

MARINE DEBRIS IN THE NORTH PACIFIC OCEAN: DISTRIBUTION AND
ABUNDANCE PATTERNS AT SEA, AND INGESTION BY TWO
SYMPATRICALLY-BREEDING ALBATROSS SPECIES

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Chapter 1: Literature Review

Plastic in the marine environment, trends in marine debris and ingestion by seabirds.

Marine Debris History and Sources

Plastics have only existed since 1907 with the invention of Bakelite (AmericanChemistry, 2007) and have only proliferated widely over the last 50 years. In 1988, 30 million tons of plastic were being produced annually in the United States alone (Derraik, 2002), and as of the year 2000 plastic production had exceeded 150 million tons per year, with further increases expected. Because plastics are durable and inexpensive to produce they have been widely used for a wide variety of products, many of which are single use (Laist, 1987). The buoyant nature of plastics makes them subject to being transported by ocean currents once they enter the marine environment. Plastics are highly resistant to ageing and degradation, however, exposure to ultra-violet rays and seawater cause the polymers become brittle and break into smaller pieces (Moore, 2008). Despite this mechanical breakdown, the individual polymers remain intact. The time required to degrade these polymers is yet unknown, especially if small fragments are ingested by living organisms (Andrady, 2005). With production of plastics increasing, it is safe to assume that plastic accumulation rates in the ocean environment will increase, unless successful cleanup or mitigation efforts are implemented.

Plastic enters the marine environment from two major sources. Ship based litter contributes a lot of the plastic pollution to the marine environment, both from fishing and merchant fleets as well as recreational vessels worldwide. In 1975 it was estimated that

the fishing industry accounted for 135,400 tons of lost fishing gear and 23,600 tons of dumped packing material worldwide. In addition, merchant ships were responsible for an additional 639,000 plastic containers dumped every year. Recreational boats, cumulatively contribute a large part of the marine litter. For instance, recreational vessels contribute an estimated 52% of all litter dumped in U.S. waters according to estimates by the U.S. Coast Guard (Derraik, 2002). The dumping of plastics in the ocean may have been reduced by the passing of the Marine Pollution convention (MARPOL) Annex V in 1988, which created international law banning the dumping of plastics at sea. However, due to the problems associated with enforcement in the high seas, the effect of the law is hard to quantify (Spear et al., 1995). Plastic can also enter the marine environment through land based sources. Plastics comprised of packing material, bags and bottles are carried into the oceans by streams, rivers and municipal drainage systems with the areas of highest input located around densely populated areas (Derraik, 2002). This plastic input has increased dramatically over time, with the amount of plastic in U.S. municipal waste streams having tripled during the 1990's (Moore, 2008). In one attempt to quantify the amount of plastic entering the ocean from a municipal river source, Moore et al. (2005) sampled three rivers in Los Angeles, California during both high and low flow conditions. An average estimated 36,788 kg of plastic fragments bigger than 1 mm were entering the ocean per day during maximum flow rates, and even during minimum flow conditions, an average estimated 141 kg per day were entering the ocean.

Because of these high input rates and their persistence in the environment, plastics make up the dominant (60-80%) proportion of total marine debris worldwide (Derraik, 2002). Plastics remain the dominant category of marine debris even in distant uninhabited

sites. For instance a recent study looking at accumulation of debris in the Northwestern Hawaiian Islands (NWHI) found that between 1990 and 2006, 70% of all debris examined from beaches at French Frigate Shoals was plastic, with 14 tons of fishing gear removed from the NWHI in 1999 (Morishige et al., 2007).

The Ecological Impacts of Marine Debris

Most research on the impacts of marine debris have been focused on the deleterious effects of lost fishing gear, such as ghost nets which entangle marine mammals and turtles at sea, and cause severe damage to coral reefs and other nearshore habitats when they wash ashore (Laist, 1997; Morishige et al., 2007). However, 96% of the plastic found in the North Pacific consists of small fragments of post user plastics and production pellets or nurdles (Robards et al., 1997). These small oval and spherical pellets are shipped from production factories to plastic injection plants to be melted into user plastics, as well as being used as filler in children's stuffed toys. Billions of nurdles were lost every year from shipping containers and plastics factories, and millions found their way to the ocean (McDermid and McMullen, 2004), however current data would suggest that the number of nurdles entering the ocean is now significantly reduced as regulation and awareness has increased (Vlietstra and Parga, 2002).

There are many complex problems associated with marine debris (Moore, 2008):

1) Fouling of beaches by plastic devalues the experiences of beachgoers which has a negative effect on the tourist industry. Additionally, medical waste can pose a public health hazard; 2) Entanglement of marine life can cause death. Lost or abandoned fishing 'ghost' nets float throughout the oceans capturing marine life indiscriminately; 3) Ingestion of plastic pieces by marine organisms, including seabirds, turtles and marine

mammals can injure or even cause the death of individuals; 4) The persistent nature of plastic polymers, and their buoyancy provides ideal habitat for bryozoans, barnacles, polychaete worms hydroids and molluscs. Thus, plastics may provide more efficient methods of dispersing invasive species across ocean barriers; 5) Plastics can be sources of toxins and sinks for Persistent Organic Pollutants (POPs) which can accumulate in organisms ingesting plastic fragments (such as seabirds, which can lead to reduced reproductive success) and microscopic particles such as by the zooplankton at the base of the food web; 6) Fouling organisms can cause plastics to lose their buoyancy, causing them to sink to the sea floor. Here they can cause a barrier, inhibiting gas exchange with the sediments and possibly affecting the composition of the sedimentary ecosystems; 7) Debris can accumulate on or destroy coastal nursery habitat threatening coastal species; 8) Marine debris can foul ship keels and obstruct intake ports and propellers, putting crew and vessels at risk (Moore, 2008).

Perhaps the most pressing ecological issue is the ingestion of plastic and the entanglement in debris by marine megafauna. All over the world's oceans, marine debris poses a risk to many endangered and threatened species. In the NWHI alone, the endangered Hawaiian monk seal (*Monachus schauinslandi*), hawksbill (*Eretmochelys imbricate*) and olive ridley (*Lepidochelys olivacea*) sea turtles, along with the threatened green (*Chelonia mydas*) sea turtle are all threatened by entanglement in marine debris (Morishige et al. 2007). In addition to marine mammals and turtles, seabirds around the world are susceptible to entanglement in fishing nets and line, and also to the ingestion of plastic found at sea. While entanglement is a conservation concern for a broad range of species, this review focuses on the specific issues of plastic ingestion by seabirds.

Quantifying Marine Debris at Sea

Some studies have attempted to describe plastic occurrence and densities in the ocean by directly sampling floating plastic at sea. Moore et al. (2001) sampled neustonic marine debris through the central region of the North Pacific Subtropical Gyre (NPSG), a known area of high debris accumulation. Their sampling yielded a mean abundance of 334,271 pieces km⁻², with a mean mass of 5114 g km⁻². This abundance is much higher than previous estimates of plastic levels in this area during the 1970s-1980s, when estimated mean abundances between 3370 to 96,100 pieces km⁻² and mean masses between 0.5 to 1 kg km⁻² were found (Day and Shaw, 1987). This recent study reported a higher abundance and mean mass than the previous peak values recorded for the North Pacific, which originated from an area 500 miles east of Japan, where an abundance of 316,800 pieces km⁻² and a mean weight of 3.5 kg km⁻² was recorded (Day et al., 1990).

While a lot of interest and research has been directed at the plastic accumulations in the North Pacific Subtropical Gyre, Law et al. (2010) presented findings of increasing plastic accumulation in the North Atlantic Subtropical Gyre. During the time period of 1986 to 2008 over 60% of 6,136 surface tows showed presence of plastic. Over the 22 year period, strong inter-annual variation was observed in the debris concentrations sampled without a long term temporal trend. The authors attributed this lack of an increasing trend to the possibility of increases in land based plastic input being offset by decreases in ship based input as a result of international regulations preventing plastic being dumped at sea (Law et al., 2010).

Other ocean areas around the world have mirrored this increasing trend in the abundance of plastic particles. Debris around the coastline of the United Kingdom

doubled from 1994 to 1998, plastic levels in the Southern Ocean increased 14-15 fold during the 1990s, and plastic levels around the coast of Japan increased 10 fold in 20 years during the 1970s and 1980s (Moore, 2008). The rate of accumulation in Japan increased again during the 1990s when plastic levels increased another 10 fold in only 2-3 years (Moore, 2008). The NPSG and Japan are not the only areas of plastic accumulation in the North Pacific. The Gulf of Alaska has shown increases in small plastic particles from 0-132 particles km⁻² (1974-1976) to 3370 particles km⁻² (1985), to 12,800 particles km⁻² (1985-1988). The Bering Sea has also seen similar increases in plastic levels, increasing from 68, to 80, to 600 particles km⁻² respectively during these same time periods (Robards et al., 1995).

While a majority of studies of marine debris at sea have relied on nets to sample and accurately describe the debris communities, these methods are time consuming and offer limited spatial resolution, determined by the inherent length of a net tow (~ 1 nautical mile) and the sampling (tows are spaced out by 10s – 100s of kilometers) (Moore, 2008; Law et al., 2010). Visual surveys for marine debris performed using the same techniques developed for visual surveys of marine birds or marine mammals, offer a low cost, high spatial resolution method to monitor marine debris that can easily be adapted to any ship of opportunity. Yet, to date, few studies have rigorously quantified floating debris in the North Pacific using visual methods (Dahlberg and Day, 1985; Pichel et al., 2007). A study by Dahlberg and Day (1985) conducted observations of marine debris from a Japanese fishing vessel on a transit from Alaska to Hawaii to Japan. During the cruise 727 objects were observed of which 80% were plastic. The majority of the debris was observed between 31° and 39° N, in an area of surface convergence. This

study also noted how sightability of marine debris declines with increasing distance from the vessel, with 80% of the objects detected within 100 m of the vessel. The authors also discussed the significance of color in determining sightability whereby white objects were recorded relatively far from the vessel and clear objects were very difficult to detect at all distances. The wider acceptance of visual surveys for marine debris monitoring at sea requires the development of standardized methods that take into account the size and color of the debris. This is a critical step necessary to confidently compare different studies across platforms and observers.

At sea surveys use strip transect methods to count seabirds (Tasker et al., 1984) and line distance sampling to count marine mammals (Buckland et al., 1993). Chapter 2 will explain the assumptions and methodologies more in depth, and their potential application to marine debris surveys.

Plastic Ingestion by Seabirds

The pervasive nature of plastic pollution has been documented in ocean waters worldwide, with plastic pollution documented in the tropics (Spear et al., 1995), subtropics (Moore et al., 2001) as well as temperate and sub-polar regions (Robards et al., 1995) of the Pacific. Plastic pollution has also penetrated the strong Antarctic Circumpolar Current, reaching distant Southern Ocean sites such as Inaccessible Island (Ryan and Moloney, 1993). This global documentation of plastic pollution on beaches and at sea has been mirrored in the prevalence of plastic ingestion by seabirds. This section of the review will focus on studies conducted in the North Pacific; however,

many of the patterns in ingestion incidence and factors that influence plastic ingestion will hold true for seabird populations worldwide.

Not only has marine debris become a widespread and pervasive pollutant throughout the world's oceans (Derraik, 2002), but the ingestion of plastic by sea birds has been documented across the globe and in a multitude of species. Recent studies have estimated that 44 % of all seabird species are affected by marine debris (Laist, 1997).

In the North Pacific, the species with the longest recorded history of plastic ingestion are the Hawaiian albatrosses. First reported in 1969 (Kenyon and Kridler, 1969) for Laysan Albatross (*Phoebastria immutabilis*), incidence of plastic ingestion has been consistently high for both Laysan and Black-footed albatross (*Phoebastria nigripes*) (Fry et al., 1987; Sileo et al., 1990; Kinan and Cousins, 2000). Plastic ingestion by Pacific albatrosses will be discussed in depth later in the review.

The Wedge-tailed Shearwater (*Puffinus pacificus*) is another Hawaiian breeding procellariid that ingests plastic. First reported by Fry et al. (1987) from a colony on Manana Island, Oahu, a majority (60%, n=20) of adults showed the presence of small (2-4 mm diameter) plastic pieces were pellets. A recent study of breeding wedge-tailed shearwaters in Australia found an ingestion level of 43% (n=30) in chicks (Hutton et al., 2008). In contrast, Spear et al. (1995) collected Wedge-tailed Shearwaters at sea in the Eastern Tropical Pacific and found a much lower incidence of ingestion (9 %, n=23) with all pieces of plastic from a post-user origin. These colony-based findings yielded substantially higher plastic ingestion rates than those reported by Spear et al. (1995), suggesting the important influence of the timing (season) and location (e.g., colony-based vs. at-sea) as determinants of the incidence of plastic ingestion in this species.

Blight and Burger (1997) examined seabirds accidentally entangled in a Pacific squid gillnet fishery off the coast of British Columbia, Washington and Oregon. The Black-footed Albatross showed 100% incidence of plastic (n = 3). This was the same result observed for the rest of the procellariiformes examined in this study, the Fork-tailed Storm petrel (*Oceanodroma furcata*) (n = 7), Leach's Storm petrel (*O. leucorhoa*) (n = 1), Northern Fulmar (*Fulmarus glacialis*) (n = 3), and Stejneger's Petrel (*Pterodroma longirostris*) (n = 1), which all showed 100% incidence of plastic. Despite the small sample sizes, this study highlights the susceptibility of the procellariiformes to ingesting plastic, most likely due to their shared foraging method of surface feeding.

The other species examined by Blight and Burger (1997), which ranged widely in ingestion incidence (from 0 – 89%), forage by means of diving for prey, making them less likely to ingest floating plastic. The exception being the Tufted Puffin (*Fratercula cirrhata*) with an incidence of 89% (n = 9), and the Horned Puffin (*F. corniculata*) with an incidence of 50% (n = 2). Further, the mean number of plastic pieces was far greater for the surface feeding birds (20.8) than for the divers (1.4).

Habitat use Effects on Plastic Ingestion

The foraging habitats and ocean domains inhabited by particular seabird species are important determinants influencing plastic ingestion rates. This may have much to do with the likelihood of encountering plastic pollution at-sea, when foraging for concentrated prey in highly productive areas or by searching vast areas of the marine environment for over-dispersed prey. At one level, certain nearshore seabirds such as alcids are likely to be impacted by coastal human pollution and fishing activities (Nevins et al., 2005). Far ranging seabird species such as the procellariiformes that are dependent

on prey accumulation features such as frontal systems will be at risk from plastic pollution that has dispersed from its source and is concentrated by the same oceanographic features that congregate the buoyant and weakly swimming natural prey for the birds (Franks, 1992; Pichel et al., 2007).

Because seabirds range so far, many are likely to encounter plastic debris far away from their breeding sites (Cooper et al., 2004). For instance, a study by Spear et al. (1995) highlighted this disparity among sites by sampling seabirds for plastic ingestion in the tropical East Pacific. Neustonic tows for plastic pollution showed low densities both in the Equatorial Counter Current (24 pieces km⁻²) and the South Equatorial Current (137 pieces km⁻²). Overall incidence was high among the procellariiformes, with 71% (n = 24) of species containing plastic. However, a high number of procellariids were examined in this study comprising three migratory life-history patterns: (i) year round residents of the tropical Pacific, (ii) birds that bred in the South Pacific and wintered in the tropical Pacific, and (iii) birds that bred in the South Pacific but wintered in the North Pacific. When examining a subset of these procellariiformes which had sample sizes greater than 5 birds, the incidence of ingested plastic was seen to rise between 1984 to 1990 and then decline after. Spear et al. (1995) assert that this decrease in plastic ingestion after 1990 may be in response to the MARPOL Annex V law banning plastic dumping at sea.

Spear et al. (1995) also demonstrated that species foraging in the North Pacific showed much higher levels of plastic ingestion incidence and loads than species that foraged in the South Pacific or in the Tropical Pacific. In particular, Sooty Shearwaters (*Puffinus griseus*), which breed in New Zealand and winter in the North Pacific showed significantly higher incidence of plastic ingestion when migrating across the tropical

Pacific towards New Zealand after wintering in the North Pacific than during their northward migration towards the North Pacific (Spear et al., 1995). The proportions of different types of ingested plastic were also influenced by the marine ranges of seabird species. South Pacific breeding species showed a higher proportion of pellets while North Pacific breeding species showed a higher proportion of user plastics. This difference is likely due to the composition of plastics available to these species in different ocean regions, as evidenced by studies of plastic pollution in the North Pacific (Day and Shaw, 1987; Moore et al., 2001) and the prevalence of industrial pellets in the South Pacific (Gregory, 1978). This was supported by two specific examples of the White-faced Storm-petrel (*Pelagodroma marina*), a planktivorous species from the South Pacific, with a dominance of pellets (100%), and the Leach's Storm-petrel, a planktivorous species from the North Pacific with a dominance of user plastics (95%) (Spear et al., 1995).

Plastic ingestion in North Pacific Albatross

Two species of albatross breed in the Hawaiian archipelago. The Laysan Albatross has large population numbers of around 2.5 million birds and breeds on atolls throughout the NWHI, at a few isolated sites on Lehua, Oahu and Kauai, Main Hawaiian Islands, and in Baja California, Mexico (Whittow, 1993; Naughton et al., 2007). The Black-footed Albatross has a smaller population size of around 300,000 birds and its breeding sites are limited to the atolls of the NWHI and Japan (Naughton et al., 2007; Awkerman et al., 2008).

These two albatross species likely differ in the threat that marine debris poses to them due to different foraging strategies, breeding location and food habitats. Laysan

Albatross are shown to disperse from their colonies generally north towards the Bering Sea and the Aleutian Islands (Whittow, 1993; Fernández et al., 2001). Foraging in colder transition zone and subarctic waters during the rearing season (Hyrenbach et al., 2002; Kappes et al., 2010). Black-footed Albatross disperse across a wider range, going north towards Alaska while also foraging off the coasts of North America and Japan (Fernández et al., 2001; Awkerman et al., 2008), but staying restricted to more tropical waters and the California Current during the rearing season (Hyrenbach et al., 2002; Kappes et al., 2010). Colony location may be a factor in defining the foraging locations of Black-footed Albatross with birds from the more south-eastern colony of French Frigate Shoals dispersing more towards North America (Fernández et al., 2001), while birds from the north western colony of Kure Atoll disperse west towards Japan (Hyrenbach, pers. comm.).

Plastic ingestion in Laysan Albatross was first reported in 1969, when a study revealed that 74% (n = 100) of chick carcasses examined in the NWHI contained plastic (Kenyon and Kridler, 1969). While this early study showed a high level of incidence of ingested plastic, it focused exclusively on dead chicks. A latter study looked at plastic ingestion throughout a range of body condition and found 90% (n = 50) Laysan Albatross chicks with ingested plastic (Fry et al., 1987). This study also began to address potential implications of ingesting plastic, and noted that three birds had proventricular impactions or ulcerative lesions (Fry et al., 1987). Follow-up studies showed 98% incidence of plastic ingestion in Laysan Albatross chicks (Sileo et al., 1990; Sievert and Sileo, 1993), with a high proportion (27%, n = 350) having large plastic loads (volume > 22cm³), as determined by endoscopic assessment (Sievert and Sileo, 1993). By contrast, a lower

proportion of Black-footed Albatross (16%, n = 142) met this criterion of plastic load ingestion (Sievert and Sileo, 1993). Yet, it is unclear to what extent this disparity was influenced by potential biases of the endoscopic sampling technique to detect the ingested marine debris, especially given the species-specific differences in the type of plastic ingested (line and foam, small fragments in the Black-footed Albatross; large plastic fragments in the Laysan Albatross). While the cause of death has been investigated in Laysan Albatross, dehydration (34%, n = 137) and suspected dehydration (18%, n = 137) were the leading causes of mortality, with no deaths attributed to direct mechanical lesions from ingested plastic (Sileo et al., 1990). More recently, the incidence of plastic ingestion using the analysis of plastic found in boluses, regurgitated matter from chicks prior to fledging, has revealed plastic ingestion rates of 100 % for both Laysan and Black-footed Albatross (Kinan and Cousins, 2000). Data on plastic ingestion by North Pacific albatrosses are summarized in table 1.

These albatross species also vary in the type of ingested plastic. Evidence suggests that Laysan Albatross are collecting larger fragments of plastic such as bottle caps and lighters while Black-footed Albatross are primarily collecting pieces of line (Kinan and Cousins, 2000). The differences in the types of plastic may also be due to documented differences in diet of these two species where Laysan Albatross rely more heavily on squid in their diet, while Black-footed Albatross rely more heavily on flying fish eggs in theirs (Harrison et al., 1983).

One likely area that North Pacific albatross are collecting plastic from is the Transition Zone Chlorophyll Front (TZCF). The TZCF is a dynamic oceanographic feature spanning the entire North Pacific basin, which marks the transition between low

chlorophyll (oligotrophic) waters to the south and high chlorophyll (eutrophic), productive waters to the north. The front is operationally defined as a surface chlorophyll density of 0.2 mg m^{-3} (Polovina et al., 2001) and it migrates north/south on a seasonal, inter-annual and inter-decadal basis (Chai et al., 2003). This convergence zone concentrates floating marine debris, as well as the buoyant and weakly swimming organisms that are natural prey items for tubenose seabirds (Franks, 1992; Pichel et al., 2007). Additionally, albatross are known to forage using this feature (Hyrenbach et al., 2002).

While previous studies of plastic ingestion in dead albatross chicks and adults have reported 100% incidence (Sileo et al., 1990; Blight and Burger, 1997), the levels and incidence of ingested plastic in fledgling chicks remains unknown. Additionally, a greater understanding of the levels of ingested plastic is needed for both adults and chicks throughout the Hawaiian Islands, in order to properly understand if ingested plastic poses a threat to these seabird populations and what the extent of that threat might be.

Long Term Studies

Long term studies offer a unique opportunity to study many issues related to marine debris. In addition to being able to monitor and track ingestion rates and types over time for wildlife management use, long term studies also allow insights into how the available debris field in the ocean is changing over time.

Vlietstra and Parga (2002) reported the incidence and amount of ingested plastic in Short-tailed Shearwaters (*Puffinus tenuirostris*) in the Bering Sea spanning four decades and compared recent results (1997-2001) to previous findings (1970-1978) to

investigate change over time. Short-tailed shearwaters breed in the South Pacific and winter in the Gulf of Alaska and the Bering Sea where they represent the most numerous seabird in the region. Plastic ingestion incidence was 84% for birds sampled during 1997-2001. This incidence of ingestion represents an increase from levels observed in the early 1970s when incidence was over 50%. Further increases were reported over the decade, however, the present levels of occurrence and amounts of plastic were not different from levels observed in the late 1970s indicating that this species has stabilized in the incidence and amounts of plastic ingested. This is an interesting result when compared to the previously reported increase in plastic densities found in the Bering Sea over the same time period.

Although Vlietstra and Parga (2002) did not notice any difference in the incidence or amount of ingested plastic, there was a significant shift in the type of plastic that was ingested. During the period of 1969-77 the composition of the plastic ingested by the shearwaters was 73% industrial pellets. The more recent sampling by Vlietstra and Parga showed that the largest component were user plastics representing 64%. This significant shift in the type but not the amount or incidence of the plastic ingested led the authors of this study to suggest that the type of plastic available for the birds in the North Pacific has changed since the 1970s. This composition change of the plastics at sea has been confirmed by in-situ studies that have documented a decline in the amount of industrial pellets (Day and Shaw, 1987). It is thought that the stabilization and change in composition may be a result of the introduction of MARPOL Annex V, since its introduction may be especially felt in the Bering Sea where cargo and fishing vessels are the primary source of plastic pollution (Vlietstra and Parga, 2002).

Similarly, stabilizations have been observed in the North Sea where ingestion by the Northern Fulmar has stabilized but not decreased (van Franeker, 2010). In the southern North Sea, the amount of plastic ingested by Northern Fulmars decreased during the 1990s, however the reduction in plastic load ceased in the 2000s and showed much larger inter-annual variation (van Franeker, 2010). When compared to other areas of the North Sea, the southern North Sea from the English Channel to the German Bight showed the highest levels of plastic ingestion with Northern Fulmars having twice as much plastic as fulmars from Scotland. These birds in turn had twice as much ingested plastic as birds from the Faroe Islands (van Franeker et al., 1995). Over time, the composition of plastics ingested by North Sea Northern Fulmars has also changed, with the birds now consuming less industrial pellets and more post user fragments (van Franeker, 2010). This contrasts with Northern Fulmars from the Canadian Arctic in which on 31% (n = 102) are shown to ingest plastic (Mallory, 2008).

A study by Robards et al. (1995) also examined plastic ingestion in North Pacific seabirds over time. From 1988-90, 63% of 24 species were found to ingest plastic with all of the procellariids showing ingested plastic. In comparison to birds examined during 1967-1977, 12 species were found to ingest plastic. Throughout both study periods, the amount of plastic ingested increased in 12 of 17 species that had shown incidence (Robards et al., 1995). This study showed that out of 4417 plastic pieces that were ingested 76.4% were industrial pellets and 21.5% user plastics. This seems to be in contradiction to the reported composition of ingested plastics from other studies (Vlietstra and Parga, 2002; Blight and Burger, 1997) as well as the composition of available plastics at sea (Day and Shaw, 1987; Moore et al., 2001). However, this

highlights the difference in the feeding method of the birds studied. Robards et al., (1995) found that 7 species accounted for 99% of all the plastic ingested and that of those species, 4 were surface feeders and 3 were pursuit divers (Table 2). Further, the cumulative number of pieces examined from divers (3962 pieces) was much larger than those examined from surface feeders (406 pieces). In addition, there was a large difference in the number of birds in each feeding category examined. The large differences in sample sizes between groups make comparisons difficult. Surface feeding birds accounted for 30% of birds included in the 7 species ($n = 360$), while diving birds accounted for 70% ($n = 817$). It must be noted that these results were influenced by the sampling design, since many of the specimens analyzed were collected for a separate unrelated study. Because overall trends are sensitive to the overall size of the dataset and the proportions of different species, it is important to examine the results of each study closely and to address, species-specific and site-specific trends.

All of these studies have highlighted how the different foraging methods (surface feeding vs. pursuit diving) affect plastic ingestion incidence and composition. This is summarized in Nevins et al. (2005). Table 3 shows while diving birds are also prone to plastic ingestion, zooplankton feeders (such as puffins) show higher rates of incidence of ingestion than fish eaters (such as murre) (Nevins et al., 2005).

Seabirds as Indicators of Plastic Pollution

Plastic ingestion by seabirds is a pervasive problem that affects many different seabird species across the globe (Robards et al., 1995; Spear et al., 1995; Laist, 1997). Seabirds forage over vast ranges of oceans without regard for exclusive economic zones

or jurisdictional boundaries. In addition, their role as upper trophic marine predators makes them susceptible to secondary ingestion of plastic via their prey (Ryan and Fraser, 1988). These features make seabirds ideal bio indicators of marine plastic pollution (Nevins et al., 2005; Hyrenbach et al., 2009). Of the seabirds, surface foragers are particularly susceptible to the ingestion of plastic. Procellariiformes tend to accumulate the highest levels of plastic, partially due to the constriction between the proventriculus and gizzard which makes regurgitation of plastic fragments difficult or impossible (Azzarello and Vanvleet, 1987).

