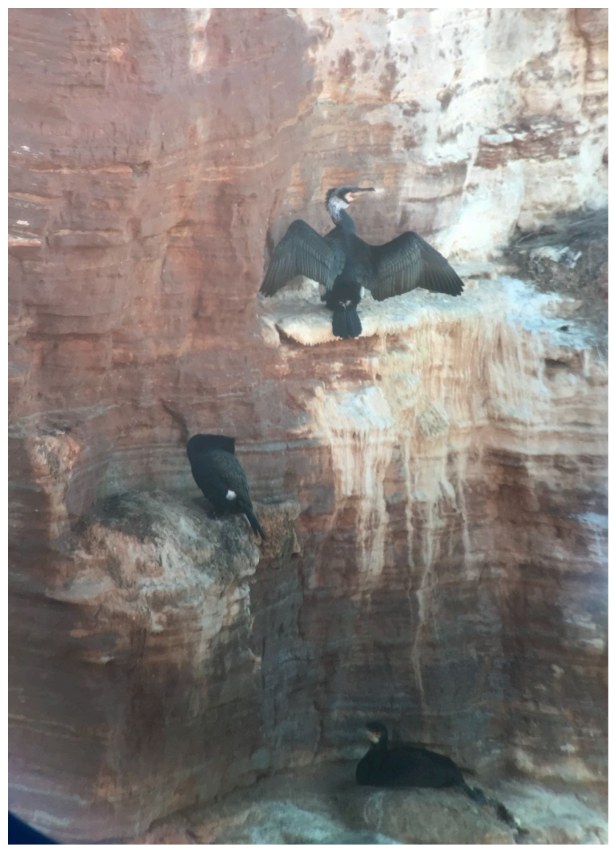


Figure 10: Two great cormorants rest while a third dries its wings in the Heligoland cliffs.

Great cormorants are opportunistic, and use material found in the environment to build their nests. While they reuse their nest sites each year, nests themselves are generally rebuilt each season. Cormorants prefer to nest in cliffs, but will also nest on open ground. While males collect nest material, females construct the nest itself. Nesting material is typically collected up until the time when chicks fledge. Without access to man-made materials, cormorant nests will be composed of seaweed, reeds, and twigs (Cramp and Simmons, 1977). Seaweed is usually collected at the surface of the water, but cormorants do sometimes dive to collect it. In environments with man-made materials, especially plastics, cormorants will readily incorporate these (Podolsky and Kress, 1989). In the Gulf of Maine in 1987, 98% of plastic found in cormorant nests was lobster line, a result of the local lobstering industry (Podolsky and Kress, 1989). In Chile, red-legged cormorants incorporated large quantities of plastic into their nests (Garcia-Cegarra et al., 2020).

Black-legged Kittiwakes

Black-legged kittiwakes *(Rissa tridactyla*) are relatively small birds in the gull family (Figure 11). They spend their lives at sea, coming to shore only to breed. They prefer to nest in steep cliffs, as these locations are inaccessible to most predators. Kittiwakes are very well adapted to building nests in cliffs, and are able to build on very narrow outcrops that many other birds (including predators that prey on kittiwake eggs or chicks) cannot land or build on. Kittiwake nests have deep nest cups, which keeps eggs and chicks from falling out, and kittiwake feet and claws are unusually strong and sharp, giving them more purchase on narrow rocks (Cullen, 1957).

Figure 11: Black-legged kittiwakes sit in their nests in the Heligoland cliffs.

Kittiwake nests must be very stable and well secured to the cliffs, as they are built on incredibly narrow rock outcrops (Cullen, 1957). Kittiwake eggs are incubated for approximately 27 days, and chicks are fed in the nest until they fledge, which can take up to six weeks (Dierschke et al., 2011). To ensure nests are secure and stable, kittiwakes build their nests primarily out of wet mud and soil, although they also incorporate fibrous material such as seaweed, and line the nest cup with finer material such as dry grasses. Mud is often collected right after rain events, and large groups of kittiwakes will go on mud-collecting missions together, likely to reduce the risk of predation for each individual (Cullen, 1957).

Interactions between kittiwakes and plastics have been documented in the past. In a Danish kittiwake colony, 39.3% of kittiwake nests contained plastic in 1992, a percentage that rose to 57.2% in 2005. The plastics in kittiwake nests at that location were deemed similar enough to the types of plastics found on nearby beaches that a preference in plastic debris was excluded (Hartwig et al., 2007). Plastic has also been found in kittiwake stomachs in Canada, where 15% of examined kittiwake stomachs contained plastics. These plastics were likely ingested accidentally during feeding at the surface of the ocean, where floating plastic could easily be mistaken for food (Baak et al., 2020).

Black-legged kittiwakes feed mostly at the surface, foraging in flocks and plunging no more than a meter underwater in pursuit of fish or invertebrates. Adept fliers, kittiwakes often travel 40 km away from their colonies to forage, although this distance reduces to approximately 27 km once their chicks hatch and food must be brought back to the nest frequently (Cramp and Simmons, 1983).

Black-legged kittiwakes have been documented breeding on Heligoland until the 1840s, when they were extirpated by extensive hunting. Isolated kittiwake breeding pairs returned in 1938, but the colony didn't properly reestablish itself until after 1952 (Dierschke et al., 2011). While the Heligoland population stabilized around 7,000 breeding pairs in 2011, a recent decline has been attributed to the climate change-caused warming of the North Sea and a change in food availability for kittiwakes (MacDonald et al., 2015). As of 2021, the kittiwake population on Heligoland consisted of 3,195 breeding pairs (NABU, 2022).

Herring and Lesser Black-backed Gulls

Gulls are diverse and widespread seabirds, being highly adaptable to human environments, and are opportunistic foragers (Cramp and Simmons, 1983).

In this study I examined a mixed nesting colony of lesser black-backed and herring gulls (Figure 12). These two species, similar in size, nest together in a mixed colony on Heligoland. Their nests cannot easily be differentiated from one another, and they are often found in mixed colonies elsewhere as well (Rothfuß, 2022; Cramp and Simmons, 1983).

Figure 12: A lesser black-backed gull (left) and a herring gull (right) sit on their nests in short vegetation.

Lesser black-backed gulls feed on fish, marine and terrestrial invertebrates, berries, and human food scraps and refuse. They can pursue insects in the air, and when plunging into water to capture food, they locate their prey at heights of 8-12 m. Lesser black-backed gulls also steal food from other birds, and are scavengers. Herring gulls' diets are similar, consisting of fish and invertebrates, the latter including large quantities of crabs and mollusks. Herring gulls also steal food from other seabirds, and are exceptionally adept at exploiting human activities for food. Herring gulls will follow fishing boats, eating fish offal and bycatch, as well as agricultural machinery on land, feeding on earthworms that are brought to the surface by plows. In fact, herring gulls have the highest breeding success when they have access to landfills. Herring gulls readily fly 25-35 km away to forage, and climb to heights of 150-200 m when looking for fish. Despite their ability to locate prey visually from a great height, calls from other conspecifics are most useful in locating new food sources (Cramp and Simmons, 1983).

Both species form multi-year, monogamous pair bonds, although the persistence of these bonds outside of the breeding season is more uncommon in lesser black-backed gulls than in herring gulls. These two gull species both nest in colonies. Herring gulls prefer to nest on rocky coasts and cliffs, while lesser black-backed gulls favor open ground or vegetated open ground. However, both will also nest on cliffs and roof-tops (Cramp and Simmons, 1983). On Heligoland, herring and lesser black backed gulls nest together on a relatively open, lightly vegetated rubble field between the base of the Heligoland cliffs and a concrete sea wall. This area is located below the southwest Heligoland cliffs, and is largely undisturbed by humans during the breeding season, as the cliffs and the area below them are closed to the public due to the dangers of rockfall (personal observation, June 2021).

Herring and lesser black backed gulls both build substantial nests primarily using vegetation. In herring gulls, both partners collect nesting material, although males contribute more than females. Nest material is collected up until the point of hatching, and material appears to be collected relatively close to the nest. Gulls will bring material to the nest when returning from foraging, when they relieve the other incubating parent on the nest. Once parents are relieved, they often remain nearby at first, collecting material from the immediate area around the nest and presenting it to their partner (Cramp and Simmons, 1983).

Various gull species' interactions with plastic have been documented (Lenzi et al., 2016; Stewart et al., 2020; Witteveen et al., 2017), including those of herring and lesser black-backed gulls (Thompson et al., 2020). Gulls incorporate plastic into their nests during nest building, collecting material from nearby locations to do so. They sometimes seem to favor ropes and packing strips in these efforts. Plastic in nests also often ends up there due to gulls ingesting plastic and regurgitating it in the nest (Witteveen et al., 2017). Gulls are able to routinely regurgitate non-digestible material that they consume normally (e.g., crab and mollusk shells, bones), and also regurgitate food in order to feed their chicks. Both types of regurgitation can import plastic and other man-made material into the nest (Thompson et al., 2020; Witteveen et al., 2017). While plastic is very commonly found in regurgitated pellets, gulls also eat and regurgitate metal and glass (Stewart et al., 2020; Lenzi et al., 2016).

METHODS

Nest Selection

I chose the species included in this study (gannets, cormorants, kittiwakes, and gulls) because their nests were readily available to be photographed (gannets, kittiwakes, and gulls) or existing images of their nests were available to me (cormorants). Depending on the species, the sample size of nests photographed relative to the total colony size varied.

Of the 3,195 breeding pairs that were counted in the Heligoland cliffs in Summer 2021 (NABU, 2022), I selected 55 kittiwake nests based on the feasibility of taking suitable photographs. Many nests were not included as they could not be viewed or photographed safely or at a suitable angle for evaluating the nest cup.

I also selected gannet nests based on the feasibility of taking a photo of as much of the nest as possible, and included nests at a variety of stages. This meant that some nests were very small, consisting of only a nest cup, and likely belonged to younger pairs, as they were often on the margins of the colony, which is a less desirable location for nesting. Other nests were more well-established, consisting of a large buildup of material from previous breeding seasons, and a (proportionally) small nest cup on top, in which the egg was laid and the chick raised. Of the 1,458 breeding pairs counted in 2021 (NABU, 2022), I photographed and included 62 gannet nests.

As the gull colony I surveyed was relatively small, I photographed nearly all gull nests in the colony. Nests that had a very poor nest cup structure or nest photos that were unfocused or underexposed were excluded. Thirty-three gull nests were included in this study.

Cormorant nest photos were taken by Gerd Carsson during a regular breeding colony count in 2020 and are assumed to be representative of the other nests in the colony. Thirty-seven cormorant nests were photographed and included in this study.

While I did not choose the nests included in this study randomly, I believe that the nests not selected are represented by those that were included, and that the level of plastic contamination in the selected nests is an accurate representation of the colonies as a whole. While less well-established gannet and kittiwake nests were more likely to be located on the edges of the colony, and closer to paths from which I could take photos, the use of a telephoto lens allowed me to sample many larger, well-established nests in the center of the colony, with many years' accumulation of material.

It was not possible to maintain a consistent angle from which I photographed each nest, since my ability to view and photograph nests was already spatially and practically limited. I therefore photographed nests at angles ranging from directly overhead (gulls and cormorants) to directly from the side (gannets and kittiwakes). This is consistent with the angles from which photos were taken in other studies examining the nest contents of gannets (Grant et al., 2021) and gulls (Thompson et al., 2020).

Weather and light conditions during photography varied, as some colonies were only accessible at certain days and times. All photos were taken under conditions of good or excellent visibility.

Photo Analysis of Nests

To evaluate the plastic contents in the nests of all four seabird species, I took photographs of nests associated with gannets, kittiwakes, and gulls. I took photos of gannet and kittiwake nests from a distance, from the publicly accessible paths along the top edge of the Heligoland cliffs, using a Panasonic Lumix DSC-G81 camera with a 400 mm telephoto lens. I took photos of gull nests from roughly one meter above each nest, with a Nikon D3300 camera and an 18-55mm lens. Photos of cormorant nests were taken by Gerd Carsson with a Sony DSC-T90 camera from a height of about one meter above each nest.