Investigating plastic ingestion by seabirds yields very valuable insights concerning marine pollution. Not only can we learn about the problems associated with ingesting plastic by these far-ranging upper trophic predators, and the threats that seabird species face from ingesting such debris, but sampling seabird populations for plastic ingestion can also yield information about the levels and types of plastics present in the ocean. While using seabird stomach contents as an indicator of marine plastic provides a useful and inexpensive alternative to sampling plastics directly at sea (McDermid and McMullen, 2004), these studies require ground-truthing the value of birds as biological indicators as a species habitat, range and diet will provide only a subsample of the available plastic in the ecosystem. Long lived seabirds such as albatross which can live longer than 80 years, are susceptible to the cumulative effects from the collection of pollutants over their life span (Auman et al., 1997).

Metrics for Cross-study Comparisons

Plastic ingestion by seabirds has been shown to be widespread throughout the North Pacific and the global ocean. The literature shows that the incidence, amount and type of plastic ingested varies greatly across species, foraging location and time period. Therefore care is needed when interpreting results from individual studies of plastic ingestion by placing them in a broader taxonomic and spatio-temporal context.

Perhaps the simplest metric for evaluating plastic ingestion is the incidence of ingestion, expressed as the percentage of sampled birds that contain any ingested plastic. This can be a useful metric for determining how strongly different species are impacted by plastic pollution, and for inferring the regional prevalence of plastic in certain ocean areas frequented by the particular species. In the case of albatross, plastic collected at sea is delivered by the foraging adults to their chicks back on remote colonies. Thus, studies on albatross chicks have found a high incidence of plastic ingestion. During 1982 and 1983 Laysan Albatross chicks examined at Midway Atoll, NWHI, exhibited an overall incidence of 90% indicating that this large species (3 kg) (Pettit et al., 1988) is highly impacted by ingesting plastic pollution (Fry et al., 1987). Furthermore, dead chicks had higher levels of plastic ingestion (mean 77 g) than live chicks (mean 36 g). Despite the small sample size for the weight study (5 dead chicks and 19 live chicks), this study provided an additional metric (ingested plastic mass) for quantifying plastic ingestion (Fry et al., 1987). The development of additional sensitive metrics is critical for assessing trends in species which, like albatrosses, already experience elevated levels of marine debris ingestion.

Looking at changes across species and over time is critical to understanding temporal and spatial patterns of plastic ingestion. While an incidence of 90% had

previously been reported in Laysan albatross chicks, a more recent study examining the boluses regurgitated by chicks an incidence of 100% (Kinan and Cousins, 2000). Further studies of plastic incidence in albatross adults and chicks confirmed their high susceptibility to plastic ingestion.

An additional useful metric is to look at the types of plastic being ingested as this can reflect the types of plastic pollution present in the oceans. Blight and Burger (1997) reported the percentage of the ingested plastic that was industrial pellets. By looking at the breakdown of ingested plastic, we can gain an understanding about the sources and origins of the debris that each species is most likely to ingest, as well as inferring the makeup of plastic debris at certain ocean locations. For example, Leach's Storm-petrel, although highly susceptible to plastic ingestion with 100% incidence, only ingested 6% industrial pellets. In contrast, the Horned Puffin, which showed 50% incidence, ingested 100% industrial pellets (Blight and Burger, 1997).

Boluses as Plastic Samples

Plastic ingestion and diet of albatross has involved analyzing boluses, the masses of indigestible material regurgitated by albatross chicks at the end of the breeding season. During May and June in the weeks prior to fledging, albatross chicks purge the indigestible material they have collected over the rearing season in a bolus (Pettit et al., 1981; Sievert and Sileo, 1993). Because the study of boluses does not require the death of the animal, this approach increases the sample size to include chicks that survive to fledge. Therefore, combining chick necropsies with bolus dissections provides a more complete picture of the levels of plastic ingestion in the albatross population as a whole.

Previous analyses of albatross bolus composition have revealed that the two species of Hawaiian albatross differ in the type of material they regurgitate (Kinan and Cousins, 2000). Black-footed Albatross boluses are regurgitated as a solid large pellet, the smaller plastic and squid beaks amalgamated with the line, flying fish eggs and organic material. This can be collected easily and it is also easy to tell if the bolus has been scavenged by crabs leading to easy assessments of if the bolus is intact and may be used for analysis. Laysan Albatross boluses consist of loosely regurgitated material that can be expelled in multiple sessions and in different places. The nature of this regurgitation introduces potential errors, since it is difficult to determine if a sample includes the entire bolus or merely part of the regurgitated material. Differences in the composition of boluses based on colony location are also known. Young et al. (2009) compared Laysan albatross boluses from Oahu and Kure Atoll and found almost 10 times more plastic present in the Kure Atoll boluses than in Oahu boluses.

Conclusions

Levels of marine debris have increased rapidly since the mid-20th century, due in large part to an increase in plastic in the marine environment which now makes up the vast majority of marine debris. The plastic in the marine environment takes many forms including production pellets, plastic fragments, nets and line. This plastic causes many problems for marine life including entanglement and ingestion. In order to understand the trends and patterns in marine debris, studies have monitored marine debris trends directly in the ocean, and through the ingestion by seabirds.

Many factors can influence the amount and type of plastic that seabirds ingest including habitat use patterns and feeding method. Long term changes in the amount and composition of the debris can be tracked through seabirds as has been done in many areas of the world. In the North Pacific, albatross have shown a long history of high amounts of plastic ingestion that is easily studied through necropsies and more recently boluses. Using boluses we are able to better track levels and types of ingested plastic in albatross populations in Hawaii and through examining ingested plastic using metrics focused on a specific application we are better able to asses both patterns in marine debris and the threat to seabirds.

Tables

Table 1. Review of plastic ingestion studies for North Pacific albatross species: Laysan Albatross (*Phoebastria immutabilis*, LAAL) and Black-footed Albatross (*Phoebastria nigripes*, BFAL).

Reference	Species	Colonies	Sample Type	Results
Kenyon and Kridler 1969	LAAL	Pearl and Hermes	Chick Carcasses	74% (n=100) incidence
Pettit et al. 1981	LAAL	Midway	Chick Carcass / Bolus	100% (n=4) incidence in carcasses, plastic present in boluses
Fry et al. 1987	LAAL	Midway	Chick / Adult Carcass	90% (n=50) incidence in chicks, 50% (n=4) incidence in adults. Weight and volume of plastics higher in dead chicks than live chicks
Sileo et al. 1990	LAAL, BFAL	Midway	Chick Carcass	94-98% (n=57) for LAAL, 67% (n=39) for BFAL
Sievert and Sileo 1993	LAAL, BFAL	Midway	Live Chicks / Bolus	26.6% (n=350) LAAL, 15.5% (n=142) BFAL with >22 cm ³ plastic
Blight and Burger 1997	BFAL	North Pacific bycatch	Adult Carcass	100% (n=3) incidence, 5.3 average pieces per bird
Auman et al. 1997	LAAL	Midway	Chick Carcass	97.6% (n=251) incidence, average plastic mass ranged (9.5 g - 23.8 g) for dead and injured chicks in 1994 and 1995
Kinan and Cousins 2000	LAAL, BFAL	Kure	Bolus	100% (n=43) incidence in both species. LAAL contained many different types of plastic, BFAL contained mostly line
Young et al. 2009	LAAL	Kure, Oahu	Bolus	100% (n=23) incidence in both colonies, Kure contained up to 10 times more plastic

Table 2. Composition of plastic types ingested by seven seabird species organized by foraging method. Data from subarctic Alaska (1988-1990) from Robards et al. 1995.

Species <i>Scientific name</i>	number of fragments	% user	% pellets	foraging method
Northern Fulmar <i>Fulmarus glacialis</i>	141	64	36	surface
Leach's Storm-petrel <i>Oceanodroma leucorhoa</i>	90	97	3	surface
Fork-tailed Storm-petrel <i>Oceanodroma furcata</i>	105	78	22	surface
Black-legged Kittiwake <i>Rissa tridactyla</i>	70	96	4	surface
Parakeet Auklet <i>Aethia psittacula</i>	3380	16	84	dive
Horned Puffin <i>Fratercula corniculata</i>	124	60	40	dive
Tufted Puffin <i>Fratercula cirrhata</i>	458	10	90	dive

Table 3. Incidence of plastic ingestion by seabirds with different diets. Reprinted in part from Nevins et al., 2005

Common Name <i>Scientific Name</i>	Diet	Incidence % (n)	Reference
Common Murre	Fish	0.8 (134)	Robards et al., 1995
<i>Uria aalge</i>		0.2 (772)	Nevins, unpublished
Tufted Puffin	Zooplankton	89.0 (9)	Blight and Burger, 1997
<i>Fratercula cirrhata</i>		24.0 (489)	Robards et al., 1995
Horned Puffin	Zooplankton	37.0 (120)	Robards et al., 1995
<i>Fratercula corriculata</i>		50.0 (2)	Blight and Burger, 1997

Literature Cited

- AmericanChemistry, 2007. The History of Plastic. American Chemistry Council.
http://www.americanchemistry.com/s_plastics/doc.asp?cid=1102&did=4665
- Andrady, A.L., 2005. Plastics in Marine Environment, a technical perspective. In: Proceedings of the Plastic Debris Rivers to Sea Conference, 2005. Algalita Marine Research Foundation, Long Beach, CA.
<http://conference.plasticdebris.org/whitepapers.shtml>
- Auman, H.J., Ludwig, J.P., Summer, C.L., Verbrugge, D.A., Froese, K.L., Colborn, T., Giesy, J.P., 1997. PCBs, DDE, DDT and TCDD-EQ in two species of albatross on Sand Island, Midway Atoll, North Pacific Ocean. *Environmental Toxicology and Chemistry* 16, 498-504.
- Awkerman, J.A., Anderson, D.J., Whittow, G.C., 2008. Black-footed albatross (*Phoebastria nigripes*). In: Poole, A., (Ed) *The Birds of North America Online*. Cornell Lab of Ornithology, Ithaca, NY. <http://bna.birds.cornell.edu/bna/>
- Azzarello, M.Y., Van Vleet, E.S., 1987. Marine birds and plastic pollution. *Marine Ecology-Progress Series* 37, 295-303.
- Blight, L.K., Burger, A.E., 1997. Occurrence of plastic particles in sea-birds from the Eastern North Pacific. *Marine Pollution Bulletin* 34, 323-325.
- Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., 1993. *Distance sampling: estimating abundance of biological populations*. London, Chapman & Hall.
- Chai, F., Jiang, M., Barber, R.T., Dugdale, R.C., Chao, Y., 2003. Interdecadal variation of the Transition Zone Chlorophyll Front, a physical-biological model simulation between 1960 and 1990. *Journal of Oceanography* 59, 461– 475.
- Cooper, J., Auman, H.J., Klavitter, J., 2004. Do the Albatrosses of Midway Atoll Select Cigarette Lighters by Color? *Pacific Seabirds* 31, 2-4.
- Dahlberg, M.L., Day, R.H., 1985. Observations of man-made objects on the surface of the North Pacific Ocean. In: Shomura, R.S., Yoshida, H.O. (Eds.), *Proceedings of the workshop on the fate and impact of marine debris*, 26-29 November 1984. Honolulu, Hawaii.
- Day, R.H., Shaw, D.G., 1987. Patterns in the abundance of pelagic plastic and tar in the North Pacific Ocean, 1976-1985. *Marine Pollution Bulletin* 18, 311-316.

- Day, R.H., Shaw, D.G., Ignell, S.E., 1990. The Quantitative Distribution and Characteristics of Neuston Plastic in the North Pacific Ocean. 1985-1988. In: Shomura, R.S., Godfrey, M.L., (Eds). Second International Conference on Marine Debris. NOAA Technical Memo., Honolulu, Hawaii.
- Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin* 44, 842-852.
- Fernández, P., Anderson, D.J., Sievert, P.R., Huyvaert, K., 2001. Foraging destinations of three low-latitude albatross (*Phoebastria*) species. *Journal of Zoology* 254,391-404.
- Franks, P.J.S., 1992. Sink or Swim: Accumulation of Biomass at Fronts. *Marine Ecology-Progress Series* 82, 1-12.
- Fry, D.M., Fefer, S.I., Sileo, L., 1987. Ingestion of plastic debris by Laysan albatrosses and Wedge-tailed shearwaters in the Hawaiian-Islands. *Marine Pollution Bulletin* 18, 339-343.
- Gregory, M.R., 1978. Accumulation and Distribution of Virgin Plastic Granules on New Zealand Beaches. *New Zealand Journal of Marine and Freshwater Research* 12, 399-414.
- Harrison, C.S., Higa, T.S., Seki, M.P., 1983. Hawaiian seabird feeding ecology. *Wildlife Monographs* 85, 1-71.
- Hutton, I., Carlile, N., Priddel, D. 2008. Plastic Ingestion by Flesh-footed (*Puffinus carneipes*) and Wedge-tailed (*P. pacificus*) Shearwaters. *Papers and Proceedings of the Royal Society of Tasmania* 142, 1-6.
- Hyrenbach, K.D., Fernández, P., Anderson, D.J., 2002. Oceanographic habitats of two sympatric North Pacific albatross during the breeding season. *Marine Ecology-Progress Series* 233, 283-301.
- Hyrenbach, K.D., Nevins, H., Hester, M., Keiper, C., Webb, S., Harvey, J. 2009. Marine debris in Alaska: Coordinating our Efforts. In: Williams, M., Ammann, E., (Eds). *Proceedings of the Marine Debris in Alaska Workshop*. Fairbanks: Alaska Sea Grant, University of Alaska Fairbanks, Anchorage, Alaska, p 57-61.
- Kappes, M.A., Shaffer, S.A., Tremblay, Y., Foley, D.G., Palacios, D.M., Robinson, P.W., Bograd, S.J., Costa, D.P., 2010. Hawaiian albatrosses track interannual variability of marine habitats in the North Pacific. *Progress in Oceanography* 86, 246-260.
- Kenyon, K.W., Kridler, E., 1969. Laysan albatrosses swallow indigestible matter. *The Auk* 86, 339-343.

- Kinan, I.T., Cousins, K.L., 2000. Abundance of plastic debris and ingestion by albatross on Kure Atoll, Northwestern Hawaiian Islands. Second International Conference on the Biology and Conservation of Albatrosses and other Petrels, 8-10 May 2000, Waikiki, Hawaii.
- Laist, D.W., 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In: Coe, J.M., Rogers, D.B. (Eds.), Marine debris: sources, impacts and solutions. Springer series on environmental management, p 99-139.
- Law, K.L., Morét -Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic Subtropical Gyre. *Science* 329, 1185-1188.
- Mallory, M.L., 2008. Marine plastic debris in Northern Fulmars from the Canadian high Arctic. *Marine Pollution Bulletin* 56, 1501-1504.
- McDermid, K.J., McMullen, T.L., 2004. Quantitative Analysis of Small-plastic Debris on Beaches in the Hawaiian Archipelago. *Marine Pollution Bulletin* 48, 790-794.
- Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A comparison of plastic and plankton in the North Pacific Central Gyre. *Marine Pollution Bulletin* 42, 1297-1300.
- Moore, C., Lattin, G., Zellers, A., 2005. Working Our Way Upstream: A Snapshot of Land Based Contributions of Plastic and Other Trash to Coastal Waters and Beaches of Southern California. Plastic Debris Rivers to Sea Conference. Algalita Research Foundation, Redondo Beach, CA.
<http://conference.plasticdebris.org/whitepapers.shtml>
- Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. *Environmental Research* 108, 131-139.
- Morishige, C., Donohue, M.J., Flint, E., Swenson, C., Woolaway, C., 2007. Factors Affecting Marine Debris Deposition at French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument, 1990-2006. *Marine Pollution Bulletin* 54, 1162-1169.
- Naughton, M.B., Romano, M.D., Zimmerman, T.S., 2007. A conservation action plan for Black-footed albatross (*Phoebastria nigripes*) and Laysan albatross (*P. immutabilis*), Ver. 1.0.
- Nevins, H., Hyrenbach, K.D., Keiper, C., Stock, J., Hester, M., Harvey, J., 2005. Seabirds as Indicators of Plastic Pollution in the North Pacific. Plastic Debris Rivers to the Sea, Redondo Beach, CA. <http://conference.plasticdebris.org/whitepapers.shtml>

- Pettit, T.N., Grant, G.S., Whittow, G.C., 1981. Ingestion of plastics by Laysan albatross. *Auk* 98, 839-841.
- Pettit, T.N., Nagy, K.A., Ellis, H.I., Whittow, G.C., 1988. Incubation Energetics of the Laysan Albatross. *Oecologia* 74:546-550
- Pichel, W.G., Churnside, J.H., Veenstra, T.S., Foley, D.G., Friedman, K.S., Brainard, R.E., Nicoll, J.B., Zheng, Q., Clemente-Colon, P., 2007. Marine debris collects within the North Pacific Subtropical Convergence Zone. *Marine Pollution Bulletin* 54, 1207-1211.
- Polovina, J.J., Howell, E., Kobayashi, D.R., Seki, M.P., 2001. The Transition Zone Chlorophyll Front, a dynamic global feature defining migration and forage habitat for marine resources. *Progress in Oceanography* 49, 469-483.
- Robards, M.D., Piatt, J.F., Wohl, K.D., 1995. Increasing frequency of plastic particles ingested by seabirds in the sub-arctic North Pacific. *Marine Pollution Bulletin* 30, 151-157.
- Robards, M.D., Gould, P.J., Piatt, J.F., 1997. The Highest Global Concentrations and Increased Abundance of Oceanic Plastic Debris in the North Pacific: Evidence From Seabirds. In: Coe, J.M., Rogers, D.B., (Eds). *Marine Debris: Sources, Impacts and Solutions*. Springer-Verlag, New York, p 71-80.
- Ryan, P.G., Fraser, M.W., 1988. The use of great skua pellets as indicators of plastic pollution in seabirds. *Emu* 88, 16-19.
- Ryan, P.G., Moloney, C.L., 1993. Marine Litter Keeps Increasing. *Nature* 361, 23-23.
- Sievert, P.R., Sileo, L., 1993. The effect of ingested plastic on growth and survival of albatross chicks. In: Vermeer, K., Briggs, K.T., Morgan, K.H., Siegel-Causey, D., (Eds.). *The status, ecology, and conservation of marine birds of the North Pacific*. Canadian Wildlife Service Special Publication, Ottawa, p 212-217.
- Sileo, L., Sievert, P.R., Samuel, M.D., 1990. Causes of mortality of albatross chicks at Midway Atoll. *Journal of Wildlife Disease* 26, 329-338.
- Spear, L.B., Ainley, D.G., Ribic, C.A., 1995. Incidence of plastic in seabirds from the tropical Pacific, 1984-91 - Relation with distribution of species, sex, age, season, year and body-weight. *Marine Environmental Research* 40, 123-146.
- Tasker, M.L., Hope Jones, P., Dixon, T., Blake, B.F., 1984. Counting seabirds from ships: a review of methods employed and a suggestion for a standardized approach. *Auk* 101, 567-577.

- Van Franeker, J.A., 2010. Fulmar Litter EcoQO Monitoring in the Netherlands 1979-2008 in Relation to EU directive 2000/59/EC on Port Reception Facilities. IMARES Report Nr C027/10, IMARES Wageningen UR.
- Van Franeker, J.A., Heubeck, M., Fairclough, K., Turner, D.M., Grantham, M., Stienen, E.W.M., Guse, N., Pedersen, J., Olsen, K.O., Andersson, P.J., Olsen, B. 2005. 'Save the North Sea' Fulmar Study 2002-2004: A Regional Pilot Project for the Fulmar-Litter-EcoQO in the OSPAR area. Wageningen, Alterra, Alterra-rapport 1162.
- Vlietstra, L.S., Parga, J.A., 2002. Long-term Changes in the Type, but not Amount, of Ingested Plastic Particles in Short-tailed Shearwaters in the Southeastern Bering Sea. Marine Pollution Bulletin 44, 945-955.
- Whittow, G.C., 1993. Laysan albatross (*Phoebastria immutabilis*). In: Poole, A., (Ed.), The Birds of North America Online. Cornell Lab of Ornithology, Ithaca NY.
- Young, L.C., Vanderlip, C., Duffy, D.C., Afanasyev, V., Shaffer, S.A., 2009. Bringing home the trash: Do colony based differences in foraging distribution lead to increased plastic ingestion in Laysan albatrosses? PLoS ONE 4, 10: e7623.

Chapter 2:

Habitat associations of marine birds and floating debris in the North East Pacific at two spatial scales

Abstract

Plastic marine debris accumulates in subtropical gyres, regions characterized by surface convergence and retention of buoyant material. While many surface foraging seabirds ingest plastic, little is known about the patterns of spatial overlap of these far ranging predators with marine debris aggregations at sea. We surveyed concurrent distributions of marine birds and debris along a 4400 km transect within the North East Pacific Ocean covering a well-known area of plastic accumulation within the sub-tropical gyre. We used line transect and strip transect methods to survey birds and debris and analyzed the community structure based on oceanographic and weather variables at two spatial scales; hourly 'bins' were used to characterize species-specific habitat associations, and daily 'transects' were used to assess overall abundance patterns. We surveyed a total of 1,343 km, which yielded 232 birds sighted across 22 species. Bird densities ranged from 0-9 birds km⁻², with higher abundance in areas of lower wind and shallower water. A total of 3868 pieces of marine debris were observed, with densities ranging from 0-15,222 pieces km⁻². Plastic debris was more abundant in areas of lower wind, deeper water and higher atmospheric pressure. Although birds and debris were segregated spatially at the small scale (hourly transects), three species did overlap with high large scale (daily surveys) plastic accumulations: Black-footed albatross, Cook's petrel and Red-tailed tropicbird.

Keywords: Marine Debris, Seabirds, Visual Surveys, Spatial Distribution, Subtropical Gyre, Pacific Ocean

Introduction

The increasing abundance of marine debris in the world's oceans represents widespread and pervasive problems for wildlife, including entanglement and ingestion (Laist, 1987; 1997). Plastics, in particular, have quickly become the dominant constituent of floating debris at sea, comprising 60-80% of total marine debris worldwide (Derraik, 2002; UNEP 2005). Because plastics are durable and inexpensive to produce they have been widely used for a variety of products, many of which are single use (Laist, 1987). Moreover, their buoyant nature and longevity makes them subject to being transported by ocean currents once they enter the marine environment (Moore, 2003). Plastics are highly resistant to ageing and degradation, however, exposure to ultraviolet rays and seawater make the plastic polymers brittle and cause them to break into smaller pieces (Moore, 2008). Yet despite this mechanical breakdown, the individual polymers remain intact. The time required to biodegrade these polymers is yet unknown, especially if small fragments are ingested by living organisms (Andrady, 2005).

Marine debris is traditionally surveyed using three approaches: (i) beach surveys, (ii) at-sea net tows, and (iii) seabird stomach contents (Ryan et al., 1999). Ongoing monitoring programs have revealed increasing amounts of marine debris both on shorelines and at-sea (Ryan et al., 1999), washing up on coastlines around the world, from Hawaii, and Brazil to the South Atlantic and Antarctic islands (Barnes et al., 2009). Large plastic accumulations have also been documented at-sea, both in the North Pacific (Day and Shaw, 1987; Moore et al., 2001) and the North Atlantic (Morét-Ferguson et al., 2010; Law et al., 2010).

Plastic ingestion by seabirds is another pervasive and increasing problem that affects many different species across the globe, from the tropics to the arctic and the Antarctic (Ryan and Fraser, 1988; Robards et al., 1995; Spear et al., 1995; Mallory, 2008). It is estimated that 44% of all seabird species have been confirmed to ingest plastic (Laist, 1997) underscoring the vast scale of the issue. Seabirds are especially susceptible to plastic ingestion because they forage over vast oceanic ranges without regard to jurisdictional boundaries, and occupy a high trophic level position in marine food webs. Thus, these far-ranging marine predators can collect widely dispersed plastic directly, or can ingest this material through secondary ingestion via their prey (Ryan and Fraser, 1988; Spear et al., 1995).

To date most studies of marine debris at sea have focused on describing the micro (< 2 mm) and meso (2-20 mm) debris field (Ryan et al., 2009) by using neuston nets to sample floating material (e.g., Moore et al., 2001; Law et al. 2010). While this method accurately quantifies all of the floating debris present over the small area the net samples (0.5 - 1 mile long deployment, by 1 – 3 m wide net opening), net tows are time intensive and provide data at coarse spatial resolution (tows separated by 10s – 100s km). While quantified visual observations of debris have not been extensively conducted in the past (but see Dahlberg and Day, 1985), they provide a continuous record of the macro (20 - 100 mm) and mega (> 100 mm) debris community that can be resolved and analyzed to multiple spatial scales. In addition, because visual observations can be easily conducted from ships of opportunity during transit, they provide a useful and inexpensive tool for monitoring marine debris accumulation and distribution at sea. However, the main limitations of visual observations are the inability to detect the smaller fragments (< 20

mm), and the inability to retrieve the material for subsequent analysis on-board the vessel. Because visual surveys do not collect the marine debris sighted at-sea, the observers have to estimate the size and color of the material in the field, during varying weather and light conditions.

This study focuses on the distribution and abundance of marine birds and floating debris over an area of known debris accumulation within the North Pacific Subtropical Gyre. The objectives of this study are to: (1) quantify the amount and types of marine debris present over a large heterogeneous ocean area, (2) characterize the seabird community over this same extent, and (3) assess the spatial overlap of the birds and the debris by identifying the oceanographic and weather variables which influence their concurrent distributions. To quantify the biological and physical variables which drive seabird and marine debris distributions we considered two spatial scales of analysis: smaller coarse scale (10s km) patterns which can explain species level relationships in abundance and how they relate to physical features, and larger meso and macro scale (50-100s km) patterns in abundance and distribution which can explain the community structure over this large ocean area (Haury et al., 1978; Hunt et al., 1999).

Methods

Survey area

We conducted surveys during a 20 day (2-21 August 2009) 4400 km SEAPLEX cruise aboard the *R/V New Horizon*. The aim of the cruise was to seek out and sample marine debris accumulations within the North Pacific Subtropical Gyre. To this end, the

vessel left from San Diego, CA (32°42'N; 117°09'W), traveled west, reaching a maximum westerly extent of 141°W, and headed north east to Newport, OR (44°36'N; 124°3'W) (Fig. 1).

Environmental data

We collected environmental data along the length of the cruise in order to identify features and conditions at sea that may influence the distributions of both birds and debris. To characterize the habitats of marine birds and debris, we related the sightings from the visual surveys to five environmental variables sampled every 15 seconds from the vessel's underway system: sea surface temperature (SST), chlorophyll-a concentration (CHL), wind speed (WSP) and sea level pressure (SLP). We derived depth (DPT) from the National Geophysical Data Center NOAA ETOPO1, a one arc-minute resolution global relief model of ocean bathymetry (Amante and Watkins, 2009), available from NOAA's National Geophysical Data Center (<http://www.ngdc.noaa.gov/mgg/global/global.html>). We subsampled these datasets to include only one data point every two minutes during on-effort periods of visual surveys. Based on the average speed of the vessel (17.6 km hr⁻¹) this sampling rate yielded a spatial resolution of ~600 m. We calculated the mean values of each variable along the survey effort as well as the coefficient of variation of SST and CHL to identify areas of surface convergence, divergence and hydrographic fronts (Hyrenbach et al., 2006). We also included two additional weather variables, known to influence the ability to detect birds at sea (Beaufort sea state and cloud cover) (Hyrenbach et al., 2007) and two

locational variables (latitude, longitude) to account for onshore/offshore and locational effects in distribution and abundance. Overall, we used 10 explanatory variables.