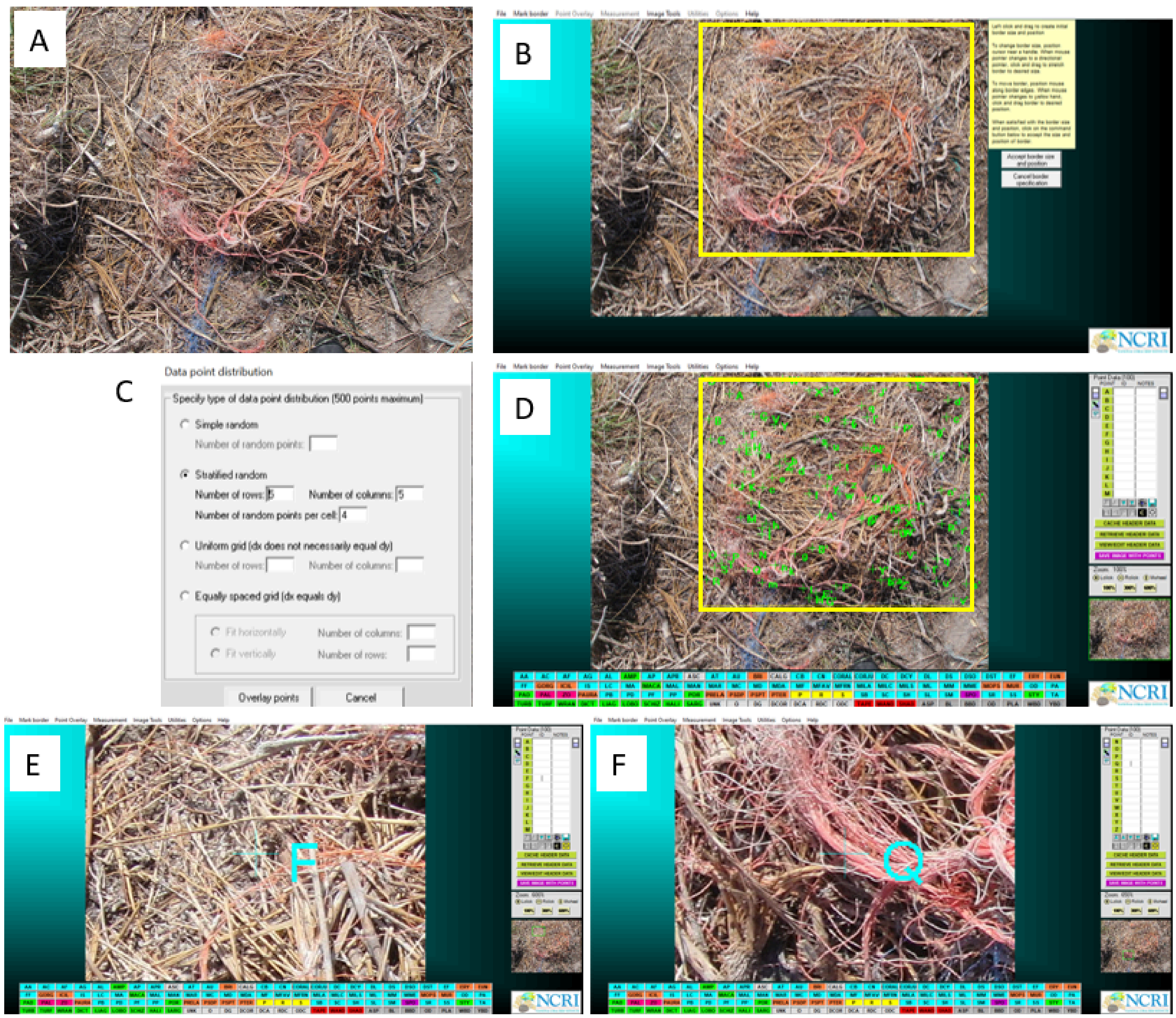
As some photos contained more than one nest, I cropped photos so that each only contained one nest. This cropping meant that while the image resolution remained the same, the size of images changed, so the relative resolution was lower in some images. Even at the lowest relative resolution, I could confidently identify plastic pieces as small as 1 cm.

I minimally edited photos to increase contrast and saturation of colors, and to rotate images so the nest material could be included as fully as possible when a horizontal/vertical box was placed over the image in the software program CPCe. During processing with CPCe, I set a border around the area of interest in the image (Kohler and Gill, 2006). I included plastic or strands of natural material that hung down below the nest cup or the bulk of the established nest in the field of examination whenever possible. Adapting the methods outlined by Thomson et al. (2020), I assigned random points to this field in a stratified manner: a 5 by 5 grid was superimposed over the field of examination and four points were randomly placed within each grid square, totaling 100 points per photo.

My stratification and point total differs slightly from the methods employed by Thompson et al. (2020), who used a 3 by 3 grid, with eleven points per grid square, totalling 99 points. I made the change in stratification in hopes that greater stratification would produce more consistent results. When I repeatedly evaluated one nest to compare methods (n = 20 passes per method), the 5 by 5 method with greater stratification yielded a significantly lower standard deviation than Thompson et al.'s method (F-test, p = 0.009, Table 3). Independently, Grant et al. (2021) also implemented a 5 by 5 stratification with a total of 100 points in CPCe evaluations of seabird nests.

I visually examined the material marked by each point and categorized it either as natural nesting material, plastic, dead bird, not part of the nest, or bird/egg (Figure 13). I further classified material recognized as plastic as either dolly rope or non-dolly rope, and made note of the color of the plastic. I primarily identified dolly rope based on morphology, but took color into account as well, as dolly rope is found primarily in distinctive orange and blue colors. Material that I could identify as dolly rope based on structure but that was either covered in dirt or guano or so bleached that the color was not recognizable was categorized as dolly rope, and the color noted as unidentifiable. In calculating the percentage of the nest that contained plastic, I excluded points classified as not part of the nest and those classified as bird/egg, so I calculated the final plastic percentage based on points identified as either plastic or natural nesting material (which included dead birds).

I evaluated each nest with CPCe twice, and used the average values for statistical analysis.



G

Nest	C N19
Points on natural material	74
Points on plastic	18
Points outside of the nest	8
Total points	100
% Plastic	19.6%

Figure 13: Evaluation of a nest image using CPCe. I opened nest photos (A) in CPCe, and placed a border around the nest (B). I specified the number of points and their stratification over the image (C), and CPCe randomly placed points over the image within the border (D). Each point was labeled with a letter (A-Z, a-z, A'-Z', a'-z'), and I looked at each point to determine whether it was located on natural nest material (E), plastic (F), or was located outside of the nest/on an egg or bird. Using the number of points in each category, I calculated the percentage of plastic in the nest (G).

Measuring Composition of Plastic Types in Nests and the Environment

To compare plastic found in seabird nests with the plastic available in the environment, I used two different sources of beach litter monitoring as well as two different forms of visual examination of gannet nests. Using plastic pollution found on beaches as a proxy for environmental plastic pollution is a method often employed in the analysis of material in seabird nests (Hartwig et al., 2007; Hidalgo-Ruz et al., 2020).

Beach Plastics

Nature conservation organizations along the German coasts conduct regular beach monitoring using the methods and parameters outlined by OSPAR litter monitoring. The nature conservation and environmental education non-profit organization, Verein Jordsand, has a field station on Heligoland that conducts beach monitoring every spring tide, which occurs every two weeks. This biweekly beach monitoring data was available for a monitored Heligoland beach from January 2020 to June 2021. These data provided information about the abundance of different types of plastic (e.g., abundance of consumer plastics, foamed plastics, and fisheries-related plastics) found on Heligoland beaches.

Additionally, to investigate the color distribution of plastic found on beaches compared to plastic found in gannet nests, I selected four beaches on Heligoland and the Heligoland Dune and collected all fibrous and thread/band-like plastic. Once a week from May 7, 2021 to June 20, 2021, I examined one of the four beaches (Figure 14). I randomly determined which beach I examined each week by assigning each beach a number and using a random number generator. I sampled all four beaches at least once in the seven-week period.

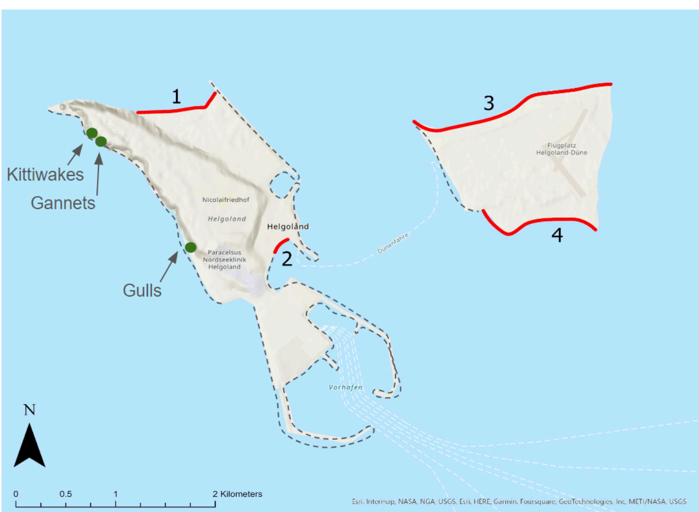


Figure 14: Heligoland beaches on which I conducted beach litter monitoring in Summer 2021. Nesting colonies are labeled dots, and sea and harbor walls are illustrated with dotted lines.

In order to compare the color composition of beach plastic to plastic quantified in photos of nests, I measured beach plastic and calculated the two-dimensional surface area of each piece that I collected (Figure 15). This surface area measurement simulates how each piece of plastic would be evaluated by CPCe if it were photographed in a seabird nest. Hereafter, “area” refers to this measurement of two-dimensional surface area. I took measurements with a centimeter ruler and a micrometer (MMO micrometer model MXL1), rounding length to the nearest millimeter, and diameter to the nearest micrometer. When measuring the diameter of round ropes, threads, and fibers, I measured three spots along the length of the plastic and calculated the average diameter from that. I did this as diameter often varied along the length of the material due to degradation or damage. I then used this average to calculate the two-dimensional surface area of each piece. Additionally, I categorized plastics as either dolly rope fragments or non-dolly rope fragments, and recorded the color of the plastic.

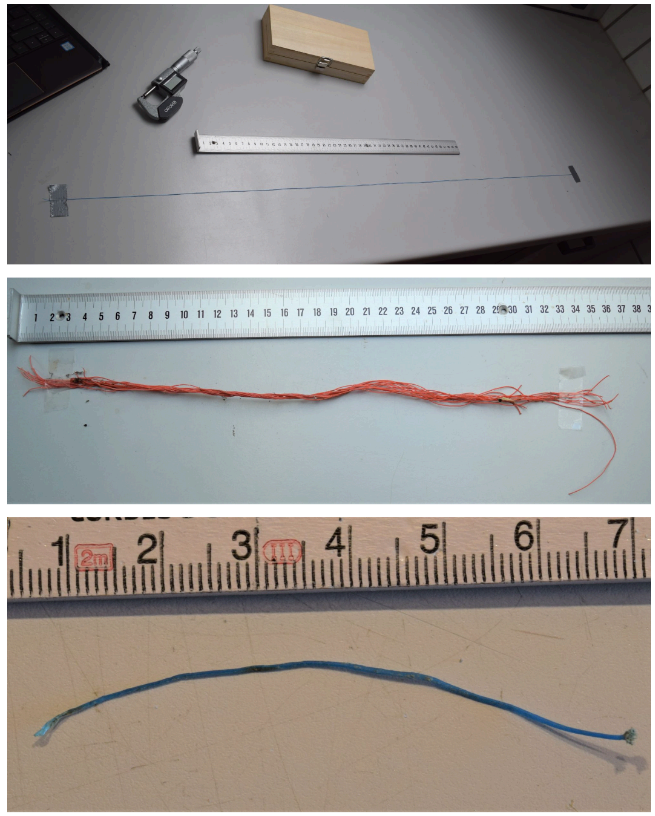


Figure 15: Plastics found on beaches were measured and photographed. Rulers in images are in cm.

Nest Plastics

To compare the makeup of gannet nests to the composition of plastic found on the beaches of Heligoland, I also conducted a visual evaluation of all gannet nests. Using a scope (Zeiss, Conquest Gavia 85), a coworker and I examined 623 gannet nests and counted or estimated the number and type of plastic objects found in each nest. When we counted large numbers of dolly ropes that were often matted together and discolored by weather/guano or buried under other material, we used visible changes in color or structure to indicate a new dolly rope strand or bundle. In order to accurately compare these data with that collected from litter found on beaches, we followed OSPAR classification guidelines for differentiating ropes from lines. We identified dolly ropes by their characteristic structure and colors, we classified non-dolly rope fibrous material with a diameter of less than 1 cm as a line, and fibrous materials with a diameter of more than 1 cm were classified as ropes.