Seabird surveys and density estimates

A single observer (AJT) surveyed seabirds from the flying bridge of the *R/V New Horizon*, at a 10 m eye height above sea level, while the vessel was transiting between stations. The observer surveyed on one side of the track-line, based on sighting conditions (e.g., glare and wind), and recorded all birds sighted within a 300 m range following standardized strip transect methods (Tasker et al., 1984). The observer identified the birds to the lowest possible taxonomic level, and recorded their behavior (flying, sitting, feeding, ship-following), taking care to prevent re-counting birds following the vessel. To prevent observer fatigue, survey effort was restricted to a maximum of 8 hours per day, and split into approximately 1 hour transects (length = 17.1 - 20.6 km) spread throughout the day to maximize survey coverage. We recorded the Beaufort sea state (BFT, scores on a quantitative scale from 0 to 7) and cloud cover (CC, quantified as the proportion of the sky obscured by clouds ranging from 0 to 100%) at the beginning and the end of each transect (Hyrenbach et al., 2007). The observer also recorded potential seabird prey (flying fish and flying squid), sighted within the 300 m strip width.

We calculated densities of seabirds and their prey (number km⁻²) by dividing the total number of sightings by the area surveyed (survey distance × 300 m). Because these seabird densities include multiple behaviors and assume that all species were perfectly

detectable within the 300 m strip width, they provide a metric of relative rather than absolute abundance (Tasker et al., 1984; Spear et al., 1995).

Marine debris surveys and density estimates

The same observer carried out a marine debris survey concurrently with the seabird observations. Because we had no preconceptions about the ability to sight debris at sea, we followed standardized line distance sampling (Buckland et al., 1993). The observer counted all pieces of marine debris sighted out to the horizon, and recorded their perpendicular distance from the ship's track-line assigned into one of seven pre-determined distance bins: 0-10 m, 10-50 m, 50-100 m, 100-200 m, 200-300 m, 300-600 m and > 600 m. Perpendicular distance from the ship was determined using a hand-held range finder when the debris was directly abeam of the ship (Heinemann, 1981), and these distances were used to determine the effective strip width (ESW) (Buckland et al., 1993). In addition, each piece of marine debris was assigned to one of three pre-determined size classes, based on its larger dimension: Small (2-10 cm), Medium (10-30 cm) and Large (> 30 cm). The color of each piece and a description were also recorded.

Line distance sampling quantifies how the ability to sight targets depends on their distance from the trackline, as well as on both inherent qualities (e.g., target color and size) and external conditions (e.g., weather conditions). Thus, surveys and targets with varying detectability are pooled and analyzed separately (e.g., Forney and Barlow, 1993; Hyrenbach et al., 2001). In this analysis, we considered two inherent target qualities (the size and color of the marine debris) and one external factor (the sea state during surveys).

We pooled the marine debris sightings into nine groups based on size and color, to provide larger sample sizes for calculating the ESW estimates. We considered three size classes (small, medium, large) and three color classes: white, high visibility colors (orange, yellow, red) and low visibility colors (green, brown, blue, black, clear). To examine the effect of sighting conditions on marine debris detectability we ran simple linear regressions of sighting distances as a function of Beaufort sea state for each debris group separately. Because there were no significant negative slopes, indicative of decreasing detectability with increasing sea state we used marine debris sightings across the entire range of environmental conditions (Beaufort range 0-4) in subsequent analyses. We used the DISTANCE 6 software (Thomas et al., 2010) to calculate the ESW's for the nine aforementioned marine debris groups.

As the passive targets were neither attracted to, nor repulsed from the vessel, we calculated the detection function $f(0)$ using half normal, hazard rate and uniform models (Hyrenbach et al., 2001). For each marine debris group, we selected the model which best described the perpendicular sighting distance distribution and minimized Akaike's Information Criteria (AIC). Next, we calculated correction factors to standardize the apparent densities of each of the nine marine debris groups with respect to the group with the widest ESW (Ballance and Pitman, 1998). The total number of sightings were multiplied by the correction factor for each group to yield a corrected number of sightings. Densities (pieces km⁻²) for each group were determined by dividing the corrected number of sightings by the effective area surveyed (survey distance × maximum ESW).

Spatial scales of analysis

To examine the role of oceanographic processes and physical features in structuring the dispersion of marine birds and debris, we analyzed their overlap at two different spatial scales. We first used the one hour transects to determine the environmental variables influencing the abundance and distribution of seabirds and marine debris species over a finer scale (10s km). To avoid potential detectability biases, we discarded from the analysis those transects where the ship speed was less than 15 km hr⁻¹. To ensure our analysis addressed a consistent spatial scale, we also removed from the dataset those transects that were anomalously long or short, and thus fell outside of the mean \pm 2 S.D. transect distance (range = 14.9 – 21.1 km, n = 74 transects).

We then used daily surveys to determine the community composition of birds and debris species and how the environmental variables explain that composition over the larger macro scale of the study area. We pooled the hourly transect data into 15 distinct daily surveys, separated by nightly transit periods (range = 33.7 – 152.5 km, n = 15 daily surveys).

Statistical analysis

The finer-scale analysis (at the transect scale) investigated seabird and marine debris aggregation, by characterizing their abundance when all species (birds) and groups (marine debris) were pooled. Before we conducted the statistical analyses, we addressed the lack of normality in the seabird and marine debris densities by log transforming the data as follows: $y' = \log(y + 1)$ (Zar, 1984). We also determined to what extent these

explanatory variables were cross-correlated. To this end, we performed all possible pairwise correlations between the 10 explanatory variables using Pearson correlations (Zar, 1984).

Because many of these variables were cross-correlated, we determined the environmental variables driving seabird and marine debris distribution using forward Generalized Linear Models (GLMs) step-wise procedures, whereby the model assesses each environmental variable and retains those with the highest explanatory power.

We adopted a hierarchical approach designed to analyze the geographic patterns first, and to characterize the associations with environmental variables next. We anticipated a geographic pattern in the distribution of marine debris and seabirds, due to the underlying distribution of marine debris (e.g., the eastern garbage patch) and seabirds (e.g., distance to shore-based breeding colonies). Thus, we first performed a best-fit step-wise GLM using only latitude (LAT) and longitude (LON). We then removed these geographic effects by performing a second GLM on the residuals from the geographic model using the remaining environmental variables.

The larger-scale analysis (at the daily survey scale) examined the distribution of individual seabird species and marine debris groups, using the 15 daily surveys (distance range = 33.7-152.5 km). We removed daily surveys with no sightings, as well as those species sighted during only one day because these samples did not provide information for quantifying the seabird – debris community structure (McCune and Mefford, 1999). We averaged the environmental variables across each day, and analyzed the daily scale distribution of seabirds and marine debris using Non-metric Multi-Dimensional Scaling (NMDS). We chose NMDS, which plots the samples (daily transects) and the individual

taxa (seabird species and marine debris groups) in relation to multivariate axes of environmental variables, because of its lack of assumptions about the underlying statistical distributions and its ability to organize the data along a continuum, rather than into discrete groupings (McCune and Mefford, 1999). Because the number of seabirds and debris sighted daily varied greatly, we normalized the daily surveys and weighted each daily sample equally in the NMDS analysis using the Sorensen (Bray-Curtis) similarity index (Hyrenbach et al., 2003). We used the PC ORD software to conduct these analyses, and assessed statistical significance using randomizations with 1000 iterations.

Results

Oceanographic Observations and Environmental Conditions

We surveyed a total of 1343 km along the 4400 km cruise track, during 74 hourly transects and 15 daily surveys, separated by “off effort” night-time periods. The SEAPLEX cruise traveled from the southern California Current and into the Subtropical Gyre, an area influenced by the North East Pacific subtropical high pressure center (Fig. 1). During the westward transit, the vessel traveled over deep water (>3000 m) and did not cross any seamounts (Fig. 2C). As we moved west, SST and SLP steadily increased (Fig. 2D, I), Wind speed was low and variable (Fig. 2F) and CHL remained consistently low (Fig. 2E). Conditions changed during the North-East transit towards the Oregon coast: the depth became shallower and SST dropped rapidly. Wind speed and SLP increased until a storm system interrupted our observations (after day 13). When surveys

resumed (day 14), SLP and Wind speed had decreased considerably, and CHL reached 0.2 mg m^{-3} CHL, indicating we had crossed the Transition Zone Chlorophyll Front and entered the North Pacific Transition Zone close to the Oregon coast (Polovina et al., 2001; Chai et al., 2003).

The ten environmental and habitat variables included in the distribution analyses of seabirds and marine debris were cross-correlated at the transect scale, with 25 out of 45 pair-wise comparisons yielding significant correlations. The variables were still cross-correlated to a lesser degree at the daily survey scale, with 14 out of 45 pair-wise comparisons significantly correlated (Table 1). These results indicated a clear geographic effect, with both latitudinal and longitudinal gradients, and highlighted the influence of the high pressure cell, characterized by lower wind, deeper depths, and waters of higher temperature and lower chlorophyll concentrations.

Seabird densities

We sighted 235 birds comprising 22 species over the extent of the cruise, and identified 92.7% to species (Table 2). Of these, 69% were tubenoses (order *procellariiformes*), 26% were terns, phalaropes, skuas, gulls and alcids (order *charadriiformes*) and 5% were tropicbirds and boobies (order *pelecaniformes*). The avifauna changed over the cruise, and was dominated numerically by Black-footed Albatross (*Phoebastria nigripes*) and Red-tailed Tropicbird (*Phaethon rubricauda*) in the southern warm-water areas (days 5 – 10) and by Leach's Storm-petrel (*Oceanodroma leucorhoa*) and Sooty Shearwater (*Puffinus pacificus*) in the cooler more productive waters around the CCS (days 1 - 4 and 11 - 15) (Table 3). Overall, the bird densities

varied across transects (range = 0 – 9.01 birds km⁻²) and daily surveys (range = 0.04 – 2.93 birds km⁻²) (Fig. 3A, Table 3). The highest densities occurred off of the Oregon coast and within the transition zone waters, while the lowest densities occurred far from land, within the low productivity warm gyre waters (Fig. 3A, Table 3).

Marine debris densities

We sighted a total of 3868 pieces of marine debris over the extent of the cruise, 95.5% of which were identified as plastic. The remainder was comprised of line, polystyrene foam, glass, wood, cardboard and burlap. While various different types of plastic objects were seen, fragments were the most dominant (90% of total, n = 3464). The marine debris density was also highly variable on both the hourly transect scale, ranging from 0 – 15,222 pieces km⁻², and the daily survey scale, ranging from 0 - 6334 km⁻². Small pieces (< 10 cm) of marine debris were the most abundant, accounting for 81% of the total, with medium (10-30 cm) and large (> 30 cm) pieces accounting for 14% and 5%, respectively. Despite observing a wide range of colors of marine debris, white was the dominant color with 89% of the total (Fig. 4).

The detectability of the marine debris declined as the distance from the vessel increased (Fig. 5). While large pieces were sighted out to a 600 m range, 54% occurred within the first distance bin (0-10 m) and only 1% occurred within the 300-600 m bin. In comparison, 97% of the small pieces occurred within the 10 m bin, and they were observed only out to a range of 50 m. Yet, the sea state conditions did not influence the perpendicular sighting distances for the nine groups we considered (Grp1, $r^2 = 0.002$, $m = 3.2$, $p = 0.709$; Grp2, $r^2 = 0.140$, $m = 38.6$, $p = 0.032$; Grp3, $r^2 = 0.000$, $m = 0.4$, $p =$

0.906; Grp4, $r^2 = 0.006$, $m = -2.2$, $p = 0.155$; Grp5, $r^2 = 0.029$, $m = 3.2$, $p = 0.154$; Grp6, $r^2 = 0.008$, $m = 4.9$, $p = 0.331$; Grp7, $r^2 = 0.017$, $m = 0.9$, $p < 0.001$; Grp8, $r^2 = 0.078$, $m = 3.1$, $p = 0.056$; Grp9, $r^2 = 0.006$, $m = 0.9$, $p = 0.556$).

Calculating the corrected marine debris densities required that we truncate the most distant sightings, leaving a sample size of 3715 pieces. Selecting the best fit model and truncation distance for each marine debris group resulted in Effective Strip Width's (ESW) ranging from 33.2 m for large white pieces to 5.4 m for large low visibility pieces (Fig. 5, Table 4). Using the group specific correction factors, we calculated a corrected numbers of sightings and used these corrected sightings and the maximum ESW of 33.2 m to estimate marine debris densities ranging from 1.57 pieces km^{-2} for large white pieces to 392.94 pieces km^{-2} for small white pieces (Table 5).

These correction factors were then used to calculate the corrected total marine debris densities for each hourly transect (Fig. 3B). Densities of marine debris were lowest close to the California coast and highest within the subtropical gyre. Densities declined as the vessel moved towards Oregon, however a spike in density was observed within the transition zone waters close to Oregon. At the daily transect scale, marine debris densities ranged from 0 to 6334.12 pieces km^{-2} (Table 3). Daily density distributions mirrored those at the hourly transect scale, with the highest densities in the subtropical gyre and an area of high density within the transition zone waters off of Oregon (day 15, Fig. 6B).

Transect scale communities

We used the average values of the 10 environmental and habitat variables measured within the 74 hourly transects, along with hourly transect scale densities for seabirds (all

taxa combined) and marine debris (all groups combined) to identify the variables with the most explanatory power. The step-wise GLM first accounted for geographic effects, by relating seabird and debris density to latitude and longitude (Table 6A, C). We then analyzed the residuals using a second step-wise GLM with the remaining environmental variables. The GLM results showed that marine debris density was negatively related to latitude and longitude (Table 6A). Once this geographic effect was accounted for, the marine debris was positively related to depth and sea level pressure, and negatively related to wind speed (Table 6B). Together, these analyses explained 93% of the variance in the log-transformed marine debris data. The GLM results also showed that seabird density was positively related to latitude and longitude (Table 6C). Finally, after accounting for this geographic effect, seabird density residuals were negatively related to wind speed and depth (Table 6D). Together, these analyses explained 45% of the variance in the log-transformed seabird data.

Daily scale communities

The 15 daily transects were analyzed using NMDS ordination. The number of daily marine debris observations for each group was sufficient to allow for all 3715 sightings to be included in the NMDS analysis. Conversely, we only considered those 9 seabird species, which only appeared in more than one day (Table 2). We also included sightings of flying fish and flying squid in the analysis. All ten environmental and habitat variables were used as explanatory variables in the NMDS ordination, which produced a two axis solution that explained 80.2% of the observed variance in the bird and debris community composition. Axis one ($r^2 = 0.33$) captures a longitudinal gradient characterized by a

decrease in temperature, depth and atmospheric pressure, and a concurrent increase in chlorophyll concentration (Table 7). Axis two ($r^2 = 0.47$) describes a longitudinal gradient characterized by an increase in temperature and depth, and a decrease in wind speed and chlorophyll concentration. These two axes were orthogonal (76.3%) and statistically significant ($p = 0.019$). Overall, the NMDS stress was 6.63, suggesting that it is a good ordination with no risk of drawing false inferences (Clarke, 1993).

The NMDS also revealed interesting associations between the daily surveys and the different taxa. For instance, the daily surveys were arranged into two clusters on the ordination plot: days 4 - 13 were characterized by deep subtropical gyre waters, and days 1, 2, 3, 14 and 15 were characterized by low atmospheric pressure and colder waters (Fig. 7A). The ordination plot of the species and marine debris groups mirrored that of the daily surveys. The subtropical gyre days supported the lowest bird densities and the highest debris densities. Furthermore, this cluster was characterized by the presence of all nine marine debris groups and the avifauna was comprised of tropical – sub-tropical taxa (Black-footed Albatross BFAL; Cook’s Petrel COPE, *Pterodroma cooki*; and Red-tailed Tropicbird RTTR), as well as Flying Fish (FF) and Flying Squid (FS). Conversely, the shallower, cold water cluster of days was characterized by an avifauna dominated by transition zone – trans-Pacific taxa (Red-billed Tropicbird, RBTR, *Phaethon aethereus*; Leach’s Storm-petrel LESP; Buller’s Shearwater BUSH, *Puffinus bulleri*; and Ashy Storm-petrel ASSP, *Oceanodroma melania*). Two species, South-polar Skua (SPSK, *Catharacta maccormicki*) and Red-necked Phalarope (RNPH, *Phalaropus lobatus*) were not associated with either cluster due to its distribution across a wide range of environmental conditions (Fig. 7B).

Discussion

This study assessed the community structure and distribution of marine debris and birds over a large area of the North East Pacific. Following the multi-scale approach advocated by Haury et al. (1989), our study documented different habitat associations of seabird and marine debris distributions over meso-scales (100s km) and coarse-scales (10s km). The large-scale analysis, using daily surveys, revealed that marine bird and debris communities were associated with water mass distributions (e.g., water temperature) and atmospheric patterns (e.g., atmospheric pressure). The small-scale analysis, using hourly transects, did not reveal significant habitat associations of seabirds and marine debris. We interpreted these results as evidence that basin-wide seabird and marine debris abundance and community structure are shaped by similar oceanographic processes (e.g., wind and currents).

Our results showed that daily-scale marine debris distributions were influenced by a number of environmental factors, with denser debris concentration in pelagic (deep-water) calm (lower wind, higher pressure) areas. This conclusion agrees with previous studies of marine debris distributions in the North East Pacific from at-sea sampling (Day and Shaw, 1987; Moore et al., 2001) and oceanographic modeling (Kubota, 1994; Moore, 2003). These modeling exercises highlight debris retention at the ocean convergence zone formed by surface Ekman drifts at the North Pacific subtropical high pressure area. Because Ekman drifts and geostrophic currents are extremely weak within this convergence area, marine debris is effectively trapped and accumulated in this area (Kubota, 1994; Moore, 2003).

Additionally, the marine debris community showed some geographic and habitat separation between the six groups we considered, with the smaller white pieces occurring furthest west in the area of the highest atmospheric pressure and warmest sea surface temperatures. This pattern suggests that the debris community within the center of the gyre is dominated by older (smaller and weathered) pieces, while a greater proportion of newer pieces (larger and colorful) occurring further towards the eastern edge of the large scale aggregation area. Notably, the North American continental is located to the east of the study area.

While the community level daily analysis identified the large-scale marine debris concentration area, the smaller-scale transect analysis did not identify specific habitat variables that explained the finer scale abundance of marine debris. The transect-level analysis documented higher marine debris abundance in transects over deeper and warmer water and with higher sea level pressure. However, when we tested for the influence of temperature and color fronts using fine-scale (resolution: 2-minute, 0.6 km) sea surface temperature and chlorophyll-a concentration data collected by the vessel, our model did not find any significant associations.

Nevertheless, the transect-scale analysis did reveal differences in the marine debris and seabird abundance in relation to depth, with high bird densities in shallower waters to the east. Higher seabird densities closer to shore are to be expected due to higher productivity of continental shelf – slope waters (Gould and Piatt, 1993). As described previously, marine debris was more abundant in the deep-water and low productivity gyre waters to the west.

The community level analysis, involving nine marine debris types, nine seabird species and two seabird prey groups, revealed that only a few trans-Pacific species overlapped with the large-scale area of high marine debris aggregation. Of the three species found to occur with debris, the Black-footed Albatross is highly susceptible to ingestion of marine debris (Blight and Burger, 1997; Kinan and Cousins, 2000) and the Cook's Petrel has a record of plastic ingestion during the breeding season (Imber, 1996). Yet, because both of these species are far-ranging surface foraging *procellariiform* seabirds, it is unclear when and where they collect this debris at sea. For instance, the albatross travel between their breeding colonies in Hawaii and specific foraging areas: the subtropical frontal system during the chick-brooding period (January – February) and the productive California Current System (CCS) during the chick-rearing period (March – June) (Hyrenbach et al., 2002; Kappes et al., 2010). The Cook's Petrel breeds in the southern hemisphere and migrates into the North Pacific during the austral winter and are present offshore of Mexico and California during April-November (Bartle et al., 1993), however, it was not one of the species studied for ingested plastic in the eastern tropical Pacific by Spear et al. (1995) Thus the area of high plastic aggregation we documented within the gyre is likely not an area of high foraging activity for these species, as evidenced by their low at-sea densities in this region (This study; Wahl et al., 1989).

Nevertheless, because other oceanographic mechanisms, such as the Transition Zone Chlorophyll Front, aggregate marine debris across the North Pacific (Pichel et al., 2007) and provide persistent zones of enhanced convergence and localized productivity (Polovina et al., 2001), these far-ranging seabirds may be collecting the marine debris concentrated at these features.

Our estimates of marine debris densities from this visual survey are considerably lower than floating debris estimates derived from summer-time neuston net tows conducted in this area (Moore et al., 2001). For instance, our visual surveys revealed that debris densities varied widely over both spatial scales: debris was significantly more abundant within the subtropical gyre, with the highest estimated density during an hourly (16.8 km) transect of 15,222 pieces km⁻². In comparison, Moore et al. (2001) documented an average density of 334,271 pieces km⁻² in this same area.

Nevertheless, a critical distinction is that our visual survey samples a component of the debris field different from what is captured using net tows equipped with 333 micron-mesh. Although small (2-10 cm) pieces comprised the majority of the debris sighted in our study, we estimate that 2 cm is the lower end of what was visible and is generally accepted as the lower range size for visual sampling (Ribic et al., 1992). Conversely, net tows target meso and micro debris, generally less than 2 cm in size, and rarely captures macro debris (> 2 cm). This size segregation highlights the complementarity between visual and net tow surveys, and underscores the need to integrate both sampling methods to fully describe the debris field.

This study marks a step forward in quantifying the mega and macro debris distributions at sea. By using rigorously-defined visual survey methods, we are able to confidently describe the macro and mega debris using a standardized approach that does not require dedicated ship time and is easily transferable to any platform. Line distance sampling techniques, which required no assumptions concerning the ability to visually detect marine debris of varying size and color, lead to improved abundance estimates. Furthermore, the separation of types of debris based on factors that affect their

sightability (size and color) allows us to compare the composition of the debris field over space and time.

Our results highlighted patterns of marine debris distribution and abundance within the North East Pacific Ocean, and documented large-scale (Daily-scale) aggregation associated with the subtropical gyre (an area of higher sea surface temperature and sea level pressure), and small-scale (transect-scale) variability within this aggregation area. Furthermore, our results showed that few seabird species in the North East Pacific overlap with this large-scale zone of debris aggregation, except for two far ranging petrels.

Yet, it is unclear where these far-ranging predators ingest plastic at-sea, in large part due to the patchy nature of the distributions of marine birds and debris. For instance, marine debris abundances were patchy (Greens Index, transect-scale=0.19, daily-scale=0.25), the combined daily survey (Day 9, 52km) including the highest density hourly transect (Transect 50, 16.8km) yielded a density of 6,334 pieces km⁻². The five daily surveys within the high pressure center along the western boundary of the study area (LON > 139.9 Deg. W), yielded densities ranging from 391 – 6,334 pieces km⁻². This high degree of variation in the debris densities suggests there was smaller-scale patchiness within the larger ‘eastern garbage patch’ aggregation zone. Yet, because our model did not find any significant habitat associations, we hypothesize that other factors such as weak currents or internal waves which we did not measure could be causing small scale areas of convergence over 10s of km that may be aggregating debris.

These fine-scale (10s km) aggregations of seabirds and marine debris are difficult to characterize, and are likely influenced by dynamic physical processes (e.g., convergence

zones that aggregate floating material and make seabird prey available, Franks et al., 1992; Hyrenbach et al., 2006) and by short-lived physical and biological processes (e.g., seabird interactions with subsurface-predators, prey; Hebshi et al., 2008; Pitman and Ballance, 1990). Yet, a better understanding of these fine-scale patterns of habitat use and aggregation seem critical to identify those locations where seabirds are at risk from plastic ingestion at-sea.

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References

- Amante, C., Eakins, B.W., 2009. ETOPO1 1 arc-minute global relief model: Procedures, data sources and analysis. NOAA technical memorandum NESDIS NGDC-24, 19pp, March 2009.
- Andrady, A.L., 2005. Plastics in Marine Environment, a technical perspective. In: Proceedings of the Plastic Debris Rivers to Sea Conference, 2005. Algalita Marine Research Foundation, Long Beach, CA.
- Ballance, L.T., Pitman, R.L., 1998. Cetaceans of the Western tropical Indian Ocean: distribution relative abundance, and comparisons with cetacean communities of two other tropical ecosystems. *Marine Mammal Science* 14, 429-459.
- Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B* 364, 1985-1998.
- Bartle, J.A., Hu, D., Stahl, J.C., Pyle, P., Simons, T.R., Woodby, D., 1990. Status and ecology of gadfly petrels in the temperate north Pacific. In: Vermeer, K., Briggs, K.T., Morgan, K.H., Siegel-Causey, D., (Eds.). *The status, ecology, and conservation of marine birds of the North Pacific*. Canadian Wildlife Service Special Publication, Ottawa, p 101–111.
- Blight, L.K., Burger, A.E., 1997. Occurrence of plastic particles in sea-birds from the Eastern North Pacific. *Marine Pollution Bulletin* 34, 323-325.
- Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., 1993. *Distance sampling: estimating abundance of biological populations*. London, Chapman & Hall.
- Chai, F., Jiang, M., Barber, R.T., Dugdale, R.C., Chao, Y., 2003. Interdecadal variation of the Transition Zone Chlorophyll Front, a physical-biological model simulation between 1960 and 1990. *Journal of Oceanography* 59, 461– 475.
- Clarke, K.R., 1993. Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology* 18, 117-143.
- Dahlberg, M.L., Day, R.H., 1985. Observations of man-made objects on the surface of the North Pacific Ocean. In: Shomura, R.S., Yoshida, H.O. (Eds.), *Proceedings of the workshop on the fate and impact of marine debris*, 26-29 November 1984. Honolulu, Hawaii.
- Day, R.H., Shaw, D.G., 1987. Patterns in the abundance of pelagic plastic and tar in the North Pacific Ocean, 1976-1985. *Marine Pollution Bulletin* 18, 311-316.

- Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin* 44, 842-852.
- Forney, K.A., Barlow, J., 1993. Preliminary winter abundance estimates for cetaceans along the California coast based on a 1991 aerial survey. *Reports of the International Whaling Commission* 43, 407-415.
- Franks, P.J.S., 1992. Sink or Swim: Accumulation of Biomass at Fronts. *Marine Ecology-Progress Series* 82, 1-12.
- Gould, P.J., Piatt, J.F., 1993. Seabirds of the central North Pacific. In: Vermeer, K., Briggs, K.T., Morgan, K.H., Siegel-Causey, D. (Eds.), *The status, ecology, and conservation of marine birds in the North Pacific*. Ottawa, Canadian Wildlife Service Special Publication, pp. 27-38.
- Haury, L.R., McGowan, J.A., Wiebe, P.H., 1978. Patterns and processes in the time-space scales of plankton distribution. In: Steele, J.H. (Ed.) *Spatial pattern in plankton communities*, pp 277-327. Plenum, New York.
- Hebshi, A.J., Duffy, D.C., Hyrenbach, K.D., 2008. Associations between seabirds and subsurface predators around Oahu, Hawaii. *Aquatic Biology* 4. 89-98.
- Heinemann, D., 1981 A range-finder for pelagic bird censusing. *Journal of Wildlife Management* 45, 489-493.
- Hunt, G.L. Jr., Mehlum, F., Russell, R.W., Irons, D., Decker, M.B., Becker, P.H., 1999. Physical processes, prey abundance, and the foraging ecology of seabirds. In: Adams, N.J., Slotow, R.H., (Eds.). *Proceedings of the 22nd International Ornithological Congress, Durban, Bird Life South Africa, Johannesburg*, p 2040-2056.
- Hyrenbach, K.D., Baduini, C.L., Hunt, G.L. Jr., 2001. Line transect estimates of Short-tailed Shearwater *Puffinus tenuirostris* mortality in the South-Eastern Bering Sea, 1997-1999. *Marine Ornithology* 29, 11-18.
- Hyrenbach, K.D., Fernández, P., Anderson, D.J., 2002. Oceanographic habitats of two sympatric North Pacific albatrosses during the breeding season. *Marine Ecology Progress Series* 233, 283-301.
- Hyrenbach, K.D., Viet, R.R., Weimerskirch, H., Hunt, G.L. Jr., 2006. Seabird associations with mesoscale eddies: the subtropical Indian Ocean. *Marine Ecology Progress Series* 342, 271-279.
- Hyrenbach, K.D., Henry, M.F., Morgan, K.H., Welch, D.W., Sydeman, W.J., 2007. Optimizing the widths of strip transects for seabird surveys from vessels of opportunity. *Marine Ornithology* 35, 29-38.

- Imber, M.J., 1996. The food of Cook's Petrel *Pterodroma cooki* during its breeding season on Little Barrier Island, New Zealand. *Emu* 96, 189-194.
- Kappes, M.A., Shaffer, S.A., Tremblay, Y., Foley, D.G., Palacios, D.M., Robinson, P.W., Bograd, S.J., Costa, D.P., 2010. Hawaiian albatrosses track interannual variability of marine habitats in the North Pacific. *Progress in Oceanography* 86, 246-260.
- Kinan, I.T., Cousins, K.L., 2000. Abundance of plastic debris and ingestion by albatross on Kure Atoll, Northwestern Hawaiian Islands. Second International Conference on the Biology and Conservation of Albatrosses and other Petrels, 8-10 May 2000, Waikiki, Hawaii.
- Kubota, M., 1994. A mechanism for the accumulation of floating marine debris north of Hawaii. *Journal of Physical Oceanography* 24, 1059-1064.
- Laist, D.W., 1987. Overview of the biological effects of lost and discarded plastic debris in the marine-environment. *Marine Pollution Bulletin* 18, 319-326.
- Laist, D.W., 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In: Coe, J.M., Rogers, D.B. (Eds.), *Marine debris: sources, impacts and solutions*. Springer series on environmental management, p 99-139.
- Law, K.L., Morét -Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic Subtropical Gyre. *Science* 329, 1185-1188.
- Mallory, M.L., 2008. Marine plastic debris in Northern Fulmars from the Canadian high Arctic. *Marine Pollution Bulletin* 56, 1501-1504.
- McCune, B., Mefford, M.J., 1999. PC-ORD: Multivariate analysis of ecological data (version 4). MjM Software design, Gleneden Beach, OR.
- Moore, C.J., 2003. Trashed: across the Pacific Ocean plastics, plastics everywhere. *Natural History* 112, 46-51.
- Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. *Environmental Research* 108, 131-139.
- Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A comparison of plastic and plankton in the North Pacific Central Gyre. *Marine Pollution Bulletin* 42, 1297-1300.

- Morét-Ferguson, S., Law, K.L., Proskurowski, G., Murphy, E.K., Peacock, E.E., Reddy, C.M., 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. *Marine Pollution Bulletin* 60, 1873-1878.
- Pichel, W.G., Churnside, J.H., Veenstra, T.S., Foley, D.G., Friedman, K.S., Brainard, R.E., Nicoll, J.B., Zheng, Q., Clemente-Colon, P., 2007. Marine debris collects within the North Pacific Subtropical Convergence Zone. *Marine Pollution Bulletin* 54, 1207-1211.
- Pitman, R.L., Ballance, L.T., 1990. Daytime feeding by Leach's Storm-petrel on a midwater fish in the eastern tropical Pacific. *Condor* 92, 524-527.
- Polovina, J.J., Howell, E., Kobayashi, D.R., Seki, M.P., 2001. The Transition Zone Chlorophyll Front, a dynamic global feature defining migration and forage habitat for marine resources. *Progress in Oceanography* 49, 469-483.
- Ribic, C.A., Dixon, T.R., Vining, I., 1992. Marine debris survey manual. NOAA Technical Report NMFS 108.
- Robards, M.D., Piatt, J.F., Wohl, K.D., 1995. Increasing frequency of plastic particles ingested by seabirds in the sub-arctic North Pacific. *Marine Pollution Bulletin* 30, 151-157.
- Ryan, P.G., Fraser, M.W., 1988. The use of great skua pellets as indicators of plastic pollution in seabirds. *Emu* 88, 16-19.
- Ryan, P.G., Moloney, C.L., 1990. Plastic and other artefacts on South African beaches: temporal trends in abundance and composition. *South African Journal of Science* 86, 450-452.
- Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. *Philosophical Transactions of the Royal Society B* 364, 1999-2012.
- Spear, L.B., Ainley, D.G., Ribic, C.A., 1995. Incidence of plastic in seabirds from the tropical Pacific, 1984-91 - Relation with distribution of species, sex, age, season, year and body-weight. *Marine Environmental Research* 40, 123-146.
- Tasker, M.L., Hope Jones, P., Dixon, T., Blake, B.F., 1984. Counting seabirds from ships: a review of methods employed and a suggestion for a standardized approach. *Auk* 101, 567-577.
- Thomas, L., Buckland, S.T., Rexstad, E.A., Laake, J.L., Strindberg, S., Hedley, S.L., Bishop, J.R.B., Marques, T.A., Burnham, K.P., 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. *Journal of Applied Ecology* 47, 5-14.

UNEP, 2005. Marine Litter, an analytical overview.

Wahl, T.R., Ainley, D.G., Benedict, A.H., DeGange, A.R., 1989. Associations between seabirds and water-masses in the northern Pacific Ocean in summer. *Marine Biology* 103, 1-11

Walker, T.R., Reid, K., Arnould, J.P.Y., Croxall, J.P., 1997. Marine debris surveys at Bird Island, South Georgia 1990–1995. *Marine Pollution Bulletin* 34, 61–65.

Zar, J.H., 1984. *Biostatistical Analysis*. Prentice-Hall, Englewood Cliffs, NJ.

Figures

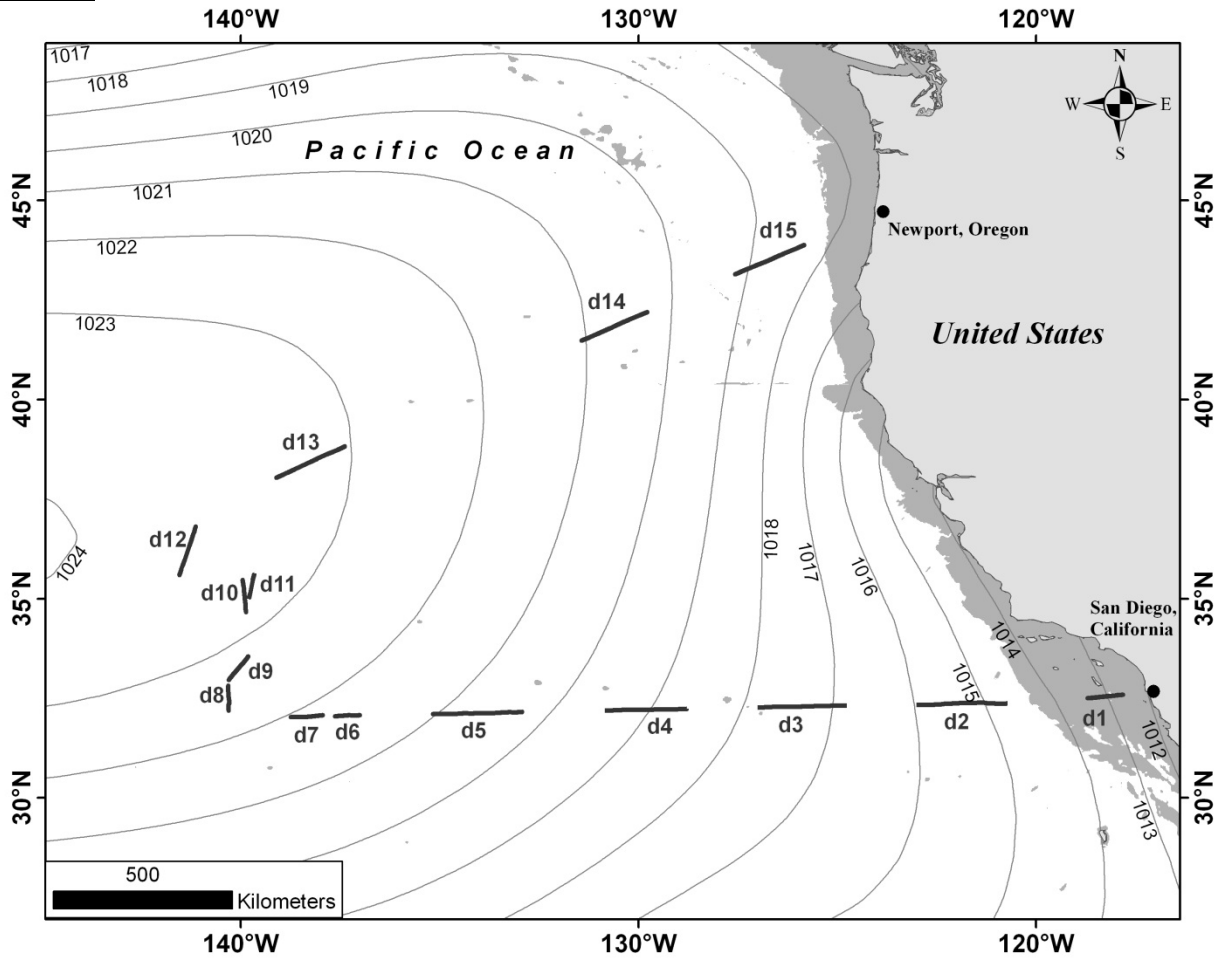


Figure 1. Map of the North East Pacific Ocean showing the study location with daily transect effort (grey lines). Monthly (August 2009) average sea level pressure (mbar) contours are superimposed and depths shallower than 3000 m are shown in dark gray.

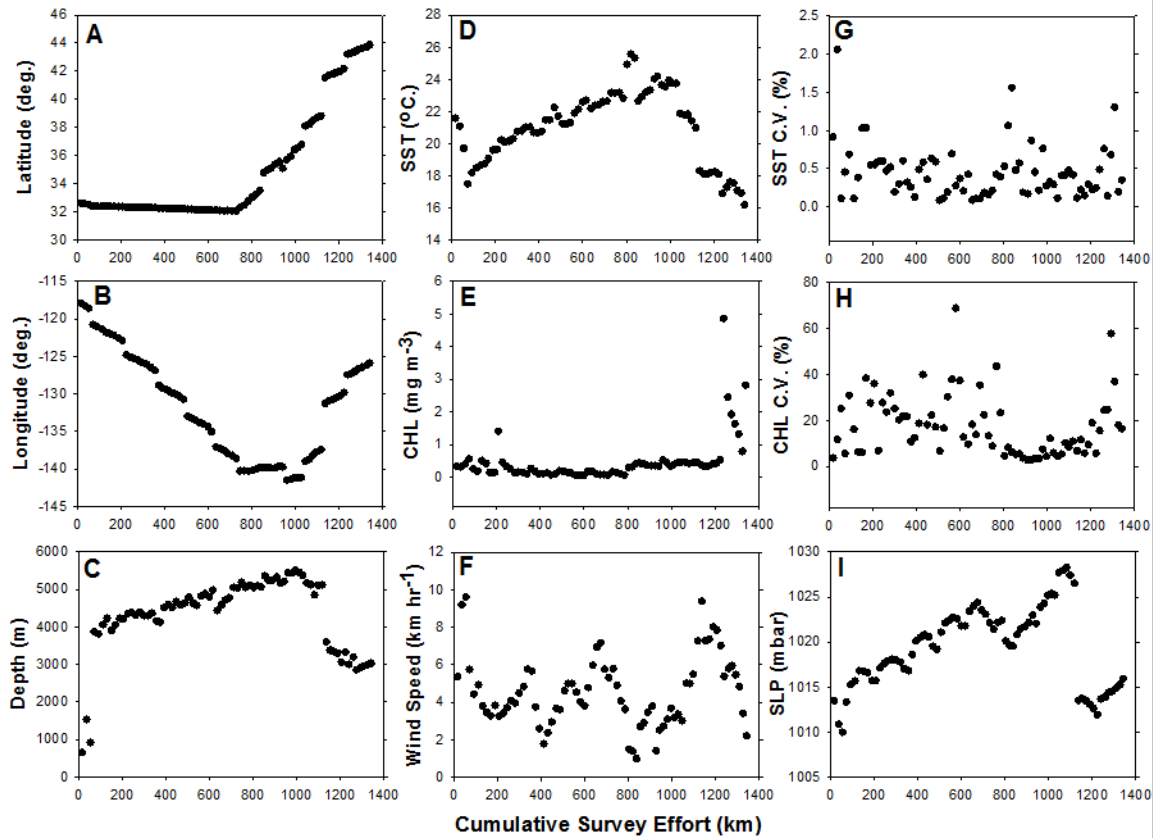


Figure 2. Spatial distribution of mean (A) latitude, (B) longitude, (C) depth, (D) sea surface temperature (SST), (E) chlorophyll-a concentration (CHL), (F) wind speed, (G) SST coefficient of variation, (H) CHL coefficient of variation and (I) sea level pressure (SLP) for 74 one hour transect bins along the cruise.

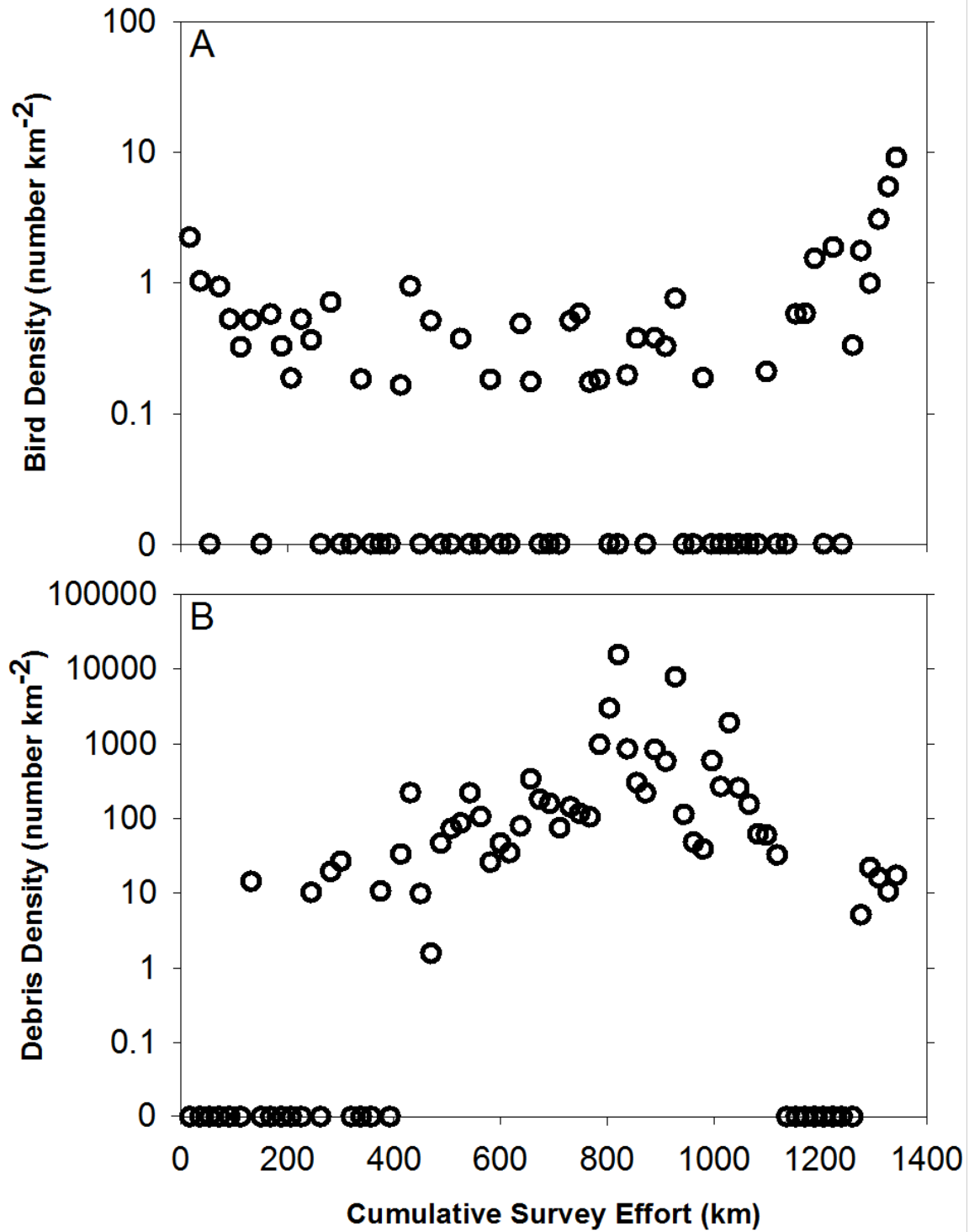


Figure 3. Density (number/km²) of birds (A) and marine debris (B) for 74 one hour transect bins along the cruise.

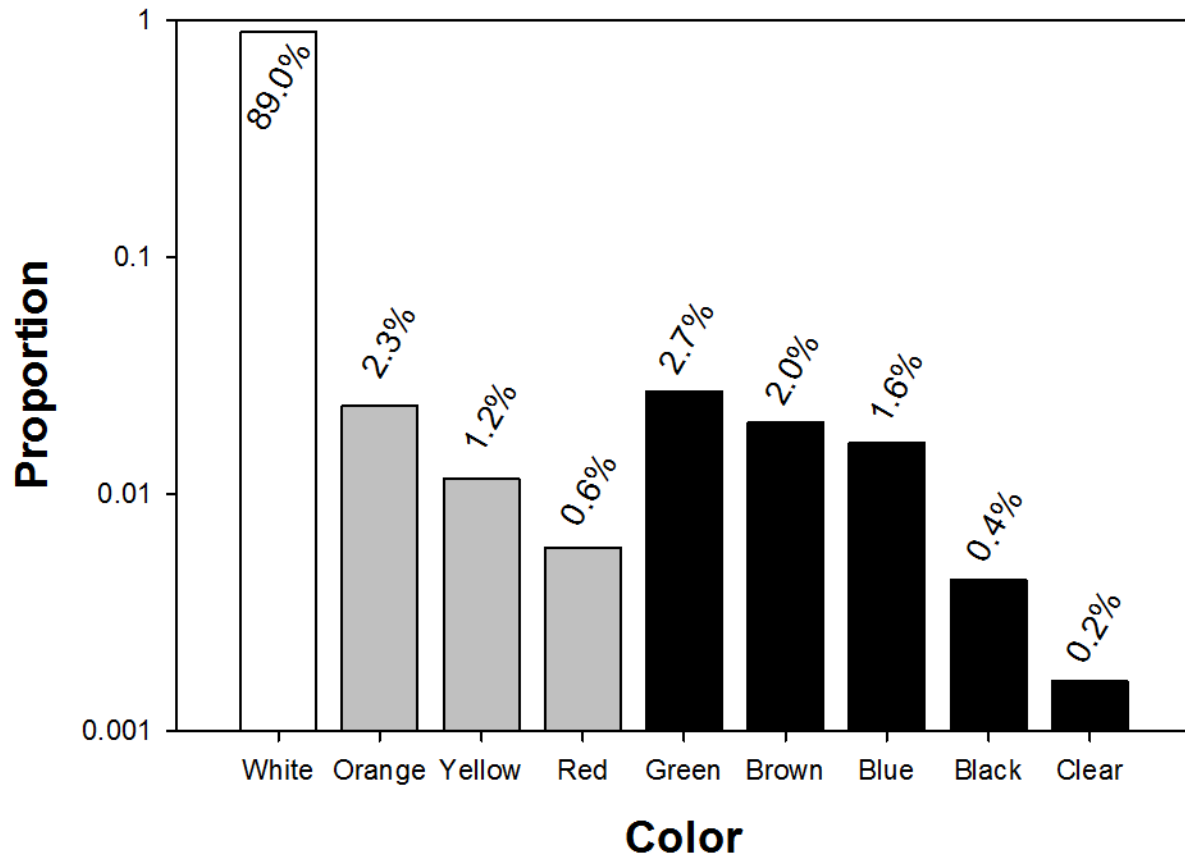


Figure 4. Proportion of colors within the observed marine debris community. Bars have been separated by their sighting ability with empty bars being the most visible, grey bars being highly visible colors and black bars being low visibility colors.

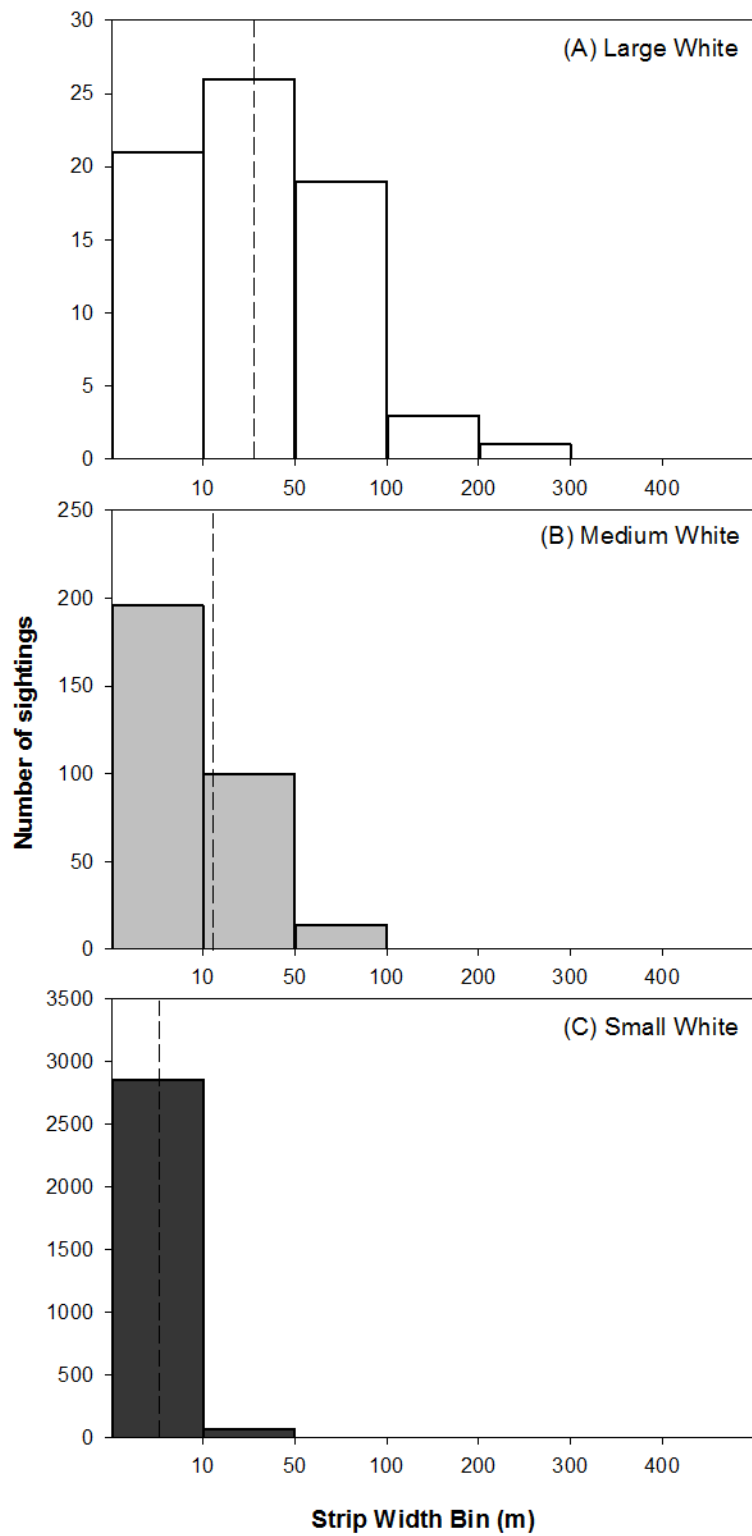


Figure 5. Distribution of sightings based on distance observed from the vessel for large white pieces (A), medium white pieces (B) and small white pieces (C) of marine debris. Also shown are the Estimated Strip Width (ESW) for each group (dashed line).

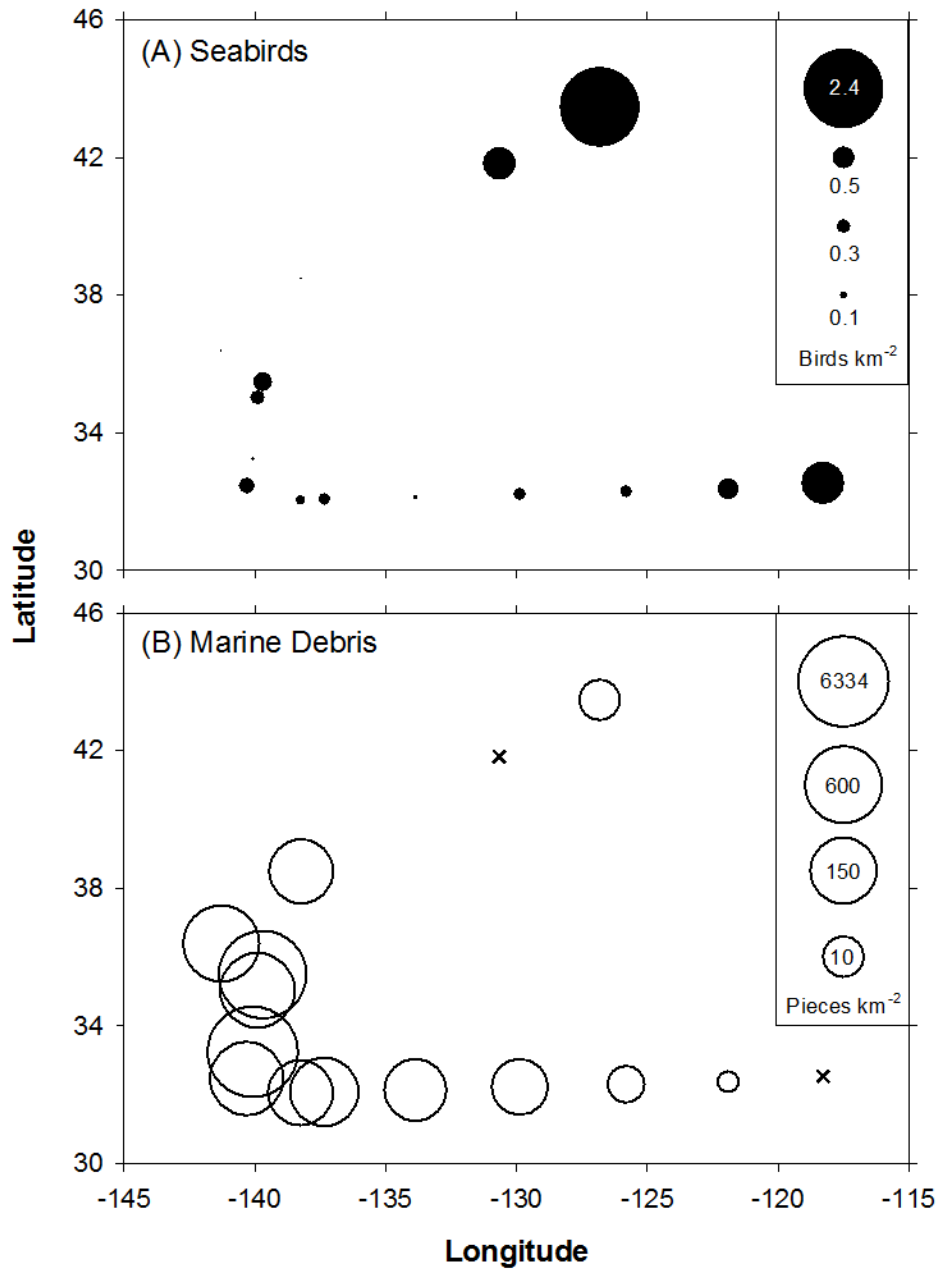


Figure 6. Log-transformed densities of birds (A) and marine debris (B) with respect to location (latitude, longitude) within the North East Pacific as covered by the cruise track. Circles shown are densities at the midpoints of daily surveys, x indicates zero density.