Data Analysis

Statistical tests were run in RStudio 2023.09.1. Because the data of average plastic content of nests was not normally distributed for kittiwakes and gulls (Appendix, Figure 32), I ran a Kruskal-Wallis test to test for significance in difference of average plastic content in nests across species. I ran Dunn tests as post-hoc tests. To test for significance, I scaled up (multiplied by 100) the proportion of nests containing plastic, the comparison of plastic types in nests and on beaches, and the color composition of plastic in nests and on beaches, and tested these data using Chi-squared tests.

Chemical and Material Analysis of Dolly Rope Fragments

With the assistance of Heather Hamilton and Willie Perreault and using an FTIR spectrometer in the Mount Holyoke College chemistry department, I analyzed the chemical composition of dolly rope fragments. We used a Bruker Alpha model FTIR spectrometer and OPUS-IR software. Three samples each of orange, blue, and black dolly rope were analyzed and the average absorption spectrum plotted for each color.

I also conducted preliminary tests of dolly rope tensile strength. I used a Travelon luggage scale with a maximum capacity of 34 kg and a self-reported ± 0.9 kg variance. I collected dolly rope strands on Heligoland beaches near the nesting seabird colonies, and the strands were in good general condition, without obvious signs of wear, discoloration, or flaking plastic. I tested a total of 15 individual dolly rope strands, three of each color. I cut 30 cm sections of the individual dolly rope strands and tied a bowline knot in either end of each section. I fastened one end to the luggage scale, and pulled at the other end until the dolly rope strand broke. I filmed each trial to record the maximum force that the analog face of the luggage scale showed prior to the dolly rope breaking.

RESULTS

Quantifying Plastic in Nests

Repetition Testing

Following the methods of Thompson et al. (2020), images of nests were analyzed twice, and averaged for further statistical analysis. This was done to reduce outliers and to produce a result closer to the true amount of visible plastic in each nest. The two repetitions of photo analysis showed that the means of the two repetitions were very slightly different from each other, but while statistically significant (paired t-test, $p < 0.001$), the difference was not very large (mean difference = 0.016, 95% confidence interval = 0.006-0.025, Appendix Table 1). This means that while one repetition calculated more plastic in nests on average, this increase was very small, ranging from 0.6%-2.5%.

Methods Experiments

To see whether a more stratified approach to image sampling (5x5 stratification as opposed to the 3x3 stratification implemented by Thompson et al., 2020) would reduce variance in the results of image sampling, twenty repetitions of each stratification were performed on the same image. The average proportions of plastic found in nests between the two methods were not significantly different from one another (two-tailed T-test, $p = 0.075$, Appendix Table 2). The variances of the two methods were different from one another, with my modified method (5x5 stratification) producing a significantly lower variance (F-test, $p < 0.01$, Appendix Table 3).

Average Proportion of Plastic in Nests

To compare the amount of plastic in the nests of different species, I compared the average amount of plastic in each species' nest (Figure 16, Appendix Table 4). Because my data are not normally distributed (a large number of zeros especially in species with a low proportion of nests containing plastic), I used a rank-sum test to compare averages (Kruskal-Wallis rank sum test, Dunn test as a post-hoc test). The average proportion of plastic found in each seabird species' nests was significantly different across the four species (Kruskal-Wallis test, $p < 0.001$, Appendix Table 5). Post-hoc Dunn tests showed a highly significant difference (Dunn test, $p < 0.001$, Appendix Table 6) between all species' average plastic content except between gulls and kittiwakes ($p = 0.24$).

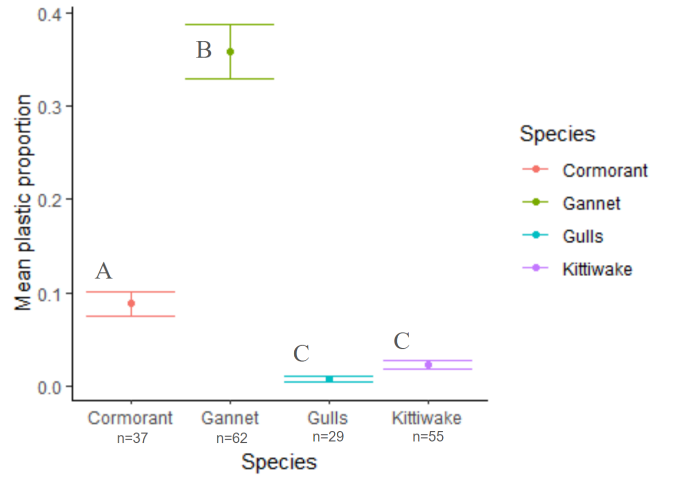


Figure 16: Average proportion of plastic in nests by species.
Letters indicate significant differences between population means.
Error bars are +/- 1 SEM.

Proportion of Nests Containing Plastic

The proportion of nests containing any amount of plastic was different across the four species examined (Figure 17, Appendix Table 7): 98% of gannet, 95% of cormorant, 44% of kittiwake, and 28% of gull nests contained plastic. For all comparisons of proportions, I ran Chi-squared tests. The difference across all four species was highly significant ($p < 0.001$, Appendix Table 8).

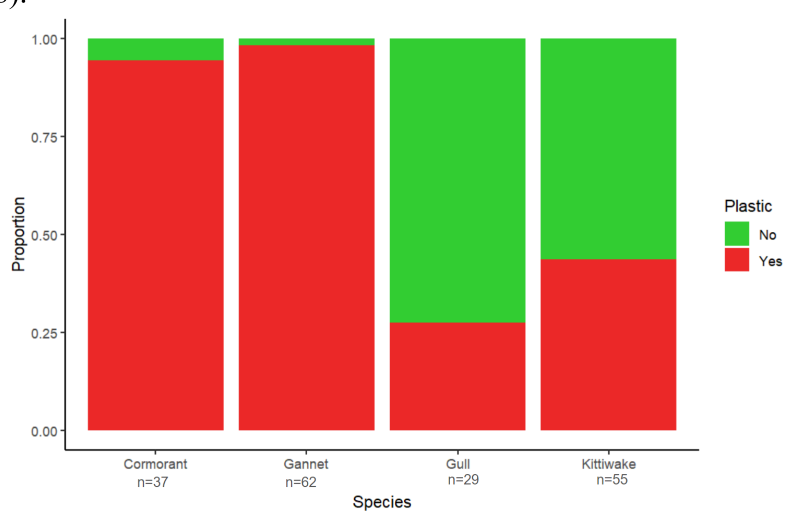


Figure 17: Proportion of nests containing plastic by species.

Types of Beach and Nest Plastic

Types of Plastic on Beaches Compared to Gannet Nests

A comparison of the types of plastic in northern gannet nests and the prevalence of those plastics in the environment showed a significant difference between the two. The visual evaluation of gannet nests (Figure 18, Appendix Table 9) indicated that the plastic in gannet nests was primarily dolly ropes and lines (96%). Analysis of beach monitoring data from Verein Jordsand on Heligoland shows that of the debris found on beaches, only 5% was dolly ropes or lines, while 38% was packaging materials and 56% was categorized as “other.” Of this “other” category, 92% were foamed plastic or plastic fragments.

The differences in proportions of packaging, line/dolly rope, and other plastic between nests and beaches were all highly significant (Chi-squared test, $p < 0.001$, Appendix Table 10). Only the proportion of rope (rope > 1 cm) was not significantly different between nests and beaches ($p = 0.52$).

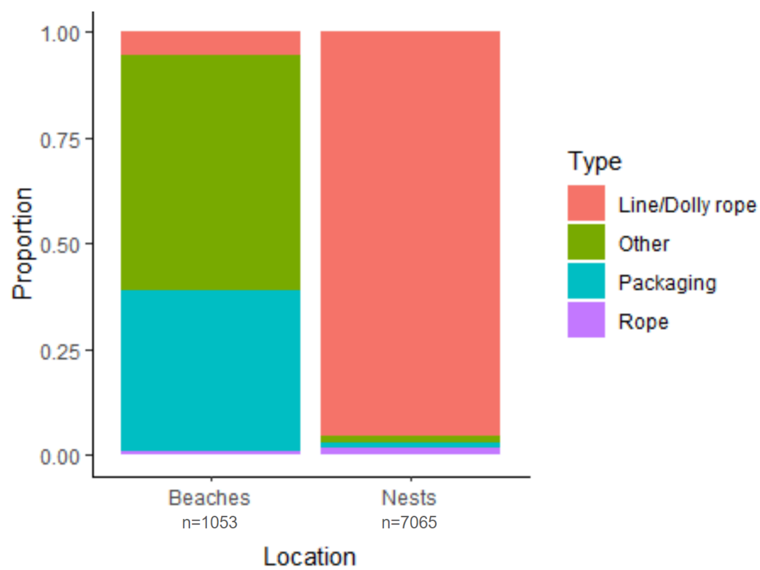


Figure 18: Proportion of different types of plastic found on beaches from January 2020 to June 2021, and in gannet nests in June 2021.

Presence of Dolly Ropes in Nests Compared to Beaches

The vast majority of plastics counted in gannet nests were categorized as line/dolly rope. I wanted to see whether this preference could be seen in the other species studied, and whether the bulk of the category of “line/dolly rope” was actually dolly rope. While dolly rope accounted for a mere 5% of beach plastic, it accounted for at least 40% of plastic in gull nests, and even more in kittiwake (67%), cormorant (73%), and gannet (93%) nests (Figure 19, Appendix Table 11). The differences across these categories were highly significant (Chi-squared test, $p < 0.001$, Appendix Table 12).

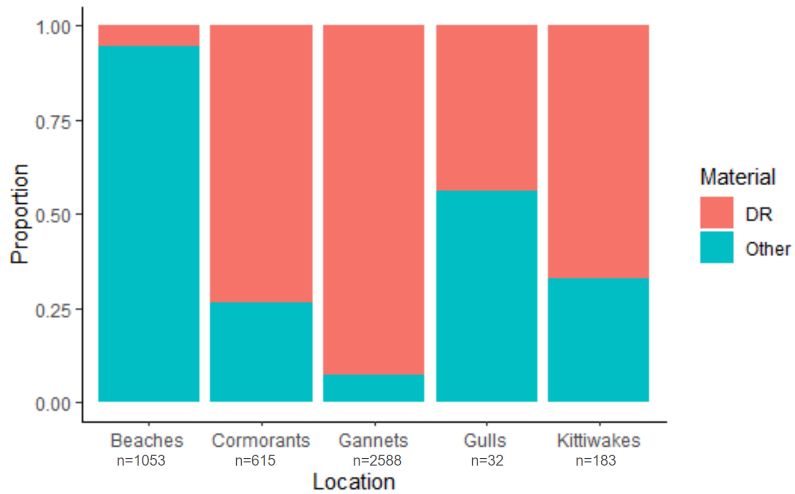


Figure 19: Proportion of dolly rope (DR) and non-dolly rope (other) plastic on beaches and in the nests of the four study species.

Color of Plastic in Nests and on Beaches

When I collected litter on Heligoland beaches in 2021, I measured the size of each piece of plastic and recorded its color. This allowed me to calculate the proportion of each color in the environment, and compare this to the proportion of each color of plastic in nests. The color distribution of fibrous plastics differed between beaches and nests of each of the four species examined (Figure 20, Appendix Table 13). While white and black plastic were most common on beaches (51% and 26%, respectively), the most common colors found in nests were orange and blue (cormorants and kittiwakes) or orange and unidentifiable/other colors (gannets and gulls). The difference in plastic color across species and on beaches was highly significantly different (chi-squared test, $p < 0.001$, Appendix Table 14) for all colors except green, which was barely significant ($p = 0.04$).

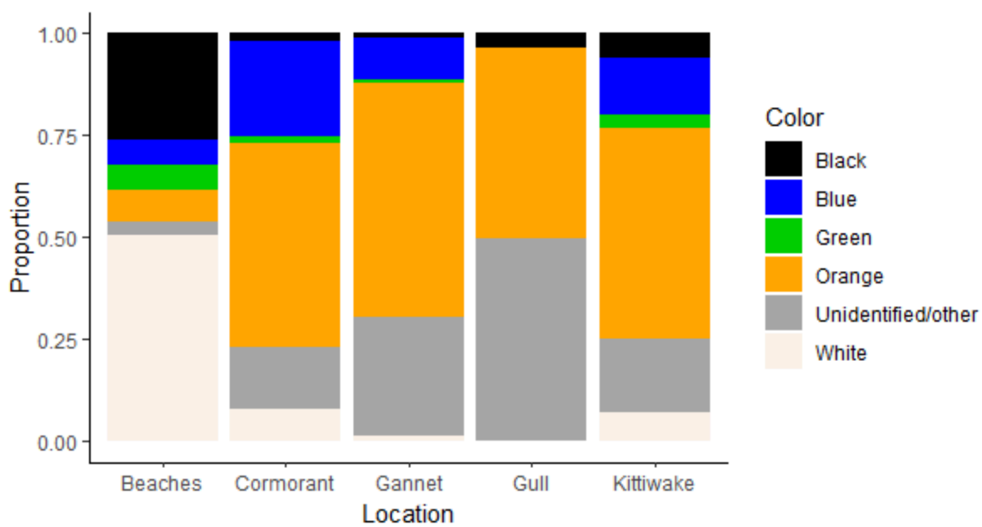


Figure 20: Proportion of different colors of plastic on beaches and in the nests of the four study species.

Beach Plastic Colors by Count and Area

Because plastics found on beaches ranged widely in size, from meter-long, 2 cm-diameter ropes, to 2 cm long, 1 mm diameter dolly rope strands, I examined the color composition of beach plastics when calculated based on area versus count. While white is the most common color of plastic (51%) found on beaches by area, blue is the most common by count (47%) (Figure 21, Appendix Table 15). The proportion of each color was significantly different between beaches and nests for all colors (Chi-squared test, $p < 0.001$, Appendix Table 16) except green ($p = 0.33$) and "other" ($p = 0.98$).

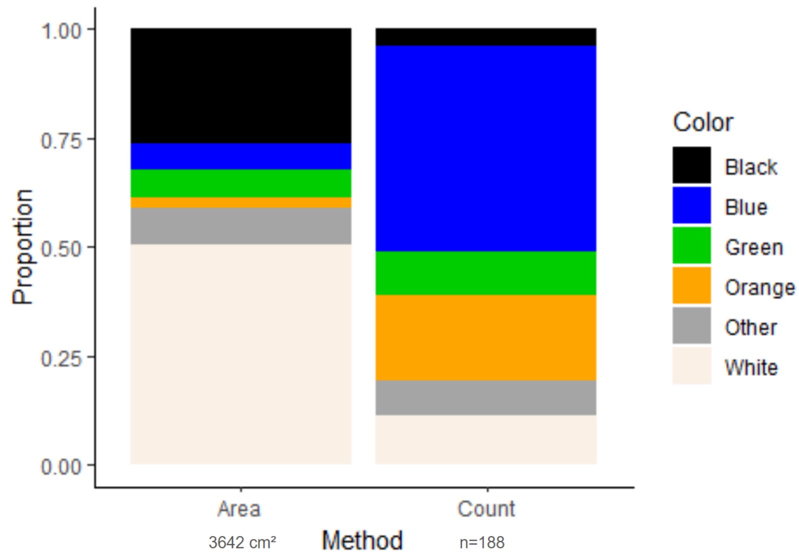


Figure 21: Proportion of different colors of plastic found on beaches from May-July 2021, by area and by count.

Dolly Rope Colors by Count and Area

The calculated proportion of blue and orange dolly ropes found on beaches based on the number of pieces found (Figure 22, Appendix Table 17) did not differ significantly from the proportion calculated based on the two-dimensional surface area of dolly rope pieces found (Chi-squared test, $p = 0.68$, Appendix Table 18). Blue dolly rope made up a slight majority of dolly ropes by both methods.

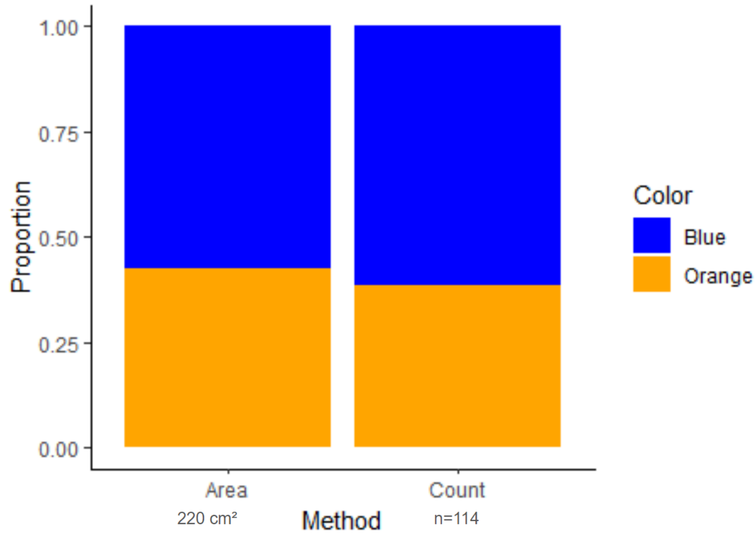


Figure 22: Proportion of blue and orange dolly rope found on beaches from May-July 2021, by area and by count.

Dolly Rope Colors in Nests and on Beaches

The color distribution of dolly ropes on beaches was different from the overall average of the nests of the four species studied (Figure 23, Appendix Table 19). While 58% of dolly rope on beaches was blue, only 15% of dolly rope in nests was blue, and while 42% of dolly rope found on beaches was orange, the percentage in nests was 85%, representing a significant difference in colors between nests and the environment (Chi-squared test, $p < 0.001$, Appendix Table 20). Only dolly rope whose color could be determined was included in this comparison, as unidentifiable dolly rope (dolly rope too bleached or covered in guano to determine the original color) likely follows the same color proportions as that which could be identified.

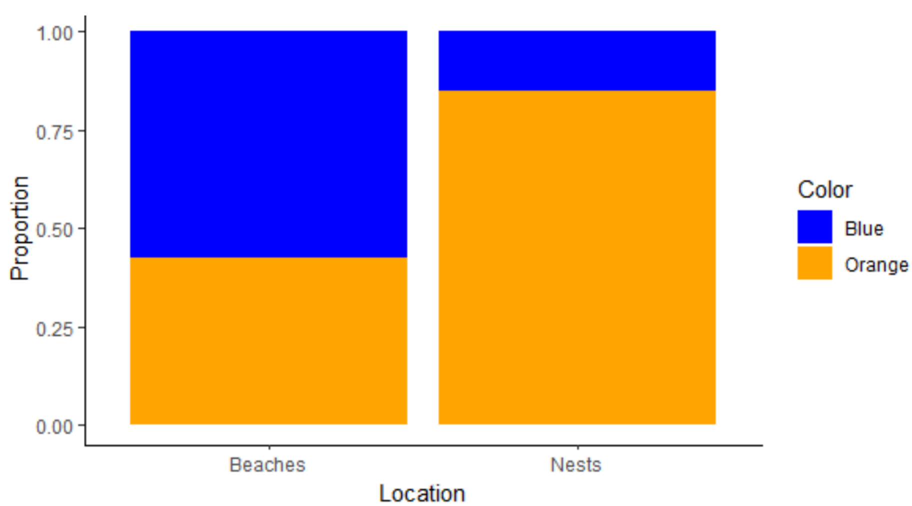


Figure 23: Proportion of blue and orange dolly rope found on beaches and in nests (averaged dolly rope color composition of nests of species studied).

Dolly Rope Colors Between Species' Nests

While the color distribution of dolly ropes differed between beaches and nests overall, the difference in dolly rope color distribution was not significant between species (Chi-squared test, $p = 0.49$, Appendix Table 22). All four species had more orange dolly rope than blue in their nests (Figure 24, Appendix Table 21).

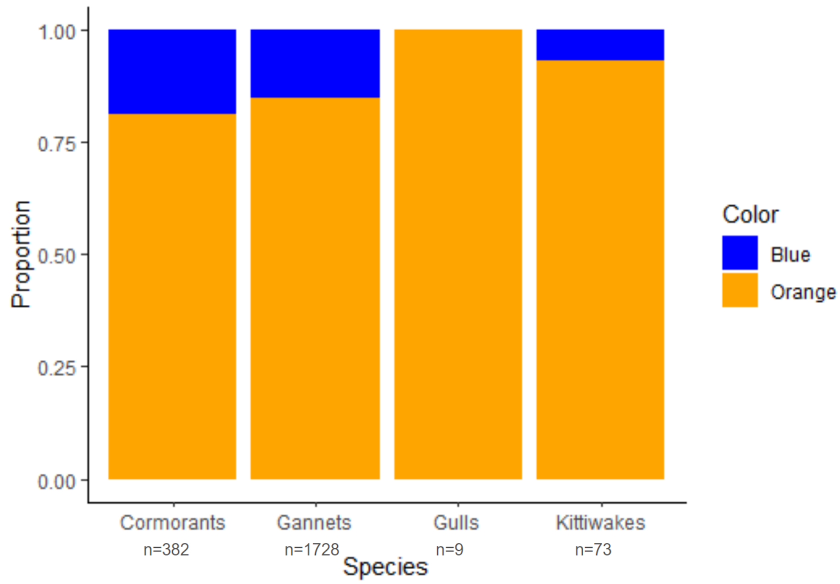


Figure 24: Proportion of blue and orange dolly rope found in the nests of the four species studied.

Dolly Rope Analysis

I collected and examined dolly rope from the beach adjacent to the nesting cliffs on Heligoland. I characterized the chemical composition of the different colored strands and attempted to evaluate the tensile strength of individual strands. As previously mentioned, most manufacturers do not disclose the polymer chemistry of their dolly ropes, although previous studies have indicated that most dolly rope is polyethylene. I conducted preliminary tests of dolly rope strand tensile strength to evaluate the strength of the strands as it might pertain to entanglement and the ability of birds to free themselves.

Chemical Composition

FTIR absorption spectra for all three colors of dolly rope closely align with the absorption spectrum of polyethylene (Figure 25). Some additional absorption spikes in dolly rope not found in the polyethylene reference spectra can be attributed to additives (H. Hamilton, personal communication, October 13, 2023). Absorption spikes in all three colors of dolly rope at approximately 1700 cm^{-1} are most likely Irganox 1076, an antioxidant and stabilizer, which has an absorption spike at 1738 cm^{-1} (Zheng and Fan, 2022). This antioxidant and stabilizer would be included in dolly rope in order to make it more resistant to heat and UV degradation, important attributes for plastics used in a marine environment. Small absorption spikes between 400 and 1400 cm^{-1}, most pronounced in blue dolly rope, could be an azo dye. An absorption increase around 3400 cm^{-1} is indicative of an additive containing a hydroxyl group, which Irganox 1076 and azo dyes both contain (H. Hamilton, personal communication, October 13, 2023).

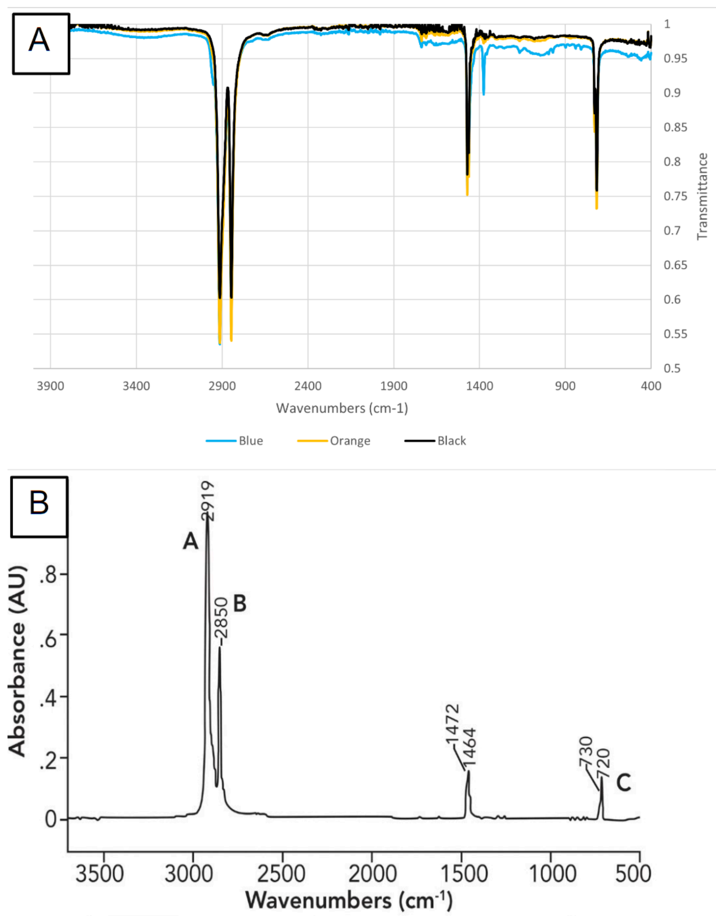


Figure 25: FTIR transmittance spectra of dolly ropes found in the environment (A), and reference FTIR absorbance spectra for polyethylene (B).