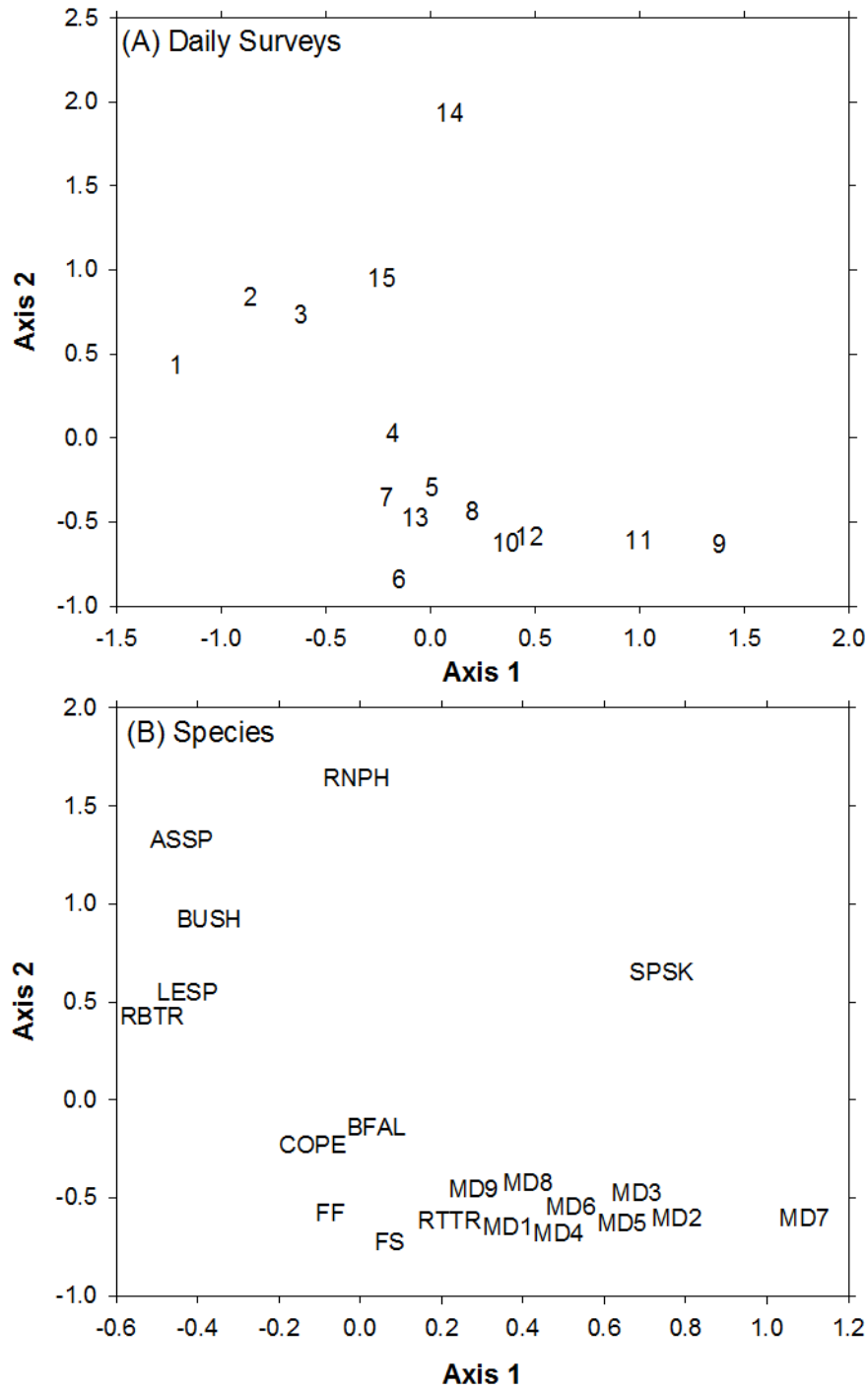


Figure 7. Results of NMDS analysis of the bird and debris communities along 15 daily transect bins (A). The nine most common bird species by number of days observed as well as flying fish (FF), flying squid (FS) and the nine distinct debris groups are plotted.

Tables

Table 1. Summary of the cross-correlations between the environmental and habitat variables over the hourly transect scale (10s km) and daily survey scale (50-100s km) habitats. Significant correlations highlighted in bold font.

(A) Hourly transect scale: Pearson correlation, r^2 critical = 0.232, n=74										
	WSP	DPT	SST	TCV	CHL	CCV	SLP	CC	LAT	LON
WSP	-	<0.05	<0.05	<0.05	>0.1	>0.1	<0.05	<0.05	>0.1	<0.05
DPT	-0.479	-	<0.05	>0.1	0.05< p <0.1	<0.05	<0.05	>0.1	<0.05	>0.1
SST	-0.419	+0.877	-	>0.1	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
TCV	-0.339	-0.081	-0.007	-	>0.1	>0.1	>0.1	>0.1	>0.1	0.05< p <0.1
CHL	+0.007	-0.205	-0.347	+0.167	-	<0.05	<0.05	<0.05	<0.05	>0.1
CCV	+0.175	-0.379	-0.346	+0.095	-0.419	-	>0.1	>0.1	<0.05	<0.05
SLP	-0.294	+0.869	+0.753	-0.187	-0.285	-0.178	-	>0.1	<0.05	<0.05
CC	+0.233	-0.120	-0.298	-0.151	+0.276	+0.012	+0.042	-	<0.05	>0.1
LAT	+0.031	+0.391	-0.307	+0.153	+0.808	-0.340	-0.289	+0.391	-	>0.1
LON	+0.261	-0.111	-0.807	+0.203	+0.087	+0.402	-0.756	-0.111	-0.055	-
(B) Daily survey scale: Pearson correlation, r^2 critical =0.514 , n=15										
	WSP	DPT	SST	TCV	CHL	CCV	ATM	CC	LAT	LON
WSP	-	<0.05	<0.05	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1	0.05< p <0.1
DPT	-0.669	-	<0.05	<0.05	>0.1	>0.1	<0.05	>0.1	>0.1	<0.05
SST	-0.549	+0.629	-	0.05< p <0.1	<0.05	<0.05	<0.05	0.05< p <0.1	0.05< p <0.1	<0.05
TCV	+0.141	-0.628	-0.453	-	>0.1	0.05< p <0.1	<0.05	>0.1	>0.1	>0.1
CHL	+0.007	-0.348	-0.571	+0.223	-	>0.1	>0.1	>0.1	<0.05	>0.1
CCV	+0.097	-0.142	-0.514	+0.470	+0.158	-	>0.1	>0.1	>0.1	0.05< p <0.1
ATM	-0.403	+0.842	+0.664	-0.546	-0.353	-0.293	-	>0.1	>0.1	<0.05
CC	+0.371	-0.056	-0.467	-0.101	+0.402	+0.013	+0.125	-	<0.05	>0.1
LAT	+0.171	-0.193	-0.511	-0.188	+0.744	-0.256	-0.209	+0.626	-	>0.1
LON	+0.469	-0.839	-0.750	+0.006	+0.268	+0.503	-0.824	-0.075	+0.006	-

Table 2. Summary of seabird observations over the cruise area in the North East Pacific Ocean during August 2009. This table shows all species sighted as well as the total number of days each species was sighted out of a total of 15. Species in bold type were included in the daily scale NMDS analysis. Also included are notes on the presence (Y), or absence (N) of known plastic ingestion. Plastic ingestion for those species without published diet studies in the North Pacific labeled as unknown (U). Plastic ingestion records originate from (Spear et al., 1995; Nevins et al., 2007; Imber, 1996; Sileo et al., 1990; Robards et al., 1997).

Order	Common name	Scientific name	Total birds	Prop. (%)	Total days	Ingest plastic
Procellariiformes	Black-footed Albatross (BFAL)	<i>Phoebastria nigripes</i>	17	7.23	10	Y
	Ashy Storm-petrel (ASSP)	<i>Oceanodroma melania</i>	6	2.55	3	U
	Fork-tailed Storm-petrel (FTSP)	<i>Oceanodroma furcata</i>	3	1.28	1	Y
	Leach's Storm-petrel (LESP)	<i>Oceanodroma leucorhoa</i>	41	17.45	8	Y
	Least Storm-petrel (LSSP)	<i>Halocyptena microsoma</i>	2	0.85	1	U
	Kermadec Petrel (KEPE)	<i>Pterodroma neglecta</i>	1	0.43	1	N
	Cook's Petrel (COPE)	<i>Pterodroma cooki</i>	6	2.55	3	U
	Bulwer's Petrel (BUPE)	<i>Bulweria bulwerii</i>	2	0.85	1	N
	Buller's Shearwater (BUSH)	<i>Puffinus bulleri</i>	9	3.83	2	Y
	Sooty Shearwater (SOSH)	<i>Puffinus pacificus</i>	61	25.96	1	Y
	Pink-footed Shearwater (PFSH)	<i>Puffinus creatopus</i>	1	0.43	1	Y
	Unidentified Shearwaters		8	3.40	1	
	Unidentified Petrels		1	0.43	2	
Unidentified Storm-petrels		4	1.70	2		
Pelecaniformes	Red-billed Tropicbird (RBTR)	<i>Phaethon aethereus</i>	2	0.85	2	U
	Red-tailed Tropicbird (RTTR)	<i>Phaethon rubricauda</i>	7	2.98	3	U
	White-tailed Tropicbird (WTTR)	<i>Phaethon lepturus</i>	1	0.43	1	U
	Brown Booby (BRBO)	<i>Sula leucogaster</i>	1	0.43	1	N
Charadriiformes	Red-necked Phalarope (RNPH)	<i>Phalaropus lobatus</i>	23	9.79	2	U
	South-polar Skua (SPSK)	<i>Catharacta maccormicki</i>	2	0.85	2	U
	Pomarine Skua (POSK)	<i>Stercorarius pomarinus</i>	4	1.70	1	N
	Elegant Tern (ELTE)	<i>Sterna elegans</i>	8	3.40	1	U
	Common Tern (COTE)	<i>Sterna hirundo</i>	15	6.38	2	U
	Arctic Tern (ARTE)	<i>Sterna paradisaea</i>	1	0.43	1	U
	Rhinoceros Auklet (RHAU)	<i>Cerorhinca monocerata</i>	5	2.13	1	N
	Unidentified Gulls		3	1.28	1	
	Unidentified Terns		1	0.43	1	
	Grand total		235	100.00		

Table 3. Total effort and median location for each binned daily transect along the cruise track. Also shown are the averaged seabird and marine debris densities for each daily transect.

Day	Effort (km)	Seabird density (birds/km ²)	Dominant seabird species	Relative abundance (%)	Debris density (pieces/km ²)	Latitude	Longitude
1	55.65	1.08	ELTE	29	0.00	32.5405	-118.2930
2	152.47	0.42	LESP	53	1.76	32.3668	-121.9119
3	150.32	0.22	LESP	80	6.90	32.2923	-125.8086
4	130.30	0.23	LESP	50	45.17	32.2128	-129.8737
5	128.94	0.08	BFAL, COPE	50, 50	82.98	32.1240	-133.8613
6	56.80	0.22	BFAL	50	194.92	32.0676	-137.3432
7	57.21	0.17	BFAL	75	123.05	32.0412	-138.2546
8	55.06	0.31	RTTR	60	391.17	32.4559	-140.3073
9	52.10	0.07	SPSK	100	6334.12	33.2349	-140.0765
10	72.24	0.27	BFAL, RTTR	50, 50	475.03	35.0209	-139.8989
11	33.73	0.38	LESP	75	3892.64	35.4792	-139.6987
12	85.04	0.04	LESP	100	558.06	36.3798	-141.2742
13	89.88	0.04	LESP	100	110.90	38.4760	-138.2249
14	105.68	0.76	RNPH	67	0.00	41.8219	-130.6510
15	118.24	2.93	SOSH	53	9.94	43.4650	-126.8149

Table 4. Summary of the best-fit model parameters describing the perpendicular sighting distances used to estimate the effective strip width (ESW) for nine distinct marine debris groups based on size and color. The hazard rate (HR) or half normal (HN) models were chosen based on the minimum Akaike's Information Criteria (AIC).

MD Group	Description	Sightings (sample size)	Model	Truncation (m)	$\alpha \pm \text{S.E.}$	$\beta \pm \text{S.E.}$	ESW \pm S.E. (m)	AIC
1	Large White	70	H.R	400	14.28 \pm 6.49	1.33 \pm 0.25	33.20 \pm 8.58	193.92
2	Large High Vis	32	H.R	300	3.00 \pm 3.52	1.59 \pm 0.41	6.86 \pm 5.66	62.31
3	Large Low Vis	83	H.R	200	2.00 \pm 3.47	1.37 \pm 0.48	5.44 \pm 6.19	145.95
4	Medium White	410	H.R	100	7.67 \pm 1.58	1.99 \pm 0.24	13.02 \pm 1.63	496.73
5	Medium High Vis	72	H.R	100	6.38 \pm 3.24	2.15 \pm 0.59	10.37 \pm 3.36	102.08
6	Medium Low Vis	111	H.R	100	3.96 \pm 2.83	1.81 \pm 0.44	7.48 \pm 3.56	152.35
7	Small White	2925	H.N	100	4.42 \pm 0.88	-	5.54 \pm 0.11	632.96
8	Small High Vis	47	H.N	100	6.59 \pm 0.84	-	8.25 \pm 1.05	37.90
9	Small Low Vis	62	H.N	100	5.75 \pm 0.65	-	7.20 \pm 0.81	36.76

Table 5. Corrected number of sightings, encounter rate and density for each distinct marine debris group for the combined 74 hourly transects. Corrected data was obtained using the maximum ESW of 33.2 m and the correction factor.

MD Group	Sightings	Correction Factor	Corrected Sightings	Corrected Encounter rate (pieces km⁻¹)	Corrected Density (pieces km⁻²)
1	70	1.00	70.00	0.05	1.57
2	32	4.84	154.87	0.12	3.47
3	83	6.10	506.54	0.38	11.36
4	410	2.55	1045.47	0.78	23.44
5	72	3.20	230.51	0.17	5.17
6	111	4.44	492.67	0.37	11.04
7	2925	5.99	17528.88	13.05	392.94
8	47	4.02	189.14	0.14	4.24
9	62	4.61	285.89	0.21	6.41

Table 6. Results of the multiple step-wise General Linear Model (GLM) analysis of marine debris density (A, B) and seabird density (C, D).

(A) Marine Debris Location GLM, $r^2 = 0.68$, $n=74$				
Variable	Coefficient	<i>t</i> statistic	<i>p</i> value	Result
Latitude	-0.049	-2.622	0.011	Higher in South
Longitude	-0.132	-12.212	<0.001	Higher in West

(B) Marine Debris Environmental GLM of residuals, $r^2 = 0.25$, $n=74$				
Variable	Coefficient	<i>t</i> statistic	<i>p</i> value	Result
Wind speed	-0.206	-4.948	<0.001	Higher in low wind
Sea Level pressure	+0.062	+2.402	0.019	Higher in high pressure
Depth	+0.461	-3.649	0.001	Higher in deep water

(C) Seabird Location GLM, $r^2 = 0.34$, $n=74$				
Variable	Coefficient	<i>t</i> statistic	<i>p</i> value	Result
Latitude	+0.022	+5.001	<0.001	Higher in North
Longitude	+0.010	+3.950	<0.001	Higher in East

(D) Seabird Environmental GLM of residuals, $r^2 = 0.11$, $n=74$				
Variable	Coefficient	<i>t</i> statistic	<i>p</i> value	Result
Wind speed	-0.035	-3.253	0.002	Higher in low wind
Depth	-0.048	-2.412	0.018	Higher in shallow water

Table 7. Kendall tau correlation coefficients between the 10 environmental and habitat variables and the two non-metric multidimensional scaling (NMDS) axes used to characterize the habitats of seabirds and marine debris during 15 surveys.

Environmental Variable	Axis 1	Axis 2
Wind Speed (WSP)	-0.429	+0.295
Depth (DPT)	+0.600	-0.581
Temperature (SST)	+0.619	-0.752
C.V. Temperature (TCV)	-0.410	+0.352
Chlorophyll-a concentration (CHL)	-0.067	+0.238
C.V. Chlorophyll-a (CCV)	-0.524	+0.429
Sea Level Pressure (SLP)	+0.295	-0.505
Cloud Cover (CC)	+0.010	+0.162
Latitude (LAT)	+0.162	+0.162
Longitude (LON)	-0.695	+0.524

Chapter 3:

Inter-annual, inter-colony and species specific differences in plastic ingestion by Black-footed and Laysan Albatross chicks in Hawaii

Abstract

Black-footed (*Phoebastria nigripes*) and Laysan (*Phoebastria immutabilis*) Albatross in the North Pacific are known to ingest plastic at sea, which they then deliver to chicks on breeding colonies. These chicks accumulate non-digestible material including natural and plastic items over the course of the breeding season and regurgitate a bolus before fledging. We characterized the amounts and types of plastic and natural items ingested by Black-footed and Laysan Albatross chicks from two colonies within the Hawaiian archipelago; Kure Atoll (2008, 2009) and Tern Island (2009). On Kure Atoll, Black-footed Albatross boluses contained proportionally more plastic including sheets line and foam while Laysan Albatross boluses contained more fragments. These patterns were consistent across the two study years (2008, 2009). In 2009 the boluses from Tern Island were smaller and their composition differed from those from Kure, with Black-footed Albatross boluses containing more fragments and less line than Laysan Albatross. These results show that the amount and type of ingested plastic varies by colony and species, underscoring the need to understand seabird foraging ranges and behavior when using seabirds as bio-indicators of pelagic plastic pollution.

Keywords: Black-footed Albatross, *Phoebastria nigripes*, Laysan Albatross, *Phoebastria immutabilis*, bolus, plastic ingestion, marine debris, Hawaii, North Pacific Ocean.

Introduction

Plastics have proliferated in the marine environment and now make up 60-80% of total marine debris worldwide (Derraik, 2002). In the North Pacific Ocean plastic debris concentrates within the Subtropical Convergence Zone and within a high pressure area characterized by weak currents within the North Pacific Subtropical Gyre (Kubota, 1994; Pichel et al., 2007). Studies examining surface plastics within the subtropical gyre have shown sharp increases in density since the 1970s leading this area of the North Pacific to being dubbed the ‘Garbage Patch’ (Day and Shaw, 1987; Moore et al., 2001).

Plastic ingestion by seabirds is a pervasive problem that affects many species across the globe, as these far-ranging predators forage over vast ranges (Robards et al., 1995; Auman et al., 1997; Mallory, 2008). In addition, their role as upper trophic marine predators makes them susceptible to secondary ingestion of plastic via their prey (Ryan and Fraser, 1988). Albatross and other surface-foraging petrels seem particularly susceptible to ingesting plastic (e.g., Nevins et al., 2005). Birds collect plastic at sea, perhaps mistaking it for food or ingesting it along with prey such as flying fish eggs or pelagic barnacles (Harrison et al., 2003; Azarello and VanVleet, 1987). Adults feed this material to their chicks along with prey and other natural non-food items (Kenyon and Kridler, 1969; Harrison et al., 1983). Both albatross species breeding in Hawaii have a long history of documented plastic ingestion. Laysan albatross (LAAL, *Phoebastria immutabilis*) have shown high (> 90%) incidence of plastic ingestion in both dead and live chicks within a range of body conditions (Kenyon and Kridler, 1969; Fry et al., 1987; Sileo et al., 1990; Sievert and Sileo, 1993). Black-footed albatross (BFAL, *Phoebastria nigripes*) have also been found to ingest plastic with high ingestion rates (67-100% incidence) documented in both

chicks and regurgitated boluses (Sileo et al., 1990; Sievert and Sileo, 1993; Kinan and Cousins, 2000).

An additional method to study plastic ingestion in albatrosses is to investigate the castings or boluses which chicks regurgitate in the weeks prior to fledging, peaking in the latter half of May and June (Sievert and Sileo, 1993). These boluses contain the hard indigestible parts of the birds' diet including squid beaks and plastic items, and thus reflect the feeding history of the chick (Pettit et al., 1981; Young et al., 2009). Because these regurgitations originate from chicks that survive to fledge, the sampling need not be restricted to dead chicks but instead can survey a representative sample of the entire colony; even if it is unknown whether every bird produces a bolus. While previous studies using boluses to investigate plastic ingestion have been sparse, they have documented 100% incidence in both BFAL and LAAL (n = 43) from Kure Atoll (Kinan and Cousins, 2000), and colony-based differences in plastic incidence and mass for LAAL (Kure Atoll, n = 15) versus Oahu, n = 8) (Young et al., 2009). Nevertheless, previous studies have only quantified the incidence (presence / absence) and the weight (mass) of plastic in the boluses. Furthermore, it is unknown whether the amount and the type of ingested plastic varies from year to year.

Differences in plastic ingestion by species and colony location may be explained by disparities in the foraging ranges. BFAL range throughout the North Pacific foraging from North America to Alaska and Japan (Awkerman et al., 2008). However, foraging location may be somewhat dependent on colony location with birds from the more southeastern colony of French Frigate Shoals remaining in tropical waters during the brooding season and dispersing towards the California during the rearing season (Fernández et al., 2001; Hyrenbach et al., 2002); while birds from the northwestern colony of Kure Atoll disperse west towards Japan during the rearing

and post-breeding seasons (Hyrenbach and Hester, unpublished data). LAAL disperse from their colonies north towards the Bering Sea, Aleutian Islands and Gulf of Alaska, focusing their foraging on transition zone and subarctic waters during the rearing season (Whittow, 1993; Fernández et al., 2001; Hyrenbach et al., 2002).

Timing within the breeding season also likely affects inter-specific and intra-specific albatross overlap with plastic debris concentrations (Hyrenbach et al. 2002, Young et al. 2009). For instance, the foraging distributions of LAAL breeding on Oahu and Kure Atoll, at opposite ends of the Hawaiian Archipelago are spatially segregated during the incubation and chick guard phases of the breeding season (November-June) when they make frequent colony visitations (mean trip length = 2.5 days). The degree of overlap substantially declines during the post guard and non-breeding phases during June-November (Young et al., 2009). In addition, the latitudinal extent of the Subtropical Transition Zone, a known area of fishing activity and plastic aggregation which shifts position seasonally and from year to year (Polovina et al., 2001; Chai et al., 2003; Pichel et al., 2007) may influence plastic availability to foraging albatross during the breeding season.

Although plastic ingestion in Laysan and Black-footed albatross is a widespread and conspicuous phenomenon,, standardized data on the amount and type of the material ingested by these two sympatric species is generally lacking.. In this study we characterize the amount and types of ingested material regurgitated by LAAL and BFAL chicks from two colonies in Hawaii. Determining ingested plastic levels and types, and identifying colony and species specific trends may have implications for future management strategies and can provide a baseline for future monitoring of plastic ingestion using boluses. Determining the amount and type of ingested plastic, and identifying colony and species-specific trends has important implications for future

monitoring of plastic pollution impacts on albatrosses and marine debris trends at sea. Our objectives were to: 1) develop standardized bolus processing and quantification methods to facilitate comparable studies across colonies and species, 2) validate these standardized metrics using data from colonies with high and low plastic ingestion rates, and 3) use these metrics to illustrate differences in plastic amount and type between species and colonies.

Methods

Study Area

We analyzed ingested plastic from boluses regurgitated by albatross chicks on Kure Atoll (28°25'N, 178°20'W) and Tern Island (23°44'N, 166°8'W), within the Papahānaumokuākea Marine National Monument, Northwestern Hawaiian Islands (Fig. 1). We chose these two sampling sites because they harbor comparable sympatrically-breeding populations of both species. Kure Atoll has an estimated population of 2020 Black-footed albatross and 3900 Laysan albatross breeding pairs. In contrast, an estimated 4259 BFAL and 3226 LAAL breeding pairs nest at French Frigate Shoals (including Tern Island) (Naughton et al., 2007). We also chose these two sites, lying 1300 km apart, because they would allow us to compare geographic differences relating to the proximity to the Subtropical Frontal: Kure Atoll the most northern most island in the archipelago, and Tern Island southern-most sizeable colony of the archipelago.

Sample Collection

Due to the poorly understood process of bolus formation and regurgitation by albatross chicks, we do not assume that our individual samples represent all of the material consumed by a single chick, but rather that they are representative of the amount and the type of material consumed by the chicks. While BFAL boluses are generally regurgitated in a single pellet, the LAAL bolus is generally less cohesive. Thus, LAAL chicks may regurgitate multiple times over a wide area, making it inherently more difficult to collect all of the material. For these reasons, we make no assumptions about the completeness of our samples.

We analyzed Kure Atoll samples from 2008 and 2009 and Tern Island samples from 2009. Boluses were collected in May and June, as soon as possible after regurgitation to prevent the break-up of the boluses and the loss of material through scavenging. Samples were collected opportunistically on Kure (C.V. and M.H.) from monotypic areas, rinsed in water and dipped in 10% bleach solution to remove organic detritus and prevent mold growth. Boluses were then dried before shipping. Bolus samples were collected opportunistically by USFWS personnel on Tern Island and dried before shipping. Only fresh boluses that were directly observed being regurgitated or were found next to a chick were collected. Tern Island samples were rinsed with water, dipped in 10% bleach solution and dried prior to dissection and analysis in the laboratory. All bolus samples were dissected and quantified in a temperature controlled laboratory facility on Oahu.