Tensile Strength

Dolly rope sections (individual monofilaments) that I tested using the Travelon luggage scale broke at forces ranging from 4 kg to 5.5 kg, but the majority of strands broke at 5 kg. The average break force was 5.03 kg.

INTERPRETATIONS

Nests Containing Any Plastic by Species

In order to see how likely each species is to incorporate any amount of plastic in their nests, the proportion of nests from each species containing plastic was examined. Nearly all gannet (98%) and cormorant (95%) nests contained plastic, while only 44% of kittiwakes and 28% of gulls incorporated plastic. This suggests that gannets and cormorants are much more likely to incorporate plastic into their nests, overall, compared to gulls and kittiwakes.

Average Proportion of Nest that is Plastic by Species

Quantifying the amount of plastic in a given nest, and then calculating the average amount of plastic found in one or more species allows us to draw conclusions about the nesting and foraging behavior of different species, and the quantity and composition of plastic in their environment. In this study, gannet nests contained significantly more plastic on average than any other species' nests. Cormorant nests also contained significantly more plastic than those of gulls or kittiwakes, but significantly less than gannets' nests. This suggests that gannets and cormorants are more likely to include large quantities of plastic in their nests than kittiwakes or gulls. These differences are likely the result of behavioral or life history differences between the species, such as nest reuse over multiple years, or foraging for nest material on land versus at sea, since all four species are subject to the same pollution levels of the southern North Sea.

Types of Plastic Found in Nests and on Beaches

By comparing the types of plastic found on beaches to the types and quantities found in nests, we can discern whether seabirds are indiscriminately collecting plastic from the environment, or whether they have a preference for a particular type. Gannet nests contained mostly lines and dolly ropes, while plastic beach litter collected by Verein Jordsand was composed primarily of packaging and "other", which consisted mostly of foamed plastics like styrofoam. This suggests that gannets have a very strong preference for fibrous plastic, in particular dolly rope.

A strong preference for dolly rope was also clear across all four study species when I examined the proportion of dolly rope compared to other plastic in their nests (Figure 19).

Colors of Plastic on Beaches Compared to Each Species' Nest Plastic

The color composition of plastics on beaches and in nests can be used to see whether seabirds have a preference for one color over another. The proportions of colors of fibrous plastics found on beaches differ from those found in the nests of the examined species. While the color of fibrous plastic (by area) on beaches is dominated by white and black, nests contain mostly orange plastic, followed by unidentifiable and blue plastic.

This difference, however, is closely related to the types of plastic found on beaches versus nests, and their associated colors. While dolly rope and line (fibers with a diameter < 1 cm) are primarily orange and blue, ropes (fibers with a diameter > 1 cm) were often white or black (personal observation, June 2021). The seabirds studied showed a strong preference for dolly rope, and incorporated only a very small proportion of rope into their nests. This is further supported by the comparison of color composition by count versus by area (Figure 21). This shows that while white plastic is most prevalent by area, it is much less so by count, and therefore the white plastic pieces are likely relatively large. The opposite is true for blue plastic, where many pieces were found on beaches, but the area of those pieces was small.

The fact that colors are so closely tied to material type, and the prevalence of dolly rope as a material in nests suggests that perhaps the large quantities of orange in nests is due less to a preference for orange, but a preference for dolly rope, which is frequently orange.

Dolly Rope Colors on Beaches Compared to Nests

The plastic type and the color composition of beach plastics and nest plastics suggest that the seabirds in this study prefer dolly ropes. However, it is also worth examining the role of color selection within dolly ropes. The color composition of dolly rope found on beaches differs from that found in nests (Figure 20). Nests contained a much smaller proportion of blue dolly rope than was found on beaches, suggesting that the birds have a preference for orange or may avoid blue. A preference for orange is supported by the large proportion of orange dolly rope in nests compared to the significantly lower proportion found on beaches.

This trend is seen even more clearly in a breakdown of dolly rope colors in the nests of each of the observed species. All four species include mostly orange dolly rope in their nests (Figure 24), despite blue dolly rope making up over half of the dolly rope found on beaches (Figure 22).

This means that on average, the four species examined collect blue dolly rope at much lower frequencies, and orange dolly rope at much higher ones, than would be expected if they collected dolly rope independently of color. This suggests that not only do they prefer fibrous plastic, in particular dolly rope, but they specifically prefer orange dolly rope. This may be driven simply by the fact that orange is easier to see against the surface of the ocean, and therefore easier to locate and collect than blue dolly rope.

Quantification of Dolly Ropes on Beaches

Comparing the color distribution of dolly rope on beaches by count and by two-dimensional surface area serves two purposes. When identifying color, counting individual pieces of plastic produces similar results to calculating their surface area from images. It also reflects whether one color tends to occur in the environment in larger pieces than the other. If one color were present in only a few very large pieces, while the other was present in many small fragments, it would appear (by count), the latter was more prevalent in the environment, whereas image analysis of nests (based on surface area) would suggest the former was being selected more frequently.

While blue dolly rope made up a slight majority of dolly ropes by both calculations (Figure 22), this was more pronounced in count data (61%) than area (58%), which suggests that blue dolly rope pieces were more common, but also slightly smaller than orange pieces. However, the percentage of blue dolly rope was greater in both pieces and by area, and therefore indiscriminate collection of dolly rope by seabirds should result in more blue dolly rope than orange in nests, regardless of method used to calculate the proportion.

Dolly Rope Properties

Chemical composition

While the bundles of bright orange and blue monofilament that I collected on beaches and observed in nests are locally known as and assumed to be dolly rope, collecting more information about the chemical and physical properties of this material can help confirm the chemical composition of dolly rope while also providing more information about the dangers posed by it.

Based on the FTIR absorption spectra of the three colors of dolly rope tested, the dolly rope found on Heligoland beaches is made of polyethylene, containing additives consisting of an antioxidant and stabilizer (Irganox 1076), as well as azo dyes (a class of dyes used in industrial dyeing) in orange and blue dolly rope. In lieu of an azo dye, the black dolly rope likely contains soot as a pigment (H. Hamilton, personal communication, October 13, 2023).

Tensile strength

The dolly rope fragments broke at approximately 5 kg of force, or approximately 49 Newtons. Every strand broke at the junction where the center strand became part of one of the bowline knots, so the actual tensile strength may be higher in strands without knots.

Given the force needed to break a single strand of dolly rope, I estimated the approximate force an entangled bird would need to produce to free itself. Using the equation $A = F/M$, I calculated the acceleration each species of seabird would need to attain in order to break a strand of dolly rope (Appendix Table 23).

Additionally, as seabirds are often entangled in more than one single dolly rope strand, the force required to break free would be multiplied by the number of strands the bird is entangled in.

DISCUSSION

The data collected through CPCe analysis of photos provides insights into the plastic content and nest composition of the four studied seabird species. Quantitative data of the plastic contents of these seabirds' nests across multiple species and behaviors such as differing nesting strategies allows for comparisons to be made between species and between species' nests and plastic found in the environment. Understanding how different species interact with environmental plastics presents us with opportunities for utilizing species as proxies for aspects of environmental pollution and helps to identify changes (e.g., color) that might mitigate the impact of plastic pollution on nesting seabirds.

Presence and Average Proportion of Plastic in Nests

While few other studies examined the quantity of plastic in seabird nests, a comparison of the proportion of nests containing plastic can be made to other studies. In this study on Heligoland, 98% of the gannets' nests contained plastic, which is remarkably close to the 97% of gannet nests in Canada that contained plastic in 1991 (Montevecchi, 1991), and only slightly less than the 100% of Heligoland gannet nests that contained plastic in 2005 (Hartwig et al., 2007). While 95% of cormorant nests contained plastic on Niegehörn, only 37% of Canadian cormorant nests contained plastic in 1987 (Podolsky and Kress, 1987). While 44% of Heligoland kittiwake nests contained plastic, this is actually somewhat less than the 57% of Danish kittiwake nests with plastic in 2005 (Hartwig et al., 2007). Finally, the 28% of gull nests that contained plastic were remarkably close to the percentage of herring and lesser black backed gull nests that contained plastic in Scotland in 2020 (Thompson et al., 2020). These differences and changes may reflect temporal changes in the type and availability of environmental plastic, or they may reflect the different levels of pollution in different parts of the world. Lastly, they may be due to different amounts of natural nesting material available to seabirds relative to plastic (Bond et al., 2012).

While nearly all gannet (98%) and cormorant (95%) nests contained plastic, fewer kittiwake (44%) and gull (28%) nests did. When considering the average proportion of plastic in nests, gannets had the most (36%), followed by cormorants (9%), kittiwakes (2%), and gulls (1%). These two parameters yield four different basic nest conditions for the species studied: almost all nests have a large amount of plastic (gannets), almost all nests have a moderate amount of plastic (cormorants), less than half of nests have a small amount of plastic (kittiwakes), and a quarter of nests have a small amount of plastic (gulls).

Differences in Plastic Quantity by Species

Differences in the likelihood of plastic incorporation as well as in the amount incorporated in nests between these species may reflect differences in the sources of natural nesting materials used, nest reuse over time, and affinity for plastic as nest material.

Gannets and Cormorants

Gannets and cormorants are both very likely to include some amount of plastic in their nests. The tendency for these two species to include some amount of plastic in many of their nests has been observed in other colonies as well (Podolsky and Kress, 1989; Garcia-Cegarra et al., 2020; Verlis et al., 2014; Bond et al., 2012; Montevecchi, 1991; Merlino et al. 2018; Massetti et al., 2021), suggesting that gannets and cormorants have a high affinity for plastic. This may be because the plastics most frequently found in their nests are fibrous and similar in structure and density to natural nesting materials such as seaweed and grasses (Bond et al., 2012; Votier et al., 2011; Tavares et al., 2016; Lavers et al., 2013), or due to a certain curiosity or predisposed attraction to plastic debris. Gannets and cormorants also both collect natural nest material at sea and on land from the area around their nests, and therefore may encounter similar types of available material, which could also explain the similar rates of plastic incorporation in their nests.

However, gannets have, on average, much more plastic in their nests than cormorants do. This may in part be due to a historical predisposition that gannets have for incorporating anthropogenic debris in their nests, which has been documented as far back as the early 1900s (Gurney, 1913). More likely to explain the large discrepancy in average plastic quantities in nests, however, is the fact that gannets reuse their nests, year after year (Gurney, 1913; Cramp and Simmons, 1977), while cormorants generally build new nests each breeding season (Podolsky and Kress, 1989). This means that while the natural material in gannet nests slowly decomposes over years of use and exposure to the elements, plastic incorporated each year remains, and accumulates over time. Cormorant nests are representative of only one season of nest building and plastic collecting, while any given gannet nest on Heligoland may be as old as 32 years (the first gannet nest there was established in 1991 (Dierschke et al., 2011)).

Kittiwakes and Gulls

A slightly different pattern can be seen in the comparison of kittiwake and gull nests. While both species' nests contain relatively little plastic on average, and there is no significant difference in the average amount of plastic in their nests, kittiwake nests are more likely to contain some quantity of plastic. This may be due to the fact that kittiwakes forage for nest material in areas with more plastic. Kittiwakes build their nests out of mud, grass, and seaweed collected at sea (Cullen, 1957; Dierschke et al., 2011), while gulls build their nests mostly from materials collected in close proximity to the nest (Cramp and Simmons, 1989). On Heligoland, the gull colony was situated behind a relatively tall sea wall, which would reduce the amount of marine material immediately available. It should be noted that seaweed and plastics were both seen behind the seawall, since storms transport material such as seaweed and plastic over and around the wall, but that the amount was less than on nearby beaches (personal observation, June 2021). Because kittiwakes venture out to sea to collect seaweed, they are perhaps more likely to encounter plastic there and bring it back to the nest than gulls. Gulls, having less marine material available to them in the area where they primarily forage for nest material, build their nests primarily out of terrestrial grasses, twigs, and weeds.

Like gannets, kittiwakes also reuse their nests from year to year. This may also contribute to the large proportion of kittiwake nests containing plastic while maintaining a low average amount of plastic in nests. If a kittiwake incorporates a small amount of plastic in its nest one year, the plastic will likely remain there for years to come, even if very little or no plastic is added in subsequent years. Gull nests, which are not reused, represent a single season's worth of nest material collection.

Gannets and Kittiwakes

As the status of a nest as a multi-year project or a single-season investment impacts the proportion of nests containing plastic and the average amount of plastic found in nests, a comparison of gannets and kittiwakes, both of which reuse nests each year, is warranted.

While both gannets and kittiwakes reuse nests, gannet nests are significantly more likely to contain plastic, and contain significantly more plastic on average than kittiwake nests. One explanation for this is that while the bulk of a gannet's nest consists of seaweed and grass, kittiwakes primarily rely on mud. Mud allows kittiwakes to cement nests onto small rocky outcrops, and seaweed and grasses are often not added until later, when they are used to build up the walls and cushion the nest cup (Cullen, 1957). Therefore, a larger proportion of a gannet nest is made of material that is collected from the sea, where plastic is more likely to be encountered.

Another reason for the disparity between the species may be the amount of time that plastic has had to accumulate in nests. While gannets on Heligoland have been incorporating plastic in their nests since the first pair raised a chick there in 1991 (Dierschke et al., 2011), Heligoland's kittiwakes' incorporation of plastic in nests is much more recent. While kittiwakes' use of plastic in nests was observed in Denmark in 1992 (Hartwig et al., 2007), plastic in kittiwake nests on Heligoland was first noticed in 2017 (Elmar Ballstaedt, personal communication, December 14, 2021). Therefore, a greater proportion of plastic in gannet nests on Heligoland may also be due to the fact that plastic there has been accumulating for 26 years longer than in kittiwake nests.

Plastic Preference

Comparing plastics in the environment to those found in the nests of a given species can give us insight into what that species value regarding nest material. Given the relatively small proportion of lines and dolly ropes in the environment and the very high proportion of these objects in gannet nests, it is clear that gannets show a preference for fibrous plastics, especially the thin strands of lines and dolly ropes.

This preference for fibrous material has also been observed in other studies examining plastic found in Sulidae nests (Bond et al., 2012; Votier et al., 2011; Tavares et al., 2016; Lavers et al., 2013). There too, a preference for fibrous plastics, especially fisheries debris, was observed. These sources often suggest that this is likely due to the similarity of these plastics to natural nesting materials, which has also been observed in other studies (Heimstra et al., 2021; Antczak et al., 2010). I was also able to observe this similarity while collecting beach litter data. Seaweed and kelp, which are natural nesting materials found in gannet nests, closely resemble the structure of three different types of plastic that fall into the category of fibrous plastic (packing strips, rope, and dolly rope) (Figure 26). Given the morphological similarities, it is understandable that a seabird would readily include plastic in their nests alongside seaweed and kelp.

Figure 26: Morphological similarities between natural nesting materials such as seaweed and kelp (A-C), and fibrous plastics (D-F) found on beaches.

While I was able to obtain count data of plastic types only for the nests of Gannets, I did not observe any non-fibrous anthropogenic material in any of the nests examined of the four study species, suggesting that the composition of plastic types in the nests of the other species studied is similar to that of the gannet nests.

Dolly Rope

As all of the species studied disproportionately include dolly ropes in their nests (Figure 19), it is worth examining why this may be the case. Seabirds may choose dolly rope in particular due to its similarity to natural nesting materials that they usually incorporate. Dolly rope's structure is similar to long, strandy seaweed (see Figure 26), and is found in similar locations, floating at the surface of the water.

Accidental Incorporation

Although seabirds may deliberately choose to incorporate plastic into their nests, they may also collect plastic accidentally, in conjunction with natural nesting material. Gannets were observed carrying mixtures of both plastic and natural nesting material in their beaks (Figure 27), although we cannot know whether the gannets in question collected that material because of the natural material or the plastic. Some plastic may even be incorporated accidentally because it is covered in algae or tunicates, or tangled in a larger clump of seaweed (Figure 28).

Figure 27: A gannet flies back to its nest with pink plastic and seaweed in tow.

Figure 28: Dolly rope fibers intertwined with seaweed found on a Heligoland beach. Arrows indicate dolly rope fibers.

Figure 29: Much of the plastic in gannet nests appears to be (orange) dolly rope.

As ropes and non-dolly rope lines also resemble natural materials, however, their relative abundance in nests might suggest that there is something particular about dolly rope that leads to its frequent incorporation in nests. For example, gannets may prefer the type of natural material that dolly rope is most structurally similar to, but not the natural material that other types/shapes of plastic (ropes, packing strips) resemble. Another possibility may be that ropes are sometimes too large or heavy to carry up to the nest, resulting in ropes being underrepresented in nests.

An Active Preference

The disproportionate abundance of dolly rope in nests suggests an active preference for that type of plastic (Figure 29). Dolly ropes are a relatively springy material that often include knots from their time attached to trawling nets. This means that they easily tangle up with themselves and with other natural and artificial materials in nests to create sturdy mats, often with long trailing fringes. Because the polyethylene of dolly ropes is so "springy" before it is matted down, the dolly rope may also appear larger and "fluffier" than seaweed that, when wet, compresses down and lays flat (Figures 30 and 31). This greater perceived volume may be appealing to gannets.

Figure 30: A northern gannet brings a bundle of "springy," "fluffy" black dolly rope and seaweed back to its nest.

Figure 31: A gannet collects seaweed and adds to its nest.

Nest material is valuable, especially to cliff-breeding species, who will engage in intense fights over neighbors stealing nest material from one another (Cullen, 1957; personal observation, May 2021). As some of this perceived value is due to the energy expenditure associated with finding and carrying nest material back to the nest, the fact that dolly rope and other plastics are lighter than water-logged seaweed may also make plastics more appealing as they require less energy to carry. This preference would be supported by the fact that the incubation and chick-rearing time period is very physiologically taxing for gannets (Fitzgerald et al., 2022). During this stressful time period, other seabirds such as skuas have been observed expanding their normal feeding niches due to the stress of chick-rearing, resulting in increased interactions with plastic (Ibanez et al., 2020). The need to acquire resources quickly and more efficiently may lead our species to favor lightweight plastic over seaweed.

There is also a possibility, however, that the structure of dolly ropes versus ropes is not the driving force behind gannet choice. If gannets are drawn particularly strongly to the bright orange of dolly ropes, they may not actually prefer the dolly rope morphology, but simply be including as much orange as they can into their nests, which happens to mean including primarily dolly rope.

Color Preferences

Further clues to the driving forces behind incorporating certain types of plastic may also be found in the color composition of plastic in nests compared to that of plastics found on beaches.

An analysis of the colors of fibrous plastic found on beaches compared to those found in nests shows a large proportion of white and black plastic in the environment, in contrast to a large proportion of orange, blue, and unidentifiable/other plastics in nests (Figure 20). This would suggest a strong preference for orange and blue plastic in nests, and a rejection of the white and black plastic that appear to make up the majority of environmental fibrous plastic.

Here, however, we must also take a look at the color composition of beach plastic when categorized by the number of pieces of plastic of each color, not their area (Figure 21). This shows that while white and black plastic are most common by area, they are much less common than orange and blue plastic by count. This suggests that white and black plastics are often larger, and orange and blue plastics are often smaller individual pieces. This is further supported by my observations during collecting beach litter: on beaches, large objects such as ropes were frequently white or black, and dolly ropes, being small but relatively numerous, were orange and blue. In Gannet nests (and most likely the other seabirds in this study), dolly ropes/lines far outnumbered ropes 48 to 1 (96% to 2%), while the ratio of dolly ropes/lines to ropes on beaches was much closer at about 7 to 1 (5% to 0.7%) (Appendix Table 9). Therefore, the relative lack of white and black plastic in gannet nests can be explained not by an avoidance of white and black plastic, but by an avoidance of the types of plastic that tend to be white or black.

Significance of Color

Because gannets have such a strong preference for dolly rope, it is also worth examining the color composition of dolly ropes alone on beaches and in nests. On beaches, dolly ropes were relatively evenly distributed between orange and blue, with blue being slightly more common. As this was consistent between proportions calculated based on area and based on counts, orange and blue dolly ropes on beaches were generally the same size. This also suggests that when examining the color breakdown of dolly ropes, the color composition calculated by area accurately represents the color composition based on the number of dolly ropes found.

In nests, however, orange made up a significantly larger proportion of dolly ropes than blue. This was true across all study species individually and when averaged together. Since dolly ropes on beaches had slightly more blue present than orange, the fact that orange is so much more common in nests suggests a clear preference for orange.

A small caveat should be taken into consideration, however. The size of dolly rope fragments may play a role in selection of nest material, as longer pieces represent more nesting material and stopping once for a long piece of material is likely favorable to making multiple trips for multiple smaller pieces. Since blue dolly rope fragments on beaches seem to have been, on average, shorter than orange fragments, a preference for orange dolly rope may in part be explained by a preference for longer pieces of nesting material. However, the slight difference in length of material is unlikely to account for the large difference in orange versus blue dolly rope seen across all nests.

The clear preference for orange dolly rope over blue in nests also suggests that plastic inclusion in nests is not due only to morphology or that it occurs only accidentally when collecting natural materials. If that were the case, the color composition of dolly ropes in nests would reflect those found in the environment.

Such a strong preference for orange plastic within the morphological structure of dolly rope may have a number of reasons. Orange dolly ropes are perhaps somewhat similar in color to the brown and brown-green of dry kelp, whereas bright blue is not. Bright orange dolly ropes are also likely easier to see against the surface of the water than blue dolly rope. The conspicuousness of bright orange may catch the eye of seabirds more easily than blue dolly rope and increase the likelihood of that piece of plastic being collected.

Seabirds may also be drawn to bright orange because of its novelty or for some other reason, such as its use as a status symbol, or even as a way to make their nest easier to locate when returning from foraging trips. Orange and blue dolly rope may also look different to seabird species that are able to see UV wavelengths. While gannets and cormorants do not possess this ability, members of the gull family, including the gulls and kittiwakes in this study, do, and so this may account for the large proportion of orange dolly rope in their nests.

Negative Effects of Plastic in Seabird Nests

Entanglement

Plastic in nests pose several definite and a number of potential negative effects and dangers. On Heligoland, plastic from gannet and kittiwake nests is responsible for many seabird deaths by entanglement each year (Figure 4). While no official counts have been published, one estimate from 2011 put this death toll at 20-30 gannets each year, and that number has grown in recent years (personal observation, February 2023). Most entanglement deaths on Heligoland happen to gannets and common murres (Dierschke et al., 2011).

Entanglement deaths occur in multiple ways. Chicks can grow up in nests constructed of plastic, growing into loops and snares and finding themselves tethered to the nest when they attempt to fledge. Adult birds can also become entangled in plastic nesting material during the breeding season. Common murres, which often nest on narrow outcrops next to, above, or below gannets in the Heligoland cliffs, can also become entangled when they fly into plastic snares that hang down from gannet nests. In non-breeding seasons, other seabirds such as common murres return to the cliffs of Heligoland and perch in, below, or near unoccupied gannet nests. There, they can become entangled in plastic strands and die (Dierschke et al., 2011). While kittiwakes and cormorants do also occasionally die of entanglement on Heligoland, this occurs much less frequently than entanglement of gannets and murres.

As tensile strength testing of single dolly rope strands showed, even a single monofilament could withstand the force of one of the study species' attempts to free itself. While additional force and momentum caused by birds flapping their wings or acquiring speed before the slack of a piece of plastic ran out would increase the amount of force they would be able to exert on a strand of dolly rope, this is still likely lower than the force needed to break the dolly rope. Additionally, birds are often entangled not just by a single strand, so breaking free would require much more force than that needed to break a single strand. While Gerke et al. (2016) demonstrated that the tensile strength of dolly rope degrades dramatically in the environment, the duration of exposure to sunlight and saltwater needed to break down dolly rope is not documented, and it is very likely that some of the plastic found in the nests of seabirds is still relatively strong. Unfortunately, as many birds are tethered to nests by their wings or legs, they succumb to slow deaths of exhaustion, dehydration, starvation, or exposure (personal observation, February 2023; Votier et al., 2011).