Sample Processing

Twenty-five boluses were randomly chosen for each species per year per site. Prior to dissection, each intact bolus was measured for displacement volume using a graduated cylinder, with a resolution of 1 ml and dry weight using an electronic scale (Acculab © model EC211, with a resolution to the nearest 0.1g) to validate the cumulative measurements of the disparate categories post processing. Boluses were soaked in water and dissected, taking great care to separate all of the material without breaking any of the plastic pieces or squid beak mandibles. The sorted material was classified into 11 categories, belonging to four constituents: plastic, natural food, natural non-food and other. Following the recommendations of van Franeker (2008), we considered four plastics categories: pellets, sheets, line, foam and fragments. Natural food included two categories: squid beaks and other food. Natural non-food consisted of a single category encompassing nuts and twigs. Finally, the remainder of the bolus was classified as other, which included unclassified and excluded material (Table 1).

Any remaining material was separated by density and rinsed through a 2 mm screen to remove any remaining organic matter particles. Floating material was categorized as unclassified and sinking material was excluded from the analysis. After dissection, the categorized material was air dried for one week, until completely dry to the touch, before further quantification.

Sample Quantification and Analysis

Dry mass (g) and displacement volume (ml) of each bolus category was quantified and recorded. Displacement volume was measured using a 300 ml capacity 7.6 cm diameter

cylindrical container which included a cap with a mesh screen that kept the floating material below the 300 ml fill line. The dry material from each category was placed inside the dry cylinder and the cap attached. The cylinder was then filled using 300 ml of water measured using a graduated cylinder ($300 \text{ ml} \pm 3 \text{ ml}$) and when the fill line was reached, the remaining water yielded the displacement volume. Certain material types required agitation and stirring while submerged within the cylinder in order to yield accurate results. All measurements were made by a single person (A.J.T.) to keep results standardized. Finally, one of us (C.W.C.) determined the number of plastic pellets and fragments within each bolus and measured their size (longest dimension) and color.

Both the mass / volume measurements and the proportional mass/volume are important metrics when examining and comparing bolus data. To understand both the scale of ingested plastic and its composition we compared the entire mass and volume and the proportion of mass and volume of all combined plastics, all natural food and each of the 11 individual categories of the material within the boluses, as well as the number and size of plastic pieces (fragments and pellets). Because the distribution of entire mass and volume measurements were normally distributed, we did not have to transform these data for mass (one-sample Kolmogorov-Smirnov test of residuals, Kure 2008-2009, $\text{max_dif: } 0.091, p = 0.381$; 2009 Kure-Tern, $\text{max_dif: } 0.090, p = 0.389$) or volume (one-sample Kolmogorov-Smirnov test of residuals, Kure 2008-2009, $\text{max_dif: } 0.068, p = 0.748$; 2009 Kure-Tern, $\text{max_dif: } 0.102, p = 0.248$). Proportions were analyzed using arc-sine transformed data. Comparisons were made between species (BFAL / LAAL), colony (Kure Atoll / Tern Island) and year (2008 / 2009) with two-way Analysis of Variance (ANOVA) tests performed using Systat 11. First, inter-annual (2008 vs. 2009) variability for Kure Atoll BFAL / LAAL was assessed. Then, inter-colony differences (Kure vs.

Tern) in both species during the same year (2009) were tested. Finally, the color composition of the plastic fragments across both species, colonies and years was compared using G-tests (Zar, 1984).

Ocean Conditions

We compared the bolus data from each colony to the mean (\pm SD) location of the North Pacific Transition Zone (NPTZ) during the beginning (January) and end (June/July) of the breeding season. We used remotely-sensed data to assess the location of the Transition Zone Chlorophyll Front (TZCF), as indicated by the 0.2 mg m^{-3} contour (Polovina et al., 2001). We derived the chlorophyll-a concentration for the study area north of Hawaii using Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) 0.05° resolution data (<http://modis.gsfc.nasa.gov>). We used 30-day composites for January and July in 2008 and January and June in 2009.

Results

Validating Quantification Measurements

To validate the volume measurements, the mass and volume measurements were compared for all bolus categories using expected linear relationships. Initially, processing of the Kure 2008 data yielded over-estimates in the post-processing volume measurements, especially for the food and line categories, which were likely the result of trapped air bubbles. Subsequent modifications

of the measuring protocols managed to remove this bias, yielding tight relationships between pre and post-processing volume measurements.

Comparisons of the mass / volume measurements revealed significant positive linear relationships for all bolus categories ($r^2 > 0.796$, $p < 0.001$) (Fig. 2, Table 2). Relationships were strongest for fragment ($r^2 = 0.990$, $p < 0.001$) and line ($r^2 = 0.976$, $p < 0.001$) and weakest for sheets ($r^2 = 0.796$, $p < 0.001$). Slopes of the relationships ranged from 1.183 for sheets to 2.183 for foam.

The pre-processing mass and volume measurements for the entire boluses closely matched the summed post-processing mass and volume measurements (Mean difference, Mass = $3.7 \text{ g} \pm 3.3$, Volume = $3.0 \text{ ml} \pm 5.7$). The majority of the bolus material was categorized, with an average of less than 1% by mass and volume unidentified (Mass = $0.58\% \pm 0.64 \text{ SD}$, Volume = $0.54\% \pm 0.67 \text{ SD}$).

Mass and Volume Comparisons

Both mass and volume measurements were used when examining differences in bolus size and composition between colonies, species, and years. Generally, significant two-way interactions between species, colony and year were evident from the volume and mass data, with a few exceptions (Tables 3-6). For instance, the comparison between Kure Atoll boluses from 2008 and 2009, revealed that the proportion of sheets was significantly different between years for the mass measurements; but this pattern was not significant for the volume measurements. Furthermore, while both food and non-food categories did not show mass differences, there was a significant species difference when volume was considered, with the Laysan albatross boluses

having a higher amount of both categories (Table 3). Yet, due to the overall similarity of the mass and volume results, we focus the discussion on mass and provide the volumetric results for comparison (Tables 3-6).

Kure Atoll Inter-annual Differences

There was no difference in total bolus mass between 2008 and 2009 for either the BFAL or for the LAAL (Fig. 3A, Table 3). Furthermore, there were no significant inter-annual differences in the proportional mass of the bolus categories, except for sheets being proportionally higher in 2008 than 2009 (Fig. 3E, Table 3).

Kure Atoll Species-specific Differences

There was no difference in the total bolus mass between Black-footed and Laysan albatross (Fig. 3A, Table 3). Yet, the proportional mass of all plastic categories was higher for BFAL than for LAAL (Fig. 3B, Table 3). Within the different plastic categories, BFAL had proportionally higher mass of sheets, line and foam. Conversely, LAAL had a proportionally higher mass of fragments (Fig. 3, Table 3). While there was no species specific differences in the proportional mass of natural food, Laysan albatross had a higher proportional mass of squid beaks, while Black-footed albatross had a higher proportional mass of other food, which included flying fish eggs and strands, as well as fish and squid lenses (Table 3).

2009 Inter-colony Differences

The total mass of boluses in 2009 was higher on Kure Atoll than on Tern Island (Fig. 4A, Table 4). For Kure Atoll BFAL, mass was significantly greater for all plastic, sheet, line, and foam; while total mass of fragment did not differ between colonies (Fig. 5, Table 5). In comparison, Tern island BFAL boluses had significantly greater mass for all food, beaks and other food. The mass of the non-food category was not statistically different between colonies (Fig. 5, Table 5).

LAAL boluses in 2009 were greater in mass on Kure Atoll, and also included significantly more of the following categories: all plastic, foam, fragment and non-food. Conversely, the mass of line and other food was greater on Tern Island. The mass of sheets, all food and beaks showed no statistical difference between colonies (Fig. 5, Table 6).

In addition to examining mass and volume differences, we also compared the proportional mass and volume of each category between the 2009 boluses from Kure Atoll and Tern Island. The proportional mass of Kure boluses was greater for all plastic, foam, fragment, and non-food, while the proportional mass of Tern boluses was greater for line, all food, beaks and other food (Table 4).

2009 Species-specific Differences

When comparing across species only proportional mass and volume was examined due to the inherent differences in bolus formation and regurgitation. While the analysis revealed many significant differences among species for the different bolus categories, many of these disparities

were colony-specific and opposing trends were found on the two colonies. On Kure Atoll, BFAL boluses had greater proportional mass of sheet and line than LAAL, while on Tern Island, LAAL boluses had greater proportional mass of sheet and line. On Tern Island, BFAL boluses had greater proportional fragment mass, while on Kure Atoll, LAAL had higher proportional mass of fragment. For foam, BFAL boluses had greater proportional mass on both colonies, although the difference between species was much greater on Kure Atoll. There were no species-specific differences in the proportional mass of the all food, beaks, other food and non-food categories (Fig. 4, Table 4).

Fragment Description Comparisons

The number of pellets found in the boluses was low throughout all bolus groups (Mean #, 0.6 ± 1.5) and so were included with the fragments for the purposes of this analysis. The average number of plastic pieces including fragments and pellets was significantly different among bolus groups based on year, colony, and species (ANOVA, $F = 12.427$, $df = 5$, $p < 0.001$) with LAAL boluses from Kure Atoll having the greatest average number (2008 = 73 ± 70 SD, 2009 = 78 ± 39 SD) and Tern Island having the lowest average number (BFAL = 24 ± 20 SD, LAAL = 11 ± 7 SD) (Fig. 6A). Average length of pieces ranged from 13 ± 3 mm (Tern BFAL 2009) to 16 ± 2 mm (Kure LAAL 2008), with no significant difference in the lengths between bolus groups (ANOVA, $F = 1.672$, $df = 5$, $p = 0.145$) (Fig. 6B). White was the dominant color of plastic pieces found within the albatross boluses, with an average of 25 ± 27 SD pieces per bolus (Fig. 7). There were no differences in the color distribution amongst the six bolus groups (G-test, $G = 30$, $df = 45$, $p > 0.95$).

Ocean Conditions

The location of the TZCF varied over the course of the chick-rearing season (January – July) in both 2008 and 2009 (Fig. 8). Within the study area north of Hawaii (150°W to 180°W) the TZCF reached a mean maximum southern extent in January 2008 ($33.871^{\circ}\text{N} \pm 195 \text{ km}$) and 2009 ($35.032^{\circ}\text{N} \pm 353 \text{ km}$). The front reached its northern extent during the study period in July 2008 ($42.155^{\circ}\text{N} \pm 96 \text{ km}$) and June 2009 ($39.141^{\circ}\text{N} \pm 162 \text{ km}$) (Fig. 9). For Kure Atoll, the distance from the colony to the TZCF was smaller 2008 (606 – 1527 km) and 2009 (735 – 1192 km). At Tern Island, the distance to the TZCF was nearly twice as far 2008 (1127 - 2047 km) and 2009 (1255 – 1712 km).

Discussion

The total mass and volume for Kure Atoll boluses was not different between Black-footed and Laysan albatross, highlighting the comparability of the samples from these two species. Yet, the composition of the boluses varied greatly across species, when we compared the proportional mass and volume of each category. BFAL contained proportionally higher amounts of plastic than LAAL, and each species had ingested proportionally different plastic categories. These results suggest that BFAL are ingesting higher amounts of plastic than LAAL, and highlight the inherent structural differences in the albatross boluses. In particular, disparities in the compactness and integrity of the boluses may affect their fate, once they are regurgitated.

We are confident of the completeness of the Kure BFAL boluses due to their compact nature. Unfortunately, we are not as confident about the completeness of the LAAL boluses, which may be expelled in multiple loose regurgitations and may readily come apart under the action of wind and rain. Thus, the probability of collecting the entire sample for a LAAL and a BFAL is likely very different.

The number of fragments per bolus varied significantly, indicating that albatross from Kure Atoll may be foraging in areas of higher plastic density. Yet, we found indistinguishable size and color distributions of ingested plastic pieces across the six bolus groups. While the number and size of fragments can be influenced by mechanical degradation during pre-regurgitation and pre-processing, it provides interesting insights into the marine debris field. In particular, these results highlight the preponderance of white marine debris at sea (e.g., chapter 2), and the wide range of prey sizes ingested by albatross (e.g., Harrison et al. 1983).

The composition of the Kure Atoll BFAL and LAAL boluses also varied when we considered the non-plastic constituents. While the proportional mass of all food was not different between species, LAAL had a higher proportion of beaks and BFAL had a higher proportion of other food. This disparity suggests that the bolus composition reflects the species-specific differences in foraging strategy, with LAAL relying on squid as a major prey item and BFAL foraging more on flying fish eggs (Harrison et al., 1983). While diet analysis of Black-footed albatross determined flying fish eggs to be the dominant component, they were not a major component of the boluses. This is likely because eggs are digested easily and boluses mostly contain only the durable organic strands upon which the eggs are attached. Based on our results, much of the other food category in Black-footed Albatross was comprised of these strands, which are indicative of flying fish egg consumption.

Difference in the composition of plastic loads could also be explained by different foraging areas of the two species; BFAL are known to restrict their foraging during the rearing season to more southern sub-tropical and California Current System waters, while LAAL are found in more northern transition zone and subarctic waters (Hyrenbach et al., 2002; Kappes et al., 2010). The distribution of plastic marine debris may be different in these areas, possibly influencing the observed inter-specific difference in bolus composition. Based on these results, it can be hypothesized that northern transition zone / subarctic waters contain more fragments, while subtropical waters contain more sheets, line and foam. However, inferring this distribution is not this simple due to the colony-specific differences in the composition of the ingested plastics both within and between species.

The comparison of boluses collected during the same year at two colonies highlights these location / species interactions. Boluses were larger for both species on Kure Atoll than on Tern Island, suggesting possible differences in the availability of fragment, foam, line and sheet debris to albatross from these two colonies; as has previously been indicated for LAAL where Kure Atoll showed almost 10 times the amount of plastic than Oahu (Young et al., 2009). Together, these studies underscore the notion that the latitudinal distribution of colonies influences the amount of ingested plastic. Furthermore, the bolus composition revealed that for both species, the total mass of food categories was either similar or higher on Tern Island, while Kure Atoll boluses had much higher amounts of plastics.

While Kure Atoll boluses showed overall higher levels of plastic, their proportional composition revealed colony-based species-specific differences. In particular, Tern Island boluses differed from Kure Atoll bolus in that LAAL had a higher proportion of line while BFAL had a higher proportion of fragments relative to the other species. This significant

interaction highlights that in addition to the differences in plastic ingestion across colonies and species, each species is not typified by an ingested plastic signature. Rather, the species composition of ingested plastic varies by colony and foraging location.

While species-specific disparities in foraging area and diet likely play a role in the observed differences in bolus composition, the significant interaction of species and colonies further suggest differences in plastic composition in different ocean areas. Namely, the higher amount of plastic for both species on Kure Atoll may be explained by the proximity to the southernmost position of the TZCF in January when brooding adults have a limited foraging range. By looking at past tracking studies we can see that at Kure Atoll, LAAL would have access to the known plastic accumulations in the TZCF during the brooding period (Young et al., 2009) and that both LAAL and BFAL from Tern Island would have limited to no access to this area during the same period (Hyrenbach et al., 2002). Additionally colony-based differences in species-specific bolus composition may be explained by the segregation of the foraging ranges during the brooding period. We would hypothesize that Kure Atoll birds have access to high concentrations of foam, sheets and line along the TZCF, while Tern Island birds forage in tropical waters with different plastic types and concentrations. Additionally, inter-annual variability in the front location may influence bolus composition. Analysis of albatross boluses from Kure Atoll showed that there was no inter-annual variation in the total mass and volume, or in the proportional mass and volume of individual categories within the boluses. Only the sheet category showed an inter-annual difference in that there was a greater proportional mass in both species in 2008 which could have resulted from the extremely low amounts of material in this category.

While we focused our discussion on mass measurements due to the high level of correlation between the mass and volume results, both parameters are important indicators of bolus contents.

Although volume measurements are more difficult and time consuming, they can be important for assessing potential detrimental effects of plastic ingestion on seabirds. For instance, foam, due its low density, may be under-represented in mass calculations, even though it would take up more space inside the stomach than its mass would suggest. Thus, volume may better describe boluses composition relative to the volume limitations of an albatross chick stomach; however, our results show that the volume of different bolus categories can be extrapolated using linear relationships based on the mass of that material.

Previous studies of plastic ingestion by Hawaiian albatrosses have largely focused on a single colony or species (Auman et al., 1997; Fry et al., 1987; Sievert and Sileo, 1993). Our study shows that a multi-species and multi-colony approach is needed to fully characterize the variation present in the patterns of plastic ingestion within these sympatric albatross species. In particular, the segregation of foraging locations by species (Kappes et al., 2010) and colony (Young et al., 2009), highlight the importance of considering multiple colonies when assessing plastic ingestion in these two sympatrically-breeding albatrosses. Furthermore, this information is critical when attempting to use albatross as biological sensors of marine debris, by sampling vast, yet different areas of the North Pacific Ocean relying on the full complement of species and colony sites available to researchers. The availability of data from multiple colonies and species make albatross boluses valuable tools to study marine debris across the North Pacific Ocean.

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References

- Auman, H.J., Ludwig, J.P., Summer, C.L., Verbrugge, D.A., Froese, K.L., Colborn, T., Giesy, J.P., 1997. PCBs, DDE, DDT and TCDD-EQ in two species of albatross on Sand Island, Midway Atoll, North Pacific Ocean. *Environmental Toxicology and Chemistry* 16, 498-504.
- Awkerman, J.A., Anderson, D.J., Whittow, G.C., 2008. Black-footed albatross (*Phoebastria nigripes*). In: Poole, A., (Ed) *The Birds of North America Online*. Cornell Lab of Ornithology, Ithaca, NY.
- Azzarello, M.Y., Van Vleet, E.S., 1987. Marine birds and plastic pollution. *Marine Ecology-Progress Series* 37, 295-303.
- Blight, L.K., Burger, A.E., 1997. Occurrence of plastic particles in sea-birds from the Eastern North Pacific. *Marine Pollution Bulletin* 34, 323-325.
- Chai, F., Jiang, M., Barber, R.T., Dugdale, R.C., Chao, Y., 2003. Interdecadal variation of the Transition Zone Chlorophyll Front, a physical-biological model simulation between 1960 and 1990. *Journal of Oceanography* 59, 461– 475.
- Day, R.H., Shaw, D.G., 1987. Patterns in the abundance of pelagic plastic and tar in the North Pacific Ocean, 1976-1985. *Marine Pollution Bulletin* 18, 311-316.
- Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin* 44, 842-852.
- Fernández, P., Anderson, D.J., Sievert, P.R., Huyvaert, K., 2001. Foraging destinations of three low-latitude albatross (*Phoebastria*) species. *Journal of Zoology* 254,391-404.
- Fry, D.M., Fefer, S.I., Sileo, L., 1987. Ingestion of plastic debris by Laysan albatrosses and Wedge-tailed shearwaters in the Hawaiian-Islands. *Marine Pollution Bulletin* 18, 339-343.
- Harrison, C.S., Higa, T.S., Seki, M.P., 1983. Hawaiian seabird feeding ecology. *Wildlife Monographs* 85, 1-71.
- Hyrenbach, K.D., Fernández, P., Anderson, D.J., 2002. Oceanographic habitats of two sympatric North Pacific albatross during the breeding season. *Marine Ecology-Progress Series* 233, 283-301.
- Kappes, M.A., Shaffer, S.A., Tremblay, Y., Foley, D.G., Palacios, D.M., Robinson, P.W., Bograd, S.J., Costa, D.P., 2010. Hawaiian albatrosses track interannual variability of marine habitats in the North Pacific. *Progress in Oceanography* 86, 246-260.
- Kenyon, K.W., Kridler, E., 1969. Laysan albatrosses swallow indigestible matter. *The Auk* 86, 339-343.

- Kinan, I.T., Cousins, K.L., 2000. Abundance of plastic debris and ingestion by albatross on Kure Atoll, Northwestern Hawaiian Islands. Second International Conference on the Biology and Conservation of Albatrosses and other Petrels, 8-10 May 2000, Waikiki, Hawaii.
- Kubota, M., 1994. A mechanism for the accumulation of floating marine debris north of Hawaii. *Journal of Physical Oceanography* 24, 1059-1064.
- Mallory, M.L., 2008. Marine plastic debris in Northern Fulmars from the Canadian high Arctic. *Marine Pollution Bulletin* 56, 1501-1504.
- Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A comparison of plastic and plankton in the North Pacific Central Gyre. *Marine Pollution Bulletin* 42, 1297-1300.
- Naughton, M.B., Romano, M.D., Zimmerman, T.S., 2007. A conservation action plan for Black-footed albatross (*Phoebastria nigripes*) and Laysan albatross (*P. immutabilis*), Ver. 1.0.
- Pettit, T.N., Grant, G.S., Whittow, G.C., 1981. Ingestion of plastics by Laysan albatross. *Auk* 98, 839-841.
- Pichel, W.G., Churnside, J.H., Veenstra, T.S., Foley, D.G., Friedman, K.S., Brainard, R.E., Nicoll, J.B., Zheng, Q., Clemente-Colon, P., 2007. Marine debris collects within the North Pacific Subtropical Convergence Zone. *Marine Pollution Bulletin* 54, 1207-1211.
- Polovina, J.J., Howell, E., Kobayashi, D.R., Seki, M.P., 2001. The Transition Zone Chlorophyll Front, a dynamic global feature defining migration and forage habitat for marine resources. *Progress in Oceanography* 49, 469-483.
- Robards, M.D., Piatt, J.F., Wohl, K.D., 1995. Increasing frequency of plastic particles ingested by seabirds in the sub-arctic North Pacific. *Marine Pollution Bulletin* 30, 151-157.
- Ryan, P.G., Fraser, M.W., 1988. The use of great skua pellets as indicators of plastic pollution in seabirds. *Emu* 88, 16-19.
- Sievert, P.R., Sileo, L., 1993. The effect of ingested plastic on growth and survival of albatross chicks. In: Vermeer, K., Briggs, K.T., Morgan, K.H., Siegel-Causey, D., (Eds.). *The status, ecology, and conservation of marine birds of the North Pacific*. Canadian Wildlife Service Special Publication, Ottawa, p 212-217.
- Sileo, L., Sievert, P.R., Samuel, M.D., 1990. Causes of mortality of albatross chicks at Midway Atoll. *Journal of Wildlife Disease* 26, 329-338.
- van Franeker, J.A., 2008. Fulmar litter EcoQO monitoring in the North Sea - results to 2006. Report No. C033/08, Wageningen IMARES.

Whittow, G.C., 1993. Laysan albatross (*Phoebastria immutabilis*). In: Poole, A., (Ed.), The Birds of North America Online. Cornell Lab of Ornithology, Ithaca NY.

Young, L.C., Vanderlip, C., Duffy, D.C., Afanasyev, V., Shaffer, S.A., 2009. Bringing home the trash: Do colony based differences in foraging distribution lead to increased plastic ingestion in Laysan albatrosses? PLoS ONE 4, 10: e7623.

Zar, J.H., 1984. Biostatistical Analysis. Prentice-Hall, Englewood Cliffs, NJ.

Figures

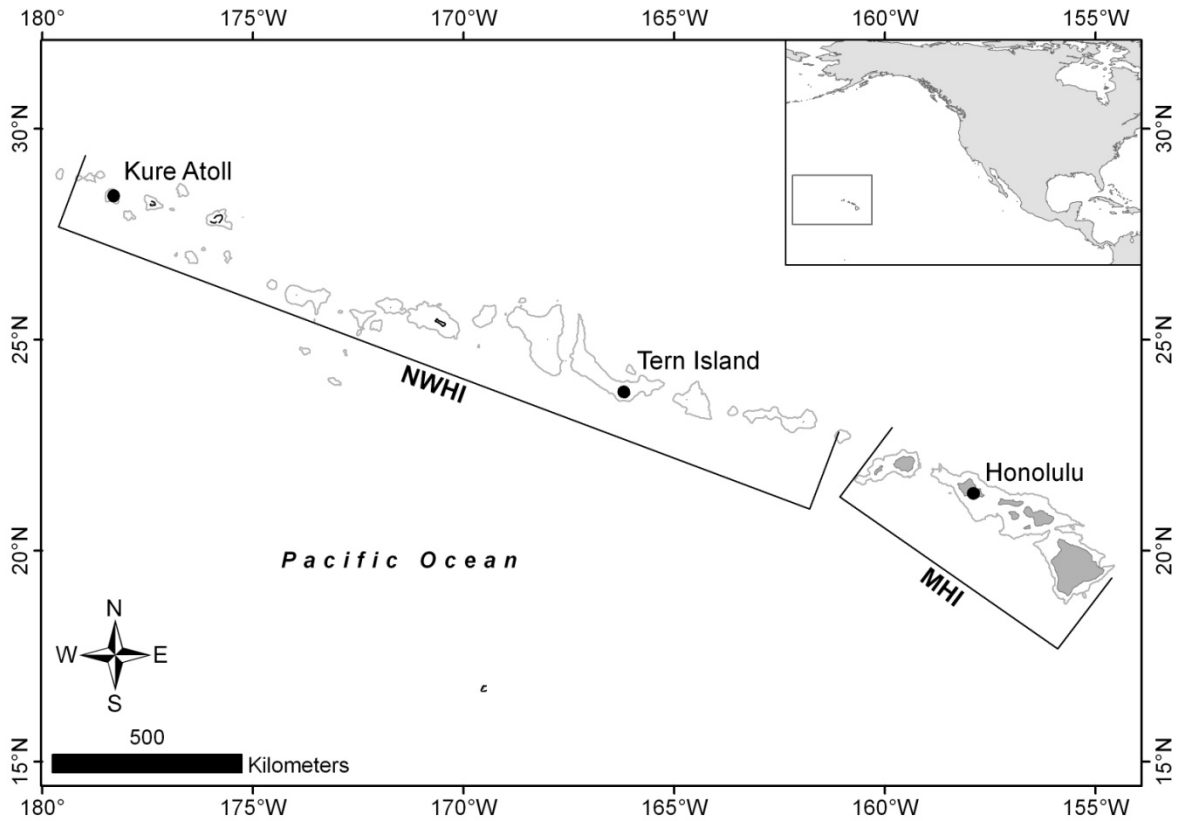


Figure 1. Map of the Hawaiian Archipelago in the North Pacific Ocean. Indicated are the Main Hawaiian Islands (MHI) and the study sites, Kure Atoll and Tern Island within the Northwestern Hawaiian Islands (NWHI).