Deaths by entanglement do not seem to have a noticeable impact on the population sizes of northern gannets or common murres, both of which have been increasing in the North Sea since the 1950s (Dierschke et al., 2011). However, in species whose populations are not growing, such as kittiwakes, and who have to contend with other environmental challenges such as changes in food availability due to climate change, losing individuals to entanglement may have a greater negative impact.

Ingestion

Plastic in seabird nests also poses a certain risk of ingestion of plastic, which can lead to blockages of the digestive tract as well as the physical filling of stomachs, both of which can lead to death (Roman et al., 2019), but the species observed here mostly utilized longer fibers that could not easily be accidentally ingested. Additionally, gulls and cormorants normally regurgitate indigestible material, which would mitigate the dangers of ingested plastic by removing much of it. Gannets and their chicks also appear to be fairly picky, and do not ingest processed food or even human-caught fish while at their nests, such as when tourists attempt to feed them (personal observation, Summer 2019).

Possible Impacts

The incorporation of plastic in seabirds' nests may also have other impacts that range from sub-lethal to neutral to beneficial.

Unwanted Neighbors

Parasites and illness are widespread and are a significant cost of living in a colony, and seabirds have to contend with a range of diseases and parasites (Khan et al., 2019, Boulinier and Danchin, 1996). Nest parasites can significantly weaken chicks and reduce their fitness, and in extreme cases, lead to abandonment of entire colonies (Khan et al., 2019). Some species' nest parasites remain in or in the vicinity of old nests until the next breeding season (Tomas et al., 2006; Steele et al., 1990). A potential effect of increasing the amount of plastic in seabird nests is a change in the parasitic load of nests comprising primarily (or to a large part) of plastic compared to nests made of natural materials. Plastic in nests may offer parasites fewer hiding spots and thus actually improve nest health for the next breeding season's chick, or it may offer parasites a more stable environment to overwinter in, as plastic doesn't erode as easily as natural materials. Some parasites have very long life cycles (Steele et al., 1990), and an increase in material in cliffs close to where new hosts will return each year may improve their ability to survive.

Nest Structure

Drainage of rainwater from and through the nest may also change depending on the plastic content of the nest. It may improve, as plastic does not absorb water, but it may also create soggy nests, as impermeable plastic fiber snarls trap water in the nest. In nests where sheeting or rigid pieces of plastic have been found, researchers have speculated that they may obstruct drainage from the nest (Hartwig et al., 2007), but the impacts of fibrous plastic on nest drainage has not been evaluated.

The insulative properties of plastic in nests may also give nests made of large quantities of plastic different thermoregulatory characteristics than those made of natural material. Even within the range of natural nesting material incorporated in nests, some materials have superior thermoregulatory properties. Gannet nests made out of seaweed, for example, were significantly warmer overnight than nests made out of grasses (Mattews et al., 2008). Since the insulative qualities of nest plastic aren't known, nests with large quantities of plastic could necessitate more or less energy expenditure from adults in order to maintain incubation temperatures.

Reduced Energetic Costs

There may also be positive aspects to utilizing plastic in nest construction. For one, if plastics are brightly colored and easier to find in the environment than natural materials, seabirds can alleviate some of the stress and energy expenditure of searching for natural nest material by collecting more synthetic material, especially during the high-stress time periods of late incubation and early chick rearing (Fitzgerald et al., 2022). Since plastic does not decompose over the winter like natural nest material, there would also be less work involved in rebuilding a nest for each nesting season, if the old nest consisted of large quantities of plastic. Especially in colonies where seabirds like gannets and kittiwakes must secure nests in steep cliffs, and reuse nests year after year, plastics may reduce the amount of work pairs have to invest in their nests each year.

Quantity Versus Impact of Plastic in Nests

Given the visibility of deaths by entanglement in and near nests containing plastic, it can be tempting to equate greater quantities of plastic with a greater danger of entanglement. However, the relationship between plastic quantity and lethality is unlikely to be that simple. While a gannet nest made primarily of old, matted dolly rope contains a large proportion of plastic, another nest with just one clump of trailing, fresh, springy dolly rope may actually be more likely to lead to a death by entanglement, despite containing a smaller proportion of plastic than the first nest. Coils of dolly rope that aren't flattened and bleached by years of sun and wind may be more likely to form a snare and get caught on a bird's foot. Additionally, when comparing plastic in the nests of different species, a nest made out of fibrous plastic will pose different dangers to its inhabitants than a nest lined with fragments of plastic.

Limitations of Photo Analysis and Potential Sources of Error

As with all analysis and monitoring tools, photo analysis of seabird nests has limitations. Image analysis using CPCe only looks at the two-dimensional surface area of the nest's structure. This ignores any materials not visible on the outer surface of the nest and assumes a relatively homogenous mixture of materials throughout the nest. As CPCe analysis calculates the two-dimensional surface area of materials in the nest, it cannot be used to give any indication of the number of individual pieces of plastic in the nest. This prevents more detailed analysis of species preference for certain types/colors of plastic, as an individual including one large piece of plastic of a certain color may not have as strong a preference for that particular color as another individual that carries a hundred very small pieces of plastic of a certain type/color into their nest.

Apart from these limitations, this study has a number of other potential sources of error. Sampling error within the CPCe evaluations is likely in a small number of cases. While many gannet nests contained dolly ropes and even discolored, bleached, or mud and guano-covered dolly ropes were recorded, it is possible that some dolly rope strands were missed. Dolly rope structure, if not clearly visible, combined with a natural coloration due to dirt or guano or bleaching can be misidentified as grasses or dried seaweed. This may have led to an undercounting of dolly ropes in some gannet and kittiwake nests.

In the visual counting of plastic and types of plastic in gannet nests through a scope, dolly ropes were almost certainly undercounted. As we were far away from the nests, counting through a scope, and dolly ropes can come in huge bushels or single monofilament threads, we mostly differentiated “one dolly rope” from another by a change in color or structure. This almost certainly undercounted dolly rope plastic, but an even higher number of dolly ropes would strengthen the arguments made previously regarding gannet dolly rope preferences.

A decision was made in this study not to include black dolly ropes in analysis of dolly rope colors for several reasons. Black dolly rope is not as common as orange or blue dolly rope on beaches and in nests (black dolly rope was identified definitively in only one nest and none was found on beaches), and because of its similarity in color to dark seaweed, a sampling error in the form of missed pieces on beaches could not be excluded. Identifying black dolly rope in nests is also very challenging, and can often only be done if the dolly rope strands are present in a characteristic bundle, hang out far beyond the perimeter of the nest, or are very new and shiny. In photos, a single black strand of dolly rope can be impossible to differentiate from a piece of seaweed. Therefore, any black dolly rope seen in nests was counted as dolly rope, but not classified as a particular color. The exclusion of black dolly ropes is unlikely to have had a serious impact on the data due to the very low volume of black dolly ropes relative to orange and blue dolly rope in the environment.

In field collections of plastic from beaches, it is possible that orange dolly rope was underrepresented because orange dolly rope can (especially when sun bleached) appear similar to drying kelp and seaweed strands. Passersby may also have picked up and removed plastic pieces they encountered, noticing large bundles of dolly rope more often than small pieces. Possibly undercounting orange dolly rope might skew the color distribution of dolly ropes slightly, but the effect on the data is unlikely to be large.

Plastic in Seabird Nests as a Bioindicator and Monitoring Element

Analyzing the plastic in a seabird species’ nests can give us interesting insights into their behavioral ecology, but not every species is well-suited to be an indicator of environmental pollution.

The four species observed in this study meet some of the stipulations suggested by O’Hanlon et al., 2019, but fall short of others. All four species are widely distributed, reasonably abundant (although the declining trend in the kittiwake population may make them less well suited than the others), and are impacted by the pollutant. However, as was seen when comparing the types of plastic in the nests of all four species to the types of plastic found on beaches, we can see that all four seabird species have a preference for fibrous material, and when examining the colors available in the environment, it is also clear that all four species prefer orange dolly rope over other materials. Because the plastic found in their nests does not reflect the plastic composition in the environment, these four species are likely not well suited to be bioindicators for the amount of plastic in the environment. Lastly, two of our species, gannets and kittiwakes, reuse their nests, so the material present in their nests will also not reflect the current quantity or types of plastic found in the environment.

Given their strong preference for dolly rope, and orange dolly rope in particular, however, these seabirds could be useful in indicating the presence or absence of dolly ropes in the environment. Especially if dolly ropes are banned or their use is otherwise discontinued, these species would likely continue to collect dolly rope until it cycled out of the environment. Keeping track of how long dolly ropes are still present after a ban can give us important information about the longevity of this type of plastic in the marine environment.

Nest Mortality Mitigation Efforts

With information from the quantification and analysis of plastic in seabird nests we can also strive to reduce some of the harmful effects of those nest plastics. Unfortunately, freeing entangled birds in the Heligoland cliffs is not possible because it would be logistically difficult, and the disruption to the colony as a whole would lead to loss of chicks and eggs. The removal of plastic nest material during the winter, when they are unoccupied, is also inadvisable as nests are rebuilt the next season, and the new plastic, which isn't matted down yet, is more deadly than the old. Accessing the nests and cliffs is also expensive, difficult, and dangerous.

However, as with all sources of pollution, we can stop or reduce the problem farther upstream. Research groups at the Thünen Institute have spent the past few years developing and testing chafing materials to replace dolly ropes, including solutions such as a return to cattle hides, or the implementation of biodegradable plastic dolly ropes, that break down in sea water and thereby reduce the dangers of entanglement. They have also examined the design of trawl nets themselves, and have come up with alternatives that do not drag along the seafloor to begin with, eliminating the need for chafing material. This would have the added benefit of reducing damage to seafloor ecosystems caused by dragging bottom trawl nets. This redesign method also reduces fuel costs for fishermen, as their nets are not encountering as much friction.

The strategy of eliminating the need for chafing material has already gained followers. In July 2023, the German crab fisher trade association (Verband der Deutschen Kutter- und Küstenfischer e.V.) put out a press release announcing that they would stop using dolly ropes as chafing material on their trawl nets. Primarily, the crab fishermen plan to eliminate the need for chafing material by preventing contact between nets and the sea floor. Citing fuel saving measures, a representative explained that it was a fiscally sound decision. In situations where net contact with the seafloor is unavoidable and chafing material must be used, yak leather or other natural materials were presented as alternatives to dolly rope (Verband der Deutschen Kutter- und Küstenfischer e.V., 2023). While German crab fishers in the southern North Sea were not large consumers of dolly rope prior to this announcement (Haschen, 2023), their willingness to commit to a different net design and natural chafing material may encourage other individuals or even trade groups to follow suit.

Another approach, given the preference seabirds seem to show for orange dolly rope, is to change the colors that dolly ropes and other plastics are made of to make them less appealing to seabirds. This would likely be the least effective approach for reducing injury and death by plastic, as the morphology of the plastic would remain appealing to birds. This would also likely be unpopular with fishermen who prefer to use bright orange dolly rope due to its visibility under low-light conditions (Bekaert et al., 2015).

Future Research

This study suggests many avenues for future research. In order to evaluate the accuracy of photo-based nest analysis, a seabird nest could be photographed and analyzed, then fully dissected, and the results of the two methods compared. The efficacy of this method of photo analysis could also be tested on species whose nests are more complicated, such as passerines (songbirds), which often have very deep nest cups, and the nest material composition may not be the same throughout.

Other image analysis methods have also recently been developed. Since collecting data and the writing of this thesis, a new method of photo analysis was developed by Grant et al. (2021), and has already been successfully implemented by Henderson et al. (2022) in Australia to evaluate the nests of silver gulls. Grant et al.'s method utilizes the free scientific image analysis software ImageJ, and functions similarly to CPCe. The ImageJ method uses grid squares as opposed to the points used in CPCe, but a human evaluator must still decide whether each grid square contains plastic. As there are generally fewer grid squares to evaluate in ImageJ than points in CPCe, however, the former method requires less time than the latter, and doesn't require the adaptation of software intended for another scientific application, as CPCe does. Another advantage of using ImageJ is that any plastic in the nest will be identified, since the whole surface area of the nest that is visible in the photo is evaluated. In CPCe, randomly generated points may not end up being placed on a given piece of plastic, which, in cases of nests with very little plastic, can erroneously imply a plastic-free nest (Grant et al., 2021). However, as even small quantities of plastic will be identified as a "contaminated" grid square in the ImageJ method, the ImageJ method is more likely to over represent small quantities of plastic in nests.