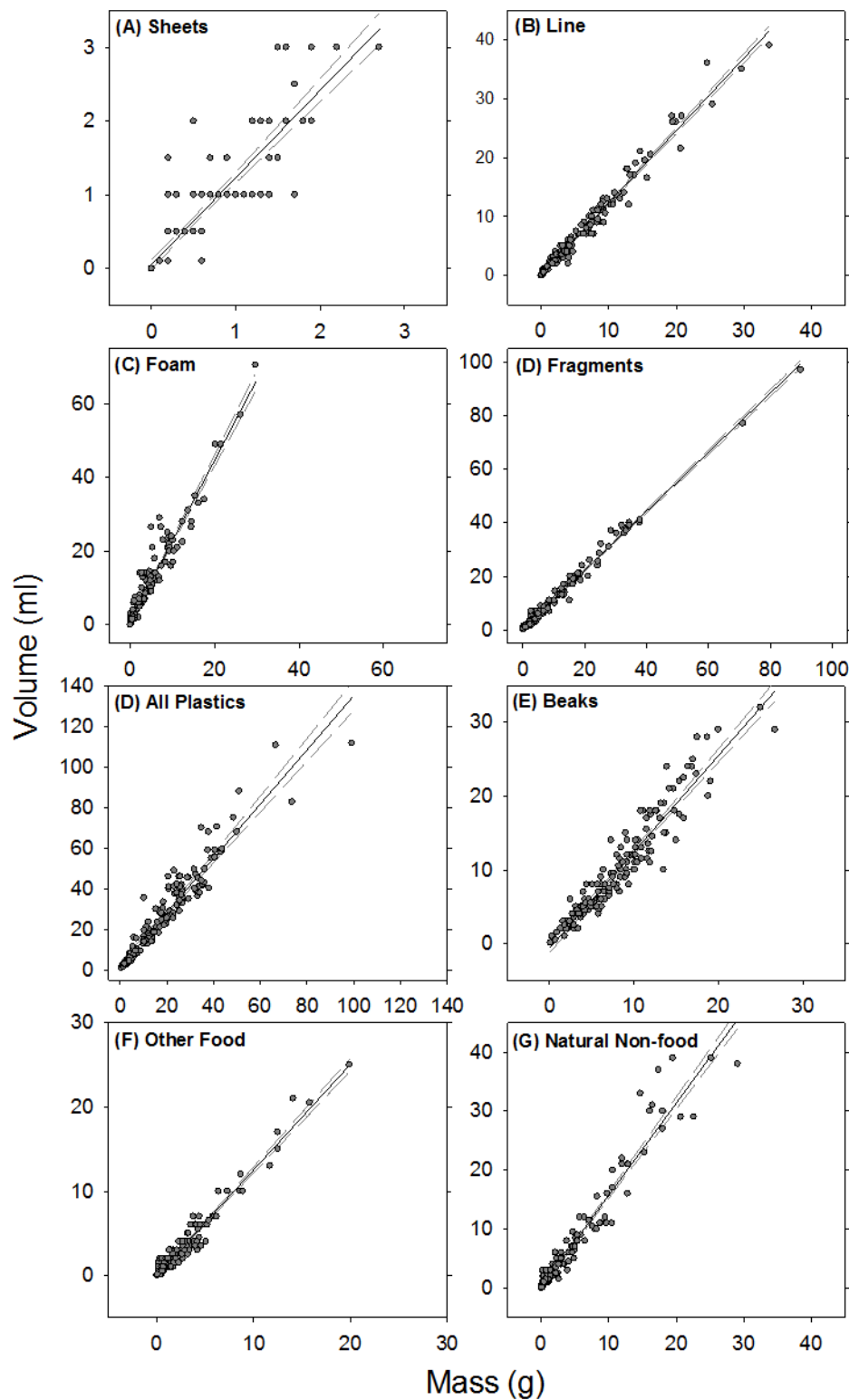


Figure 2. Comparisons of Mass (g) and Volume (ml) for all bolus category measurements. Descriptions of materials included in each category are summarized in Table 1. Regression results are shown in table 2.

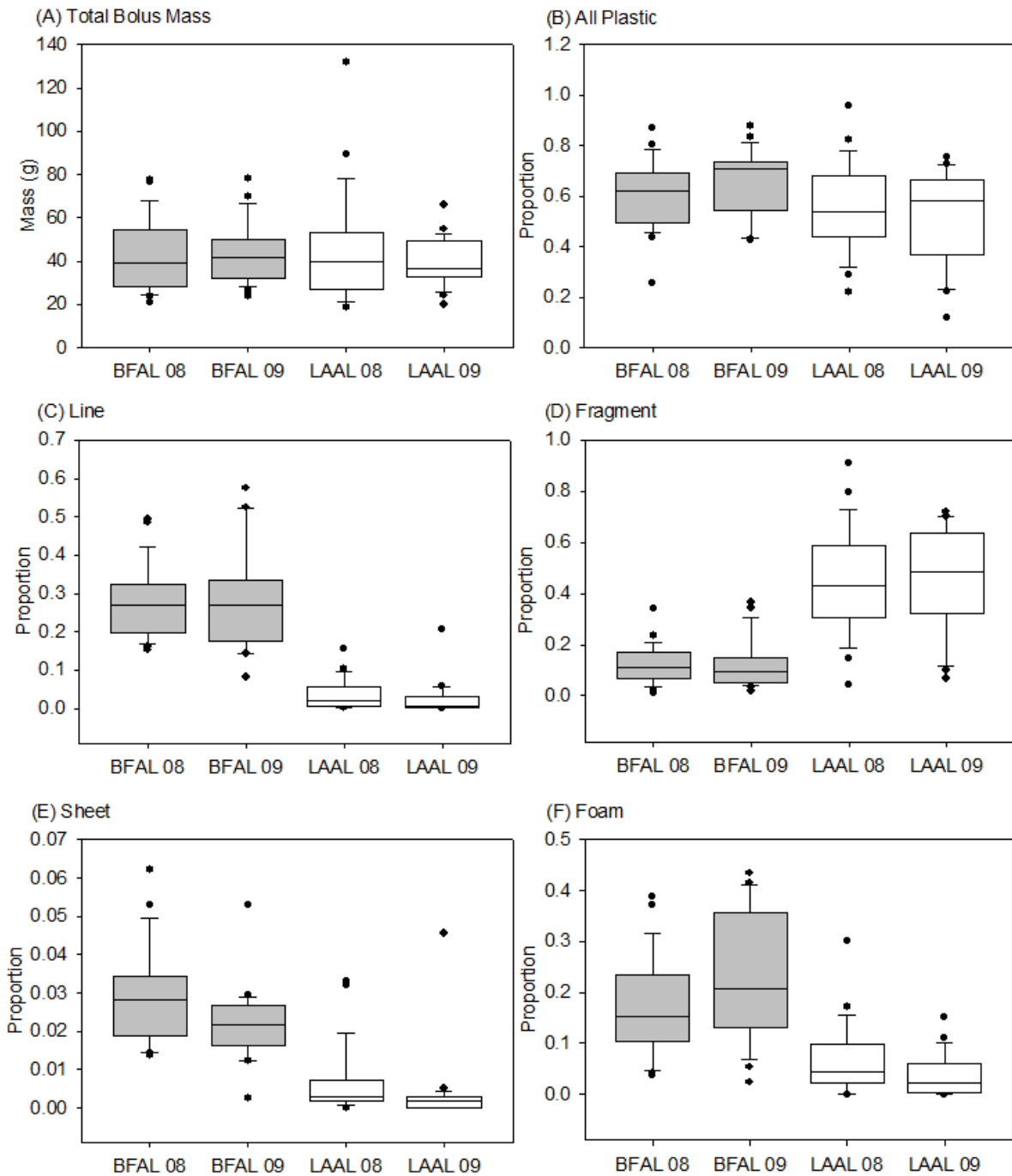


Figure 3. Box plots (mean, 25%, 75%), whisker bars (10%, 90%) and outliers of the distributions of absolute and proportional mass of the entire bolus and of different plastic categories for Black-footed (BFAL) and Laysan (LAAL) albatross from Kure Atoll in 2008 and 2009. ANOVA results are summarized in table 3.

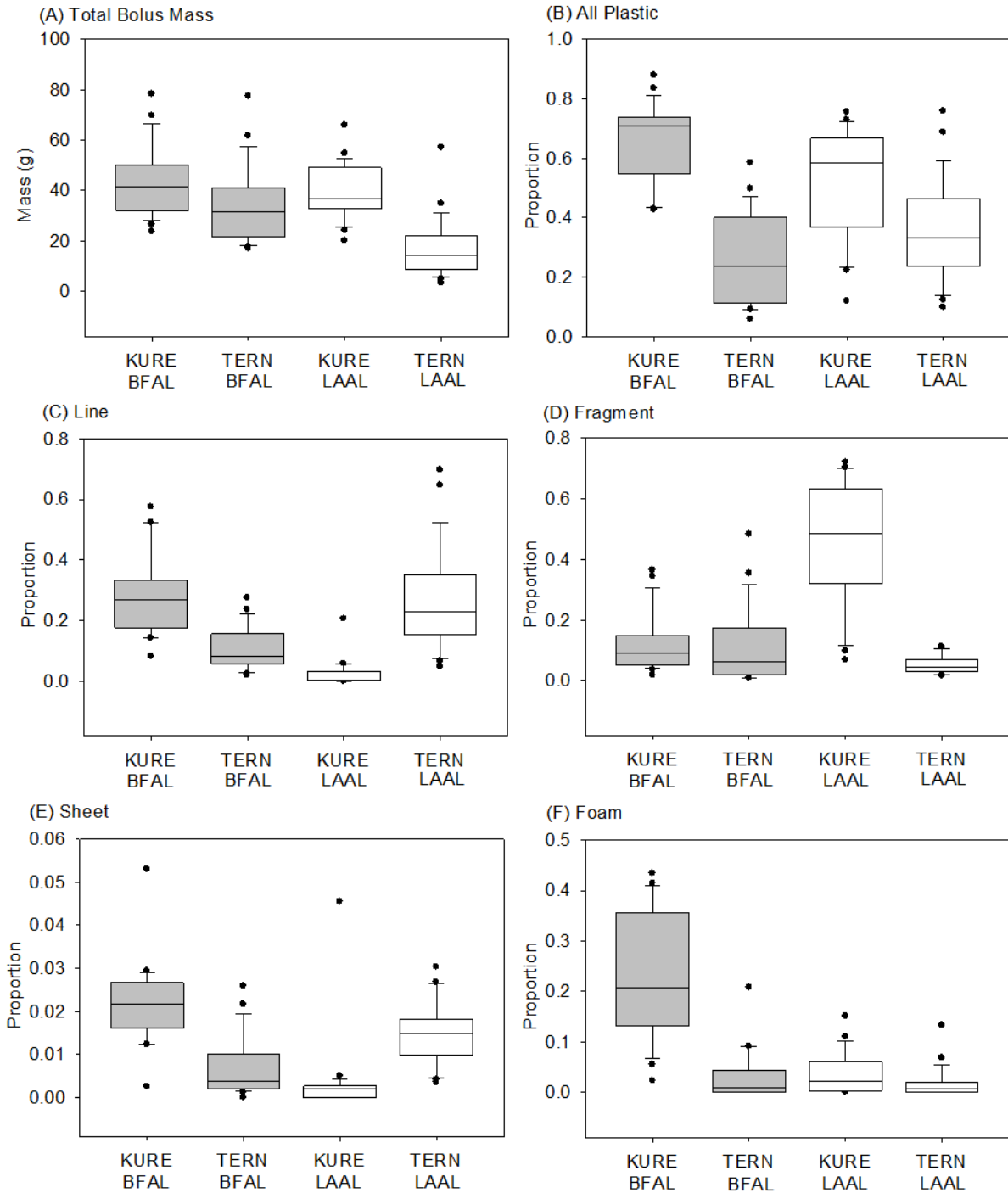


Figure 4. Box plots (mean, 25%, 75%), whisker bars (10%, 90%) and outliers of the distributions of absolute proportional mass of the entire bolus and different plastic categories for Black-footed (BFAL) and Laysan (LAAL) albatross in 2009 for Kure Atoll and Tern Island. ANOVA results are summarized in table 4.

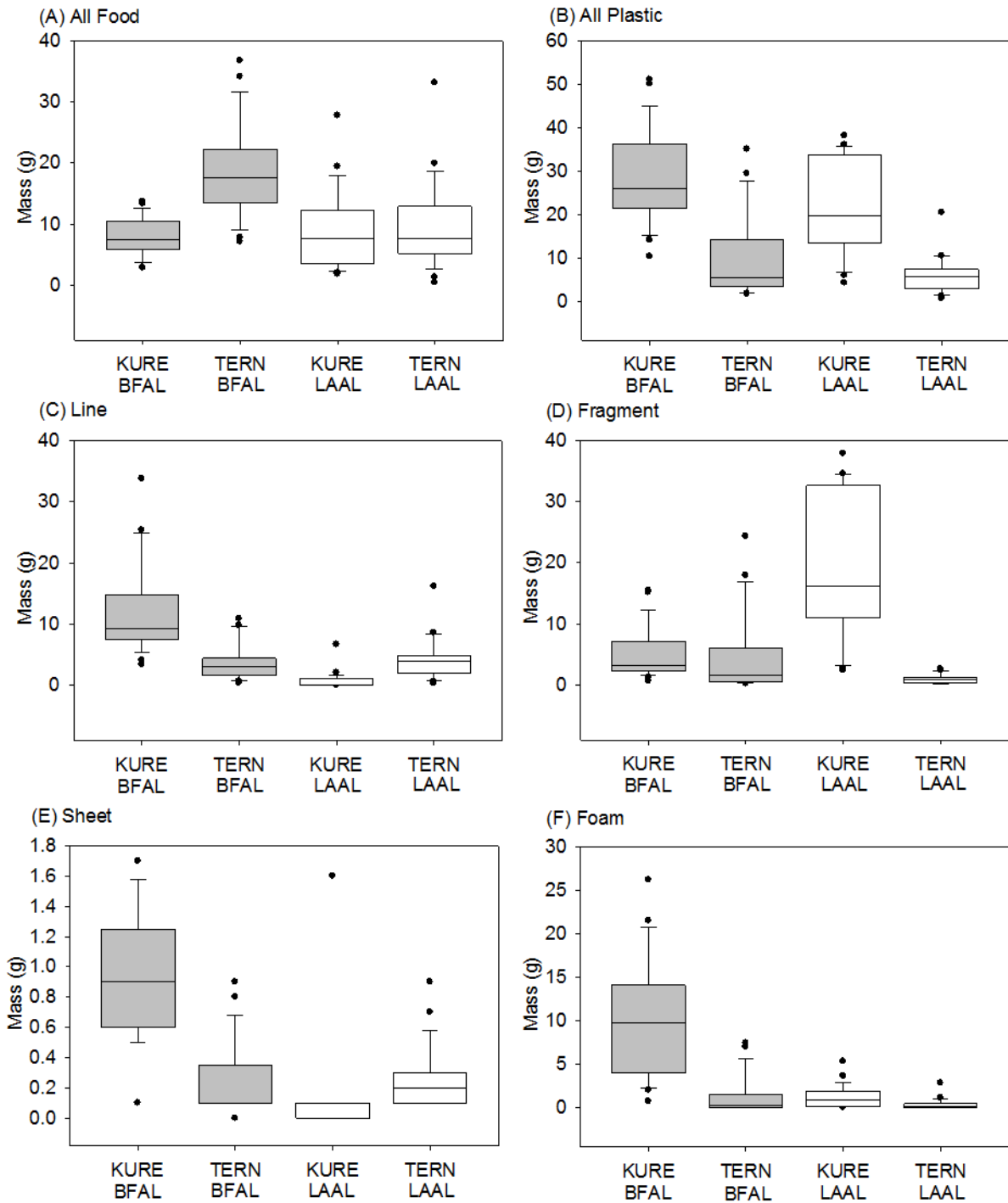


Figure 5. Box plots (mean, 25%, 75%), whisker bars (10%, 90%) and outliers in the distributions of absolute mass (g) of food and plastic categories for Black-footed (BFAL) and Laysan (LAAL) albatross in 2009 from Kure Atoll and Tern Island. ANOVA results are summarized in tables 5 and 6.

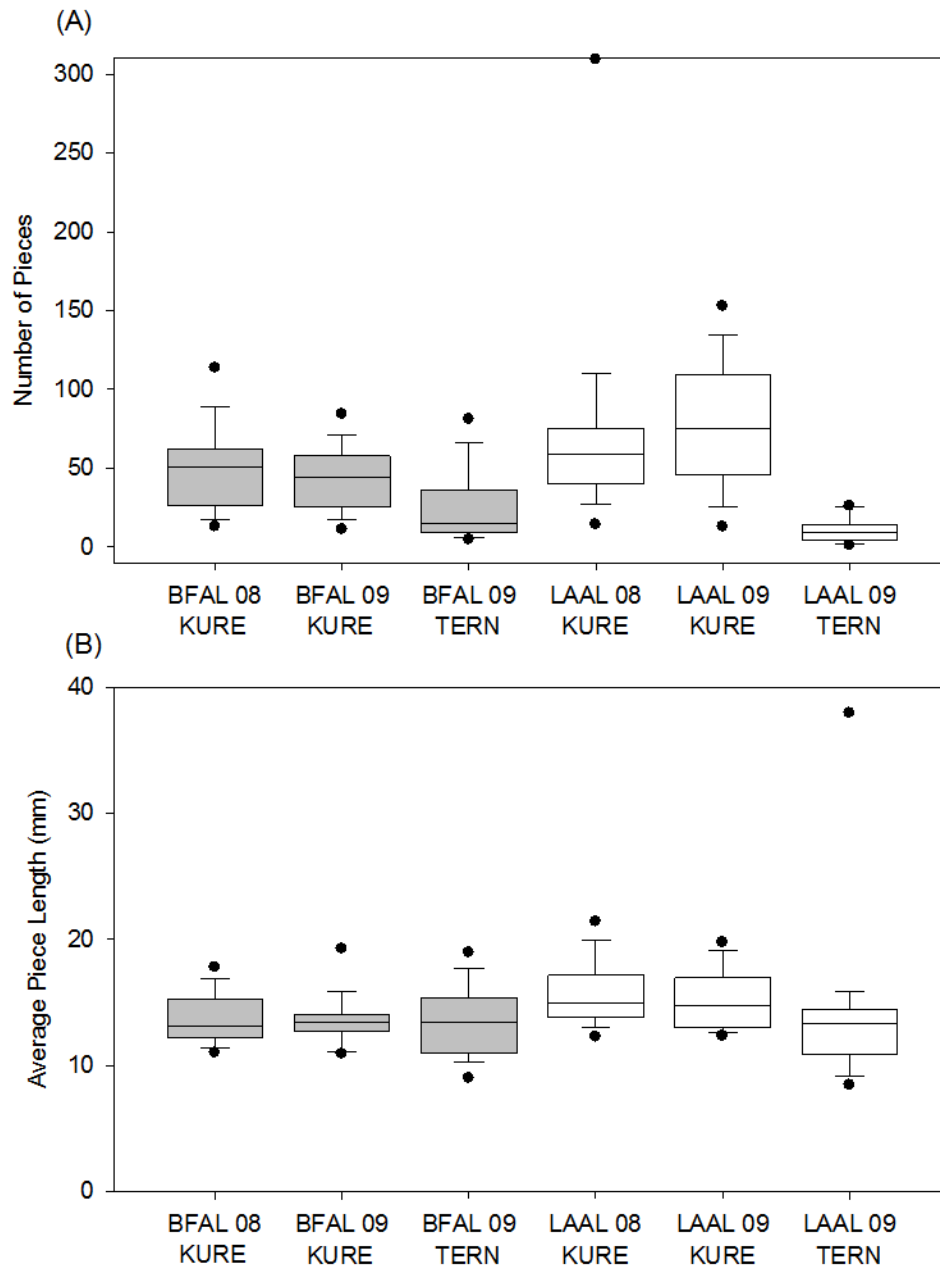


Figure 6. Box plot (mean, 25%, 75%), whisker bars (10%, 90%) and outliers in the distributions of the number of plastic pieces (fragments and pellets) per bolus (A) and plastic fragment length (B) for all six bolus samples; Black-footed albatross, Kure Atoll - 2008 and 2009, Tern Island – 2009, Laysan albatross, Kure Atoll – 2008, 2009, Tern Island – 2009.

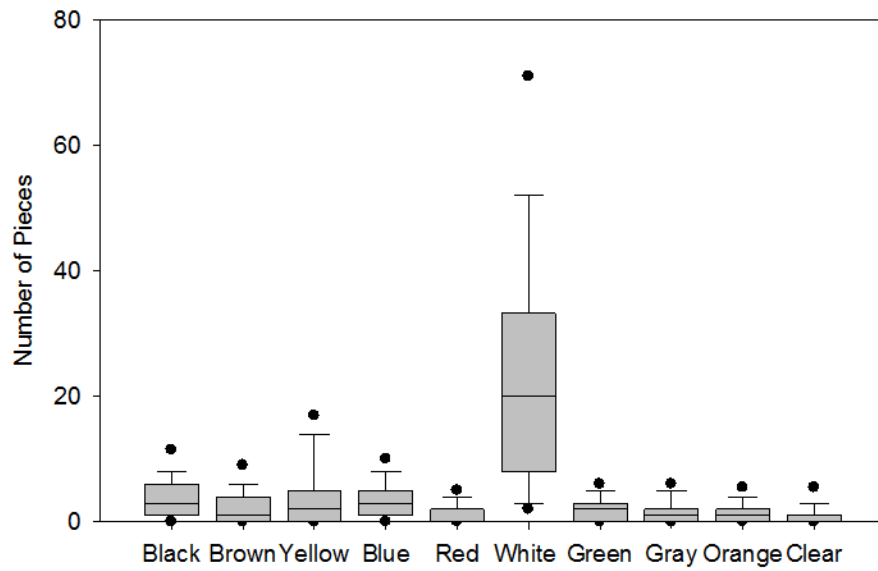


Figure 7. Box plot (mean, 25%, 75%), whisker bars (10%, 90%) and outliers in the distributions of plastic fragment colors in bolus from both Black-footed and Laysan Albatross for both Kure Atoll and Tern Island. There was no difference in the composition of color within any of the bolus samples.

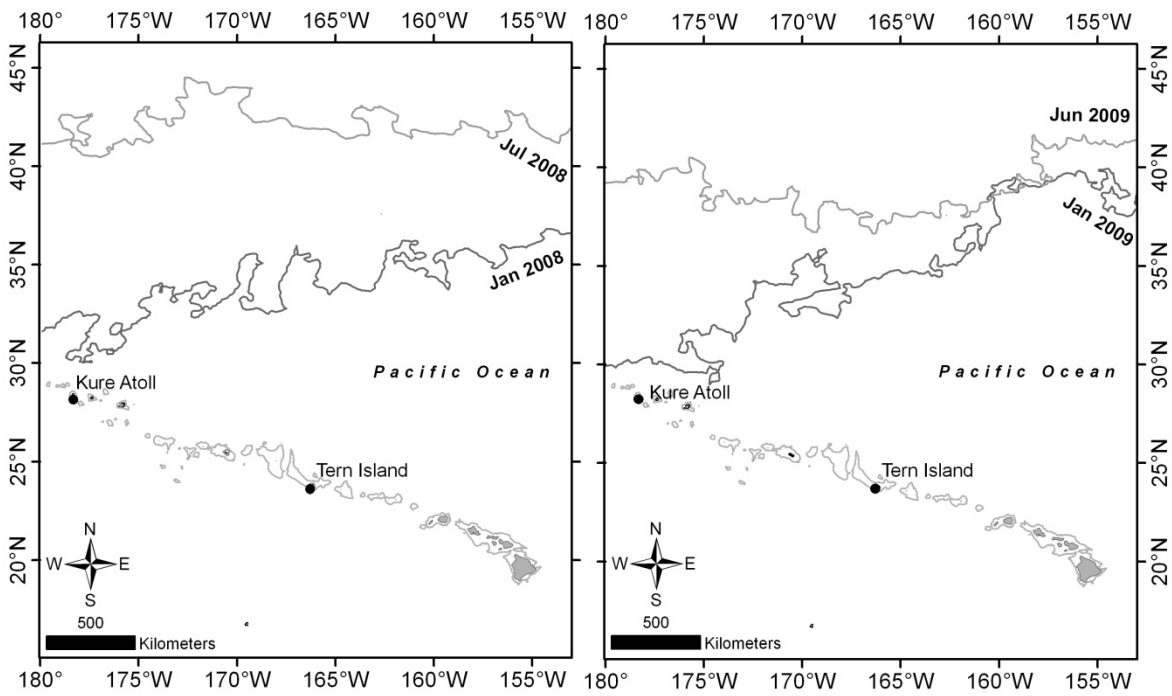


Figure 8. Map of the Hawaiian Archipelago showing the two study colonies and the southern (January) and northern (June/July) position of the Transition Zone Chlorophyll Front (0.2 mg m^{-3}) in 2008 (A) and in 2009 (B).

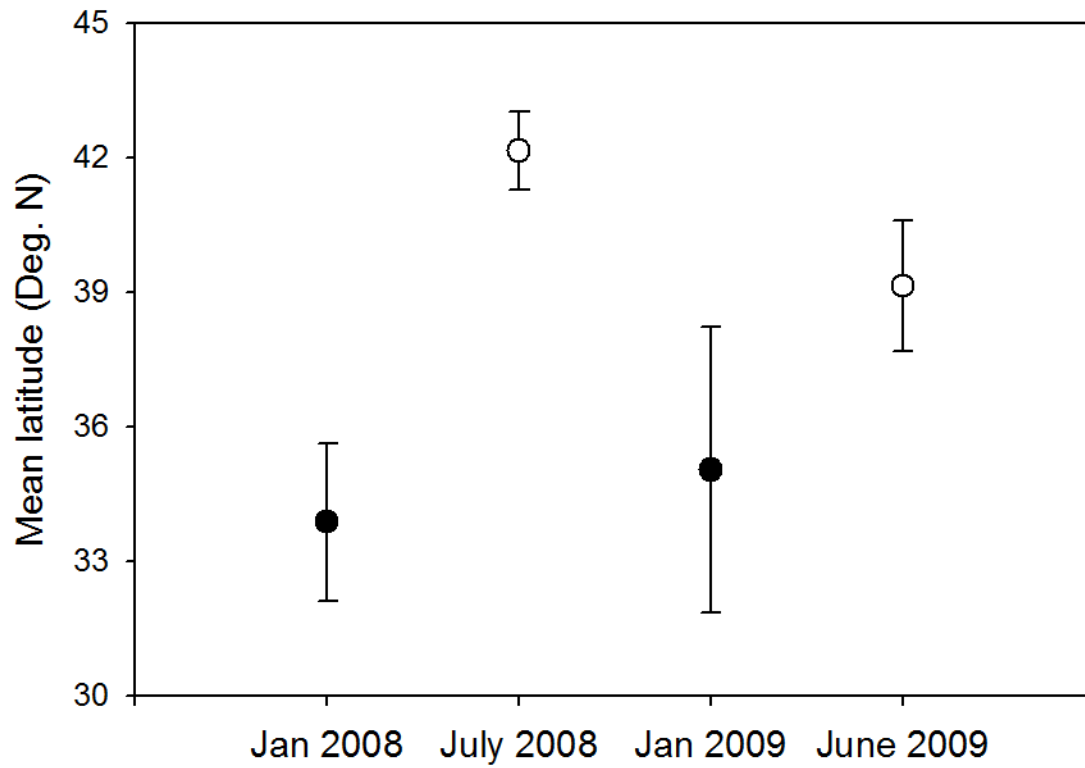


Figure 9. Mean latitude (\pm SD) of the Transition Zone Chlorophyll Front (TZCF) north of Hawaii (155 – 180 ° W) during the beginning and the end of the albatross breeding season of 2008 and 2009.

Tables

Table 1. Description of standardized categories for bolus dissections. Plastic categories are based on guidelines from van Franeker (2008).

Bolus Constituent	Bolus Category	Material Description
Plastic	Pellets	Pre-production plastic spheres or ovals
	Sheets	Thin, flattened, easily bendable plastic
	Line	Round mono or multi-filament line, rope
	Foam	Low density aerated poly ethylene foam
	Fragment	Complete or broken post-consumer plastics
Food	Beaks	Squid beak mandibles
	Other food	Flying fish eggs and strands, fish and squid lens
Non food	Natural	Plant matter and pumice
Unclassified	Unclassified	Unidentified floating material >2 mm
	Not included	Unidentified sinking material >2 mm

Table 2. Regression results for the relationships between mass and volume of all measurements within each bolus category. Data are also represented graphically in Fig. 2

Category	Intercept	Slope	r^2	p
Sheet	0.055	1.183	0.796	<0.001
Line	0.049	1.227	0.976	<0.001
Foam	1.015	2.183	0.937	<0.001
Fragment	0.310	1.100	0.990	<0.001
All plastic	1.797	1.333	0.910	<0.001
Beaks	-0.584	1.305	0.901	<0.001
Other food	0.014	1.252	0.958	<0.001
Non food	0.139	1.562	0.945	<0.001

Table 3. Two-way ANOVA results for the comparison of bolus size and composition between Black-footed albatross (BFAL) and Laysan albatross (LAAL), for Kure Atoll in 2008 and 2009. Shown are the absolute bolus mass (g) and volume (ml) and the proportional contribution of the individual bolus categories.

Category	Metric	2008		2009		Significance (<i>p</i>)
		BFAL mean (\pm SD)	LAAL mean (\pm SD)	BFAL mean (\pm SD)	LAAL mean (\pm SD)	
Entire bolus	Mass	41.6 (\pm 16.1)	45.05 (\pm 25.2)	43.3 (\pm 13.4)	40.4 (\pm 11.2)	Non sig
All plastic	Mass	0.60 (\pm 0.14)	0.56 (\pm 0.17)	0.66 (\pm 0.13)	0.52 (\pm 0.19)	Species (0.006)
Sheets	Mass	0.03 (\pm 0.01)	0.01 (\pm 0.01)	0.02 (\pm 0.01)	0.00 (\pm 0.01)	Species (<0.001), Year (<0.001)
Line	Mass	0.28 (\pm 0.09)	0.04 (\pm 0.04)	0.28 (\pm 0.13)	0.02 (\pm 0.04)	Species (<0.001)
Foam	Mass	0.17 (\pm 0.09)	0.07 (\pm 0.07)	0.23 (\pm 0.13)	0.04 (\pm 0.04)	Species (<0.001), Spp*Yr (0.017)
Fragments	Mass	0.12 (\pm 0.07)	0.45 (\pm 0.20)	0.12 (\pm 0.09)	0.45 (\pm 0.21)	Species (<0.001)
All food	Mass	0.21 (\pm 0.10)	0.27 (\pm 0.15)	0.19 (\pm 0.07)	0.25 (\pm 0.19)	Non sig
Beaks	Mass	0.15 (\pm 0.08)	0.25 (\pm 0.13)	0.15 (\pm 0.07)	0.23 (\pm 0.19)	Species (0.002)
Other food	Mass	0.06 (\pm 0.06)	0.02 (\pm 0.04)	0.04 (\pm 0.04)	0.01 (\pm 0.01)	Species (<0.001)
Non food	Mass	0.11 (\pm 0.12)	0.11 (\pm 0.13)	0.09 (\pm 0.11)	0.17 (\pm 0.15)	Non sig
Entire bolus	Volume	58.4 (\pm 23.3)	60.9 (\pm 30.9)	63.1 (\pm 21.1)	51.3 (\pm 12.7)	Non sig
All plastic	Volume	0.66 (\pm 0.15)	0.58 (\pm 0.17)	0.69 (\pm 0.15)	0.52 (\pm 0.17)	Species (<0.001)
Sheets	Volume	0.02 (\pm 0.01)	0.01 (\pm 0.01)	0.02 (\pm 0.01)	0.00 (\pm 0.06)	Species (<0.001)
Line	Volume	0.25 (\pm 0.10)	0.04 (\pm 0.04)	0.24 (\pm 0.12)	0.02 (\pm 0.04)	Species (<0.001)
Foam	Volume	0.29 (\pm 0.13)	0.14 (\pm 0.13)	0.34 (\pm 0.16)	0.08 (\pm 0.10)	Species (<0.001), Spp*Yr (0.019)
Fragments	Volume	0.10 (\pm 0.06)	0.39 (\pm 0.19)	0.10 (\pm 0.07)	0.41 (\pm 0.19)	Species (<0.001)
All food	Volume	0.17 (\pm 0.09)	0.23 (\pm 0.14)	0.16 (\pm 0.07)	0.23 (\pm 0.19)	Species (0.024)
Beaks	Volume	0.12 (\pm 0.07)	0.21 (\pm 0.12)	0.12 (\pm 0.07)	0.21 (\pm 0.19)	Species (0.001)
Other food	Volume	0.05 (\pm 0.05)	0.02 (\pm 0.04)	0.05 (\pm 0.02)	0.02 (\pm 0.02)	Species (<0.001)
Non food	Volume	0.12 (\pm 0.14)	0.15 (\pm 0.15)	0.09 (\pm 0.12)	0.20 (\pm 0.17)	Species (0.009)

Table 4. Two-way ANOVA results for the comparison of bolus size and composition between Black-footed albatross (BFAL) and Laysan albatross (LAAL) in 2009 for Kure Atoll and Tern Island. Shown are the absolute bolus mass (g) and volume (ml) and the proportional contribution of the individual bolus categories.

Category	Metric	Tern 2009		Kure 2009		Significance (<i>p</i>)
		BFAL mean (\pm SD)	LAAL mean (\pm SD)	BFAL mean (\pm SD)	LAAL mean (\pm SD)	
Entire bolus	Mass	33.8 (\pm 14.9)	17.3 (\pm 11.7)	43.3 (\pm 13.4)	40.4 (\pm 11.2)	Colony (<0.001), Species (<0.001), Col*Spp (0.010)
All plastic	Mass	0.26 (\pm 0.15)	0.36 (\pm 0.17)	0.66 (\pm 0.13)	0.52 (\pm 0.19)	Colony (<0.001), Col*Spp (<0.001)
Sheets	Mass	0.01 (\pm 0.01)	0.02 (\pm 0.01)	0.02 (\pm 0.01)	0.00 (\pm 0.01)	Species (<0.001), Col*Spp (<0.001)
Line	Mass	0.11 (\pm 0.07)	0.27 (\pm 0.17)	0.28 (\pm 0.13)	0.02 (\pm 0.04)	Colony (0.001), Species (<0.001), Col*Spp (<0.001)
Foam	Mass	0.03 (\pm 0.05)	0.02 (\pm 0.03)	0.23 (\pm 0.13)	0.04 (\pm 0.04)	Colony (<0.001), Species (<0.001), Col*Spp (<0.001)
Fragment	Mass	0.12 (\pm 0.13)	0.05 (\pm 0.03)	0.12 (\pm 0.09)	0.45 (\pm 0.21)	Colony (<0.001), Species (<0.001), Col*Spp (<0.001)
All food	Mass	0.58 (\pm 0.15)	0.53 (\pm 0.15)	0.19 (\pm 0.07)	0.25 (\pm 0.19)	Colony (<0.001)
Beaks	Mass	0.43 (\pm 0.13)	0.35 (\pm 0.14)	0.15 (\pm 0.07)	0.23 (\pm 0.19)	Colony (<0.001), Col*Spp (0.010)
Other food	Mass	0.15 (\pm 0.10)	0.18 (\pm 0.13)	0.04 (\pm 0.04)	0.01 (\pm 0.01)	Colony (<0.001), Col*Spp (0.023)
Non food	Mass	0.08 (\pm 0.07)	0.04 (\pm 0.05)	0.09 (\pm 0.11)	0.17 (\pm 0.15)	Colony (<0.001), Col*Spp (0.001)
Entire bolus	Volume	44.5 (\pm 20.1)	23.4 (\pm 15.8)	63.1 (\pm 21.1)	51.3 (\pm 12.7)	Colony (<0.001), Species (<0.001)
All plastic	Volume	0.26 (\pm 0.15)	0.39 (\pm 0.15)	0.69 (\pm 0.15)	0.52 (\pm 0.17)	Colony (<0.001), Col*Spp (<0.001)
Sheets	Volume	0.01 (\pm 0.01)	0.02 (\pm 0.02)	0.02 (\pm 0.01)	0.00 (\pm 0.02)	Species (0.041), Col*Spp (<0.001)
Line	Volume	0.10 (\pm 0.06)	0.26 (\pm 0.16)	0.24 (\pm 0.12)	0.02 (\pm 0.04)	Colony (<0.001), Species (0.001), Col*Spp (<0.001)
Foam	Volume	0.06 (\pm 0.08)	0.05 (\pm 0.07)	0.34 (\pm 0.16)	0.08 (\pm 0.10)	Colony (<0.001), Species (<0.001), Col*Spp (<0.001)
Fragment	Volume	0.10 (\pm 0.10)	0.06 (\pm 0.04)	0.10 (\pm 0.07)	0.41 (\pm 0.19)	Colony (<0.001), Species (<0.001), Col*Spp (<0.001)
All food	Volume	0.59 (\pm 0.15)	0.51 (\pm 0.13)	0.16 (\pm 0.07)	0.23 (\pm 0.19)	Colony (<0.001), Col*Spp (0.014)
Beaks	Volume	0.45 (\pm 0.13)	0.35 (\pm 0.13)	0.12 (\pm 0.07)	0.21 (\pm 0.19)	Colony (<0.001), Col*Spp (0.001)
Other food	Volume	0.14 (\pm 0.10)	0.16 (\pm 0.11)	0.05 (\pm 0.02)	0.02 (\pm 0.02)	Colony (<0.001)
Non food	Volume	0.09 (\pm 0.08)	0.04 (\pm 0.05)	0.09 (\pm 0.12)	0.20 (\pm 0.17)	Colony (0.001), Col*Spp (<0.001)

Table 5. Two-way ANOVA results of comparison between 2009 Black-footed albatross (BFAL) boluses from Tern Island and Kure Atoll. Shown are the mass (g) and volume (ml) of each bolus category.

Category	Metric	2009		Significance (<i>p</i>)
		Tern BFAL mean (\pm SD)	Kure BFAL mean (\pm SD)	
Entire bolus	Mass	33.8 (\pm 14.9)	43.3 (\pm 13.4)	0.022
All plastic	Mass	10.0 (\pm 9.3)	28.5 (\pm 10.8)	<0.001
Sheets	Mass	0.3 (\pm 0.2)	0.9 (\pm 0.4)	<0.001
Line	Mass	3.8 (\pm 3.1)	12.3 (\pm 7.4)	<0.001
Foam	Mass	1.2 (\pm 2.2)	10.1 (\pm 6.5)	<0.001
Fragment	Mass	4.7 (\pm 6.4)	5.1 (\pm 3.9)	0.781
All food	Mass	18.8 (\pm 7.9)	7.9 (\pm 3.1)	<0.001
Beaks	Mass	13.5 (\pm 4.5)	6.3 (\pm 2.8)	<0.001
Other food	Mass	5.4 (\pm 4.6)	1.7 (\pm 1.4)	<0.001
Non food	Mass	2.8 (\pm 2.9)	3.9 (\pm 6.3)	0.375
Entire bolus	Volume	44.6 (\pm 20.1)	63.1 (\pm 21.1)	0.003
All plastic	Volume	12.9 (\pm 12.1)	44.3 (\pm 18.6)	<0.001
Sheets	Volume	0.3 (\pm 0.4)	1.2 (\pm 0.7)	<0.001
Line	Volume	4.6 (\pm 3.9)	15.0 (\pm 9.5)	<0.001
Foam	Volume	3.0 (\pm 4.6)	22.4 (\pm 14.1)	<0.001
Fragment	Volume	5.0 (\pm 6.9)	5.6 (\pm 3.8)	0.714
All food	Volume	25.4 (\pm 10.9)	9.3 (\pm 4.0)	<0.001
Beaks	Volume	18.7 (\pm 6.5)	7.2 (\pm 3.7)	<0.001
Other food	Volume	6.8 (\pm 6.2)	2.1 (\pm 1.4)	0.001
Non food	Volume	3.8 (\pm 3.8)	5.8 (\pm 8.5)	0.289

Table 6. 2-way ANOVA results for relationships between Laysan albatross (LAAL) in 2009 on Tern Island and Kure Atoll. Shown are the mass (g) and volume (ml) of each bolus category.

Category	Metric	2009		Significance (<i>p</i>)
		Tern LAAL mean (\pm SD)	Kure LAAL mean (\pm SD)	
Entire bolus	Mass	17.3 (\pm 11.7)	40.4 (\pm 11.2)	<0.001
All plastic	Mass	5.9 (\pm 4.2)	21.5 (\pm 10.8)	<0.001
Sheets	Mass	0.2 (\pm 0.2)	0.1 (\pm 0.3)	0.138
Line	Mass	4.3 (\pm 3.3)	0.7 (\pm 1.4)	<0.001
Foam	Mass	0.3 (\pm 0.6)	1.3 (\pm 1.3)	0.002
Fragment	Mass	0.9 (\pm 0.8)	19.4 (\pm 11.6)	<0.001
All food	Mass	9.6 (\pm 6.9)	8.8 (\pm 6.2)	0.671
Beaks	Mass	6.1 (\pm 3.9)	8.3 (\pm 6.2)	0.143
Other food	Mass	3.5 (\pm 4.1)	0.5 (\pm 0.5)	0.001
Non food	Mass	0.6 (\pm 1.0)	7.1 (\pm 6.9)	<0.001
Entire bolus	Volume	23.4 (\pm 15.8)	51.3 (\pm 12.7)	<0.001
All plastic	Volume	8.6 (\pm 5.9)	27.1 (\pm 12.0)	<0.001
Sheets	Volume	0.4 (\pm 0.4)	0.2 (\pm 0.6)	0.086
Line	Volume	5.6 (\pm 4.3)	0.9 (\pm 1.7)	<0.001
Foam	Volume	1.2 (\pm 2.3)	3.8 (\pm 4.9)	0.022
Fragment	Volume	1.4 (\pm 0.9)	22.1 (\pm 12.9)	<0.001
All food	Volume	12.6 (\pm 9.5)	10.4 (\pm 7.2)	0.352
Beaks	Volume	8.260 (\pm 5.763)	9.660 (\pm 7.160)	0.45
Other food	Volume	4.348 (\pm 5.122)	0.716 (\pm 0.744)	0.001
Non food	Volume	0.976 (\pm 1.429)	10.880 (\pm 10.867)	<0.001

Chapter 4:

Conclusions

While plastic debris is present in ever increasing amounts in the marine environment, determining the amounts, types and sources has proven a difficult task. Thus, researchers and wildlife managers are relying on a variety of methods to determine when and where to sample this material, both at sea, on shorelines and amidst the stomach contents of marine predators (e.g., Ryan et al., 2009). While the two research studies of this project have focused on different methods to quantify marine debris, they both further our understanding of marine debris patterns in the North Pacific Ocean. It is the goal of this chapter to summarize my results, provide management implications of this work and to provide some recommendations for future application of these methods and studies.

There are many advantages to using visual methods to survey marine debris at sea. Namely, the standardized line transect methods presented here allow for the confident quantification of marine debris while the ship is in transit. Additionally, because this method does not require sophisticated equipment or dedicated ship time, it can be easily transferred to other platforms of opportunity. Another advantage of visual survey methods is the coverage of the marine debris size classes it provides, which complements other marine debris survey methods. While surveys such as this one cannot be directly compared to previous net tow studies of this area, they provide data on the macro and mega debris which net tows cannot sample. Moving forward it would be beneficial to calibrate and integrate the results of net tows and visual surveys to obtain a record of the entire marine debris field.

While the large scale distribution and increasing aggregation of marine debris centered around the high pressure center in the North Pacific Subtropical Gyre (NPSG) has been extensively documented (Day and Shaw, 1987; Moore et al., 2001), this research highlights the smaller scale variability present within this ‘garbage patch’ aggregation. Furthermore, the lack of significant associations between marine debris abundance and environmental variables (such as sea surface temperature and wind speed) at the hourly scale suggests that other physical processes must be responsible for these smaller-scale aggregations. Either weak currents or internal waves may be creating small areas of surface convergence within this low wind area, which could be, in turn, aggregating the floating debris. Alternatively because of the absence of strong winds and currents in this area, large items that have become trapped may be breaking into smaller ‘offspring’ fragments that do not drift away and get separated from the ‘parent’ item. Thus, this mechanical degradation process may be causing the observed patchiness.

While many studies have examined marine debris aggregation in the North Pacific, and much interest by the popular press has been focused on the ‘garbage patch’, there is still a lack of information on both the extent and scale of this marine debris field. Future cruises are needed to traverse the North Pacific in order to better describe the marine debris field. Because of the vast area which needs to be covered to comprehensively survey this area, it is likely that visual survey methods will be vital for achieving this objective. As long as the proper sampling protocol is followed, and biases amongst survey platforms and observers are accounted for, these methods can be used on any ship of opportunity that may be crossing the Pacific. In turn, additional mapping of debris aggregation areas can help to describe the inter-annual and seasonal variation in the marine debris field. These are critical first steps for developing marine debris trends.

Another useful method for sampling marine debris is to study the plastic ingested by marine predators. In particular, seabirds from many different families, across different foraging methods and wide oceanic ranges ingest plastic at sea. Yet, to validate this approach, information on the at-sea distribution and overlap of seabirds and marine debris is essential. This was the first study to quantify marine debris and seabird distributions concurrently, and to analyze both using the same community-level analysis.

As expected, the majority of seabirds were found in the productive continental shelves, and away from the main concentration of marine debris. However a spike in marine debris density was observed around the Transition Zone Chlorophyll Front, which could make marine debris surface concentrations available for ingestion by the seabirds that forage in this productive oceanographic feature. This front, located within the larger transition zone, contains an eastward moving current that would transport the debris from the western Pacific Ocean (Kubota, 1994). This frontal system is known to aggregate debris (Pichel et al., 2007) and is important for far-ranging oceanic predators (Polovina et al., 2001). Thus, this could be an important feature for making surface marine debris available to foraging seabirds, whenever it overlaps with their foraging range.

Over the largest area of plastic accumulation within the NPSG, only a few far ranging seabird species were found. The Red-billed Tropicbird, while found in the same area as the marine debris, shows only low levels of plastic ingestion in other studies (Sileo et al., 1990a). The Cook's Petrel was also found in this area, and while this species is restricted to waters around its breeding grounds in New Zealand during the breeding season (Rayner et al., 2008), this small (200 g) gadfly petrel undergoes trans-Pacific migrations to the productive coasts of Mexico and California during the austral winter (Bartle et al., 1990). While there is limited information on

plastic ingestion by this petrel (Imber, 1996), its trans-equatorial migration path across the Pacific Ocean and its presence in areas of high marine debris abundance suggest that further investigation into this species is warranted. The Black-footed Albatross is a species well known to ingest plastic debris (Sileo et al., 1990b; Kinan and Cousins, 2000) and was also prominently found over our survey area including the area of high debris concentration. Like the Cook's Petrel, the Black-footed Albatross traverses the Subtropical Gyre to feed in the productive shelf regions of California (Hyrenbach et al., 2002). Thus, although this area contains the highest concentration of debris, it may not be the source of the material ingested by the albatross.

Seabirds are also ideal samplers of marine debris because their populations aggregate into easily accessible large colonies during the breeding season. Using these colonies, researchers can study their diet, movements, and plastic ingestion using samples that have been collected from large ocean ranges. This study relied on samples from breeding colonies to investigate plastic ingestion by two far-ranging North Pacific albatross species.

This study of albatross boluses used standardized approaches to accurately quantify both the mass and volume of material ingested by albatross chicks. This study has shown that mass and volume generally follow a linear relationship and so time intensive volume measurements could be inferred from mass measurements. This relationship is important because volume measurements may in some cases describe the ingested material better than mass measurements can. For example, the low density of foam means that it takes up more volume than the mass measurements would suggest. Additionally, from a biological point of view, the amount of room that ingested material takes up in the stomach irrespective of the mass of material is likely more important in explaining whether low stomach volume availability contributes to dehydration and death in albatross chicks (Sileo et al., 1990b; Sievert and Sileo, 1993).

Due to the large amount and variety of plastic ingested by the Black-footed and Laysan albatross, quantifying the spatial and temporal variability in the amounts and types of ingested material is critical to validate their potential use as biological sensors of pelagic plastic. Because the Hawaiian Islands are spread over 2,400 km, variability in plastic ingestion due to restricted foraging range in the incubation and chick-guard stages of the breeding season were expected (Young et al., 2009). Additionally, differences in plastic ingestion were also expected due to the species level disparities in diet and foraging distribution (Harrison et al., 1983; Hyrenbach et al., 2002).

While this study of albatross boluses did find differences in the amount of plastic ingested on different colonies, with more ingested plastic present on Kure Atoll than Tern Island, the most relevant results are the differences between the two species, and how the composition of the ingested material changes by colony. The colony specific species differences in plastic amounts and type are important as they will influence the effective monitoring of marine debris using albatross boluses. The composition of boluses indicated much higher proportion of plastic within Kure Atoll bolus at over 50% while Tern Island boluses only contained 26-35% plastic. On Kure Atoll, Black-footed Albatross boluses were predominantly containing sheets, line and foam while Laysan Albatross boluses mostly contained hard plastic fragments. On Tern Island however, these same trends did not hold true as Black-footed Albatross boluses mostly contained hard fragments and foam, while Laysan Albatross boluses predominantly contained line but also more sheets than their Black-footed Albatross counterpart. This result indicates that the type of plastic being ingested by these albatross is not only a product of different foraging strategies and prey species, but also likely a result of the differential availability of plastic types in their distinct

foraging areas. Thus, while these two species have large basin-wide distributions in the non-breeding season, their restricted foraging ranges during the breeding season expose birds from different species and colonies to distinct marine debris compositions.

Together, these results highlight the need to consider multiple colonies when trying to quantify plastic ingestion and marine debris composition at sea, in the North Pacific Ocean. Midway Atoll is the easiest Northwestern Hawaiian Islands colony to reach with regular flights, and contains the bulk of the breeding population of both albatross species. Thus, this is the location where most studies of plastic ingestion have focused in the past. While studying the dynamics at Midway Atoll is important when considering population-level effects of plastic ingestion, the plastic variability demonstrated in this study shows that from a management perspective, multiple colonies must be considered to get a complete picture of the plastic ingestion issue. In this study, only two locations were examined, both within the Northwestern Hawaiian Islands. Moving forward, it is important to document plastic ingestion levels and composition at other breeding colonies in Hawaii, particularly on colonies that are close to each other. Midway Atoll and Kure Atoll are only 90 km away from each other and it would be useful to know if these two colonies show similar signatures between species, in which case they could be combined for future analysis and only one of these colonies would need to be considered. Likewise, the Laysan Albatross colonies at Kaena Point on Oahu and Kilauea Point on Kauai should be compared to determine if they can be merged for analysis, to yield larger sample sizes. In order to further understand the processes underlying plastic ingestion in albatrosses, it is necessary to match the plastic recovered from diet samples and chick boluses with tracking of adults to identify their potential feeding areas. Additionally, research cruises across these different areas in the North Pacific Ocean would be able to document differences in the plastic

debris field which could help explain the observed albatross plastic ingestion patterns. The visual methods put forward to survey macro and mega marine debris at sea can be used from ships of opportunity by themselves, or in concert with net tows to get a complete picture of marine debris distributions. Together, this information will build the knowledge base required to monitor the extent and scale of marine debris in the North Pacific Ocean.

The two chapters of my thesis have focused on the sampling and study of marine debris in different, yet complementary ways: the study of the overlap of available marine debris with seabird species distributions at sea, and the quantification of the patterns in the amount and type of debris ingested by albatross breeding in Hawaii. I hope that this work can inform future research directions and practices for managing potential threats to albatross and other seabirds from ingested plastic.

Literature Cited

- Bartle, J.A., Hu, D., Stahl, J.C., Pyle, P., Simons, T.R., Woodby, D., 1990. Status and ecology of gadfly petrels in the temperate north Pacific. In: Vermeer, K., Briggs, K.T., Morgan, K.H., Siegel-Causey, D., (Eds.). The status, ecology, and conservation of marine birds of the North Pacific. Canadian Wildlife Service Special Publication, Ottawa, p 101–111.
- Day, R.H., Shaw, D.G., 1987. Patterns in the abundance of pelagic plastic and tar in the North Pacific Ocean, 1976-1985. *Marine Pollution Bulletin* 18, 311-316.
- Harrison, C.S., Higa, T.S., Seki, M.P., 1983. Hawaiian seabird feeding ecology. *Wildlife Monographs* 85, 1-71.
- Hyrenbach, K.D., Fernández, P., Anderson, D.J., 2002. Oceanographic habitats of two sympatric North Pacific albatross during the breeding season. *Marine Ecology-Progress Series* 233, 283-301.
- Imber, M.J., 1996. The food of Cook's petrel *Pterodroma cookii* during its breeding season on Little Barrier Island, New Zealand. *Emu* 96, 189-194.
- Kinan, I.T., Cousins, K.L., 2000. Abundance of plastic debris and ingestion by albatross on Kure Atoll, Northwestern Hawaiian Islands. Second International Conference on the Biology and Conservation of Albatrosses and other Petrels, Waikiki, Hawaii.
- Kubota, M., 1994. A mechanism for the accumulation of floating marine debris north of Hawaii. *Journal of Physical Oceanography* 24, 1059-1064.
- Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A comparison of plastic and plankton in the North Pacific Central Gyre. *Marine Pollution Bulletin* 42, 1297-1300.
- Pichel, W.G., Churnside, J.H., Veenstra, T.S., Foley, D.G., Friedman, K.S., Brainard, R.E., Nicoll, J.B., Zheng, Q., Clemente-Colon, P., 2007. Marine debris collects within the North Pacific Subtropical Convergence Zone. *Marine Pollution Bulletin* 54, 1207-1211.
- Polovina, J.J., Howell, E., Kobayashi, D.R., Seki, M.P., 2001. The Transition Zone Chlorophyll Front, a dynamic global feature defining migration and forage habitat for marine resources. *Progress in Oceanography* 49, 469-483.
- Rayner, M.J., Hauber, M.E., Clout, M.N., Seldon, D.S., Van Dijken, S., Bury, S., Phillips, R.A., 2008. Foraging ecology of the Cook's petrel *Pterodroma cookii* during the austral breeding season. *Marine Ecology-Progress Series* 370, 271-284.
- Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. *Philosophical Transactions of the Royal Society B* 364, 1999-2012.

- Sievert, P.R., Sileo, L., 1993. The effect of ingested plastic on growth and survival of albatross chicks. In: Vermeer, K., Briggs, K.T., Morgan, K.H., Siegel-Causey, D., (Eds.). The status, ecology, and conservation of marine birds of the North Pacific. Canadian Wildlife Service Special Publication, Ottawa, p 212-217.
- Sileo, L., Sievert, P.R., Samuel, M.D., Fefer, S.I., 1990a. Prevalence and characteristics of plastics ingested by Hawaiian seabirds. In: Shomura, R.S., Godfrey, M.L., (Eds.). Second International Conference on Marine Debris. NOAA Technical Memo., Honolulu, Hawaii.
- Sileo, L., Sievert, P.R., Samuel, M.D., 1990b. Causes of mortality of albatross chicks at Midway Atoll. *Journal of Wildlife Disease* 26, 329-338.
- Young, L.C., Vanderlip, C., Duffy, D.C., Afanasyev, V., Shaffer, S.A., 2009. Bringing home the trash: do colony based differences in foraging distribution lead to increased plastic ingestion in Laysan albatrosses? *PLoS ONE* 4(10): e7623.