The relatively recent surge in artificial intelligence/machine learning software may also present new avenues in nest photo analysis. At the time that my research on this project began, an automated, machine-learning based approach to nest photo analysis was potentially possible, but definitely expensive, and would have required a significant amount of training of the program before it would be functional.

The recent commitment by German crab fishermen to stop using dolly rope will hopefully mean less dolly ropes used and lost to the North Sea in future years. Ongoing monitoring of the amount and color of dolly ropes in seabird nests in the North Sea waters adjacent to Germany may also provide information as to the speed at which dolly ropes cycle out of the environment, or how quickly a reduction in dolly rope usage is noticeable, or whether a local reduction/elimination of dolly rope use has any impact on dolly rope-wildlife interactions at all.

CONCLUSION

The problems posed by plastics in the environment are exceptionally visible in the seabird nests on Heligoland. Mounds of matted dolly rope, trailing ropes, and fragments of other debris are abundantly visible to visitors, and the remains of entangled seabirds underscore their danger.

The four seabird species examined in this study all included plastic in their nests. Gannets and cormorants were more likely to include plastic in their nests than kittiwakes or gulls, and gannet nests contained more plastic on average than cormorant nests, which in turn included more plastic than kittiwake or gull nests. These differences are likely due to where each species collects nest material, and whether they reuse their nests each year. While they clearly incorporate environmental plastic into their nests, the seabirds studied here do not do so indiscriminately, and primarily include strands of plastic, such as dolly ropes from commercial fisheries. This preference is likely due to the similar shape and structure that dolly rope shares with natural nest materials such as seaweed and kelp. The studied seabirds also showed a preference for orange dolly rope over blue, despite the two colors being present at similar abundances in the environment. This preference may simply be because orange is easier to see against the water's surface, but might also reflect some other preference. While we do not know the full extent of the impact that plastics have in seabird nests, deaths and injuries by entanglement are a definite result of plastics in nests.

Because all species studied here show such strong preferences for dolly ropes, the plastic in their nests is unlikely to accurately reflect plastic pollution in the environment. However, because of this preference, these species' nests may become good indicators of whether dolly rope is still present in the environment, especially as groups such as the German crab fisher trade association have decided to stop using dolly rope entirely.

While photo analysis currently is not as accurate in quantifying and analyzing plastic as dissecting a nest, photo analysis provides a valuable, non-destructive, and low-disturbance method of evaluating plastic in seabird nests. Through standardized, quantitative analysis of nest plastic content and composition, as demonstrated in this study, we can draw conclusions about bird behavior and ecology, and gain some information about environmental plastic. Such data can be used to develop legislative goals and frameworks for tracking or even reducing the amount of plastic in the environment.

APPENDIX

Statistical tests

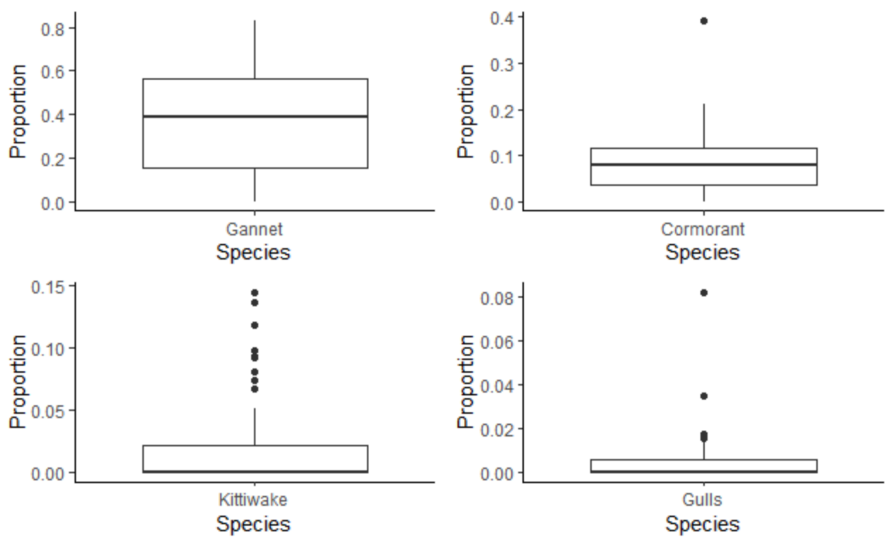


Figure 32: Distribution of data of the proportion of plastic in each species' nests.

Table 1: Paired t-test results of differences in amount of plastic calculated between repetition 1 and 2 of CPCe analysis.

T-statistic	df	p-value	mean difference:	95% confidence interval:
3.4141	182	0.000789	0.01566172	0.006610562, 0.024712868

Table 2: Welch two-sample t-test results of differences in average amount of plastic calculated using a 3x3 stratification and a 5x5 stratification.

T-statistic	df	p-value	95% confidence interval
-1.8319	30.176	0.07685	-0.064134036, 0.003473985

Table 3: F-test results of differences in variances for the two methods of stratifying points when sampling nests using CPCe.

F-statistic	numerator df	denominator df	p-value	ratio of variances	95% confidence interval
0.3252	19	19	0.009196	0.3252	0.0000000, 0.7051154

Table 3: F-test results of differences in variances for the two methods of stratifying points when sampling nests using CPCe.

F-statistic	numerator df	denominator df	p-value	ratio of variances	95% confidence interval
0.3252	19	19	0.009196	0.3252	0.0000000, 0.7051154

Table 4: The average amount of plastic in the nests of the four study species.

Species	mean_prop	sd	n	se
Cormorant	0.0879735	0.0758265	37	0.0124658
Gannet	0.3577476	0.2305364	62	0.0292782
Gulls	0.0072606	0.0173513	29	0.0032221
Kittiwake	0.0226166	0.0382596	55	0.0051589

Table 5: Statistical test results of the Kruskal-wallis rank sum test on the average amount of plastic in the nests of the four study species.

Kruskal-Wallis chi-squared	df	p-value
112.52	3	< 2.2e-16

Table 6: Post-hoc Dunn tests examining the significance of differences between the average plastic content in nests of the four study species. P-values were adjusted with the Holm method.

Comparison	Z-score	Unadjusted p-value	Adjusted p-value
Cormorant - Gannet	-3.73996	0.000184053	0.000368
Cormorant - Gulls	4.640474	3.47611E-06	1.39E-05
Gannet - Gulls	8.569258	1.04154E-17	5.21E-17
Cormorant - Kittiwake	4.154951	3.25357E-05	9.76E-05
Gannet - Kittiwake	8.963796	3.13688E-19	1.88E-18
Gulls - Kittiwake	-1.16543	0.2438471	0.243847

Table 7: Proportion of nests containing plastic by species.

Plastic	Cormorant	Gannet	Gull	Kittiwake
No	0.0540541	0.016129	0.7241379	0.5636364
Yes	0.9459459	0.983871	0.2758621	0.4363636

Table 8: Chi-squared test results of differences in proportion of nests containing plastic across species.

	X-squared	df	p-value
Nests with plastic	58.172	3	1.44E-12
Nests without plastic	113.18	3	<2.2E-16

Table 9: Proportion of different types of plastic counted in gannet nests and collected on beaches during 18 months of biweekly beach litter monitoring.

Location	Line/Dolly rope	Other	Packaging	Rope
Beaches	0.0531814	0.5584046	0.3817664	0.0066477
Nests	0.9555556	0.0148620	0.0133050	0.0162774

Table 10: Chi-squared test results of differences in proportions of types of plastic found between beaches and gannet nests.

	X-squared	df	p-value
Packaging	34.364	1	4.57E-09
Rope	0.4045	1	0.5248
Line/dolly rope	80.723	1	<2.2E-16
Other	51.536	1	7.03E-13

Table 11: Proportion of plastic that is dolly rope versus other types of plastic on beaches and in all four species' nests.

Location	Dolly rope	Other
Beaches	0.0531814	0.9468186
Cormorants	0.7349593	0.2650407
Gannets	0.9261978	0.0738022
Gulls	0.4375000	0.5625000
Kittiwakes	0.6720000	0.3280000

Table 12: Chi-squared test results of differences in proportions of dolly rope and other plastic between beaches and the nests of the species studied.

	X-squared	df	p-value
Dolly rope	79.504	4	<2.2E-16
Other	103.17	4	<2.2E-16

Table 13: Proportion of plastic of each color on beaches and in the nests of the four species studied.

Location	Black	Blue	Green	Orange	Unidentified/other	White
Beaches	0.2621534	0.0620978	0.0614898	0.0762717	0.0317072	0.5062802
Cormorant	0.0216518	0.2334838	0.0145897	0.4978624	0.1519742	0.0804381
Gannet	0.0108287	0.1029326	0.0091720	0.5743834	0.2873113	0.0153720
Gull	0.0384615	0.0000000	0.0000000	0.4635628	0.4979757	0.0000000
Kittiwake	0.0622007	0.1385297	0.0309507	0.5171815	0.1795079	0.0716295

Table 14: Chi-squared test results of differences in proportions of colors of plastic between beaches and the nests of the species studied.

	X-squared	df	p-value
White	131.64	4	<2.2E-16
Orange	37.388	4	1.50E-07
Blue	28.371	4	1.05E-05
Black	54.904	4	3.40E-11
Other/unidentifiable	53.572	4	6.47E-11
Green	10.049	4	3.96E-02

Table 15: Proportion of plastic found on beaches of each color calculated by area and by count.

Method	Black	Blue	Green	Orange	Other	White
Area	0.2621534	0.0620978	0.0614898	0.0272961	0.0806827	0.5062802
Count	0.0372340	0.4734043	0.1010638	0.1968085	0.0797872	0.1117021

Table 16: Chi-squared test results of differences in proportion of different colors when calculated by count or by area.

	X-squared	df	p-value
Black	16.897	1	3.95E-05
Blue	31.591	1	1.90E-08
Green	0.96344	1	0.3263
Orange	12.822	1	0.000343
Other	0.0005	1	0.9822
White	25.194	1	5.19E-07

Table 17: Proportion of dolly rope found on beaches of each color calculated by area and by count.

Method	Blue	Orange
Area	0.5768335	0.4231665
Count	0.6140351	0.3859649

Table 18: Chi-squared test results of differences in the proportion of blue and orange dolly ropes on beaches by method of calculating proportion (by area or by count).

	X-squared	df	p-value
Orange dolly rope	0.17104	1	0.6792
Blue dolly rope	0.11621	1	0.7332

Table 19: Proportion of dolly rope of each color on beaches and in all nests.

Location	Blue	Orange
Beaches	0.5768335	0.4231665
Nests	0.1521135	0.8478865

Table 20: Chi-squared test results of differences in proportions of blue and orange dolly rope between beaches and the average of the nests of the species studied.

	X-squared	df	p-value
Orange	14.192	1	0.000165
Blue	24.746	1	6.54E-07

Table 21: Proportion of dolly rope of each color on beaches and in the nests of each species studied.

Species	Blue	Orange
Cormorants	0.1899840	0.8100160
Gannets	0.1521135	0.8478865
Gulls	0.0000000	1.0000000
Kittiwakes	0.0684932	0.9315068

Table 22: Chi-squared test results of differences in proportions of blue and orange dolly rope between the species studied.

	X-squared	df	p-value
Orange dolly rope	25.128	3	0.4887
Blue dolly rope	21.216	3	0.0001

Table 23: Calculations investigating the acceleration that birds of each species would need to break a single strand of dolly rope (which has a tensile strength of approx. 49 Newtons).

Species	Approx. weight (kg)	A=F/M	Acceleration (m/s^2)
Gannets	3	49/3	16.34
Cormorants	2.2	49/2.2	22.29
Kittiwakes	0.4	49/0.4	98.07
Lesser black-backed gulls	0.8	49/0.8	61.29
Herring gulls	1	49/1	49
Common murres	1	49/1	49

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