Interactions of Marine Debris with Selected Seabird Species of Eastern Australia and the Application of an Ecological Risk Matrix

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Thesis Submitted to Fulfil the Requirements for PhD at Central Queensland University

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8 April 2016

Certificate of Authorship and Originality of Thesis

Thesis submitted by Krista Mara Verlis in fulfilment of the requirements for the Doctor of Philosophy in the School of Medical and Applied Sciences, CQ University, Australia.

The work contained in this thesis has not been previously submitted either in whole or in part for a degree at CQUniversity or any other tertiary institution. To the best of my knowledge and belief, the material presented in this thesis is original except where due reference is made in text.

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Abstract

Marine debris is a major persistent pollutant of oceans worldwide, with far reaching effects on the inhabitants and users of the marine environment. Marine plastic pollution is recognised as a key threatening process in Australia because of the harm it can cause wildlife through ingestion and entanglement (Chapter 1). More than 56 % of seabird species globally have been impacted by marine debris, but little is known about marine debris interactions in East Australian seabirds. The southern Great Barrier Reef (GBR) supports a high percentage of breeding and nesting seabirds, however no research existed on the interactions of marine debris with wildlife in this ecologically important area. This project was the first to examine the prevalence of marine debris on southern GBR beaches, and the first to examine marine debris interactions with two seabird species, the wedge-tailed shearwater (*Ardenna pacifica*) and the brown booby (*Sula leucogaster*). A risk matrix for marine debris interactions was applied to help inform decision makers about this pollution threat. The utility of the created risk matrix is that it can be expanded to other organisms or regions within Australia.

The prevalence of marine debris within offshore sites in the southern GBR (Capricorn-Bunker Group of islands) was examined, and compared to levels of marine debris on near-shore beaches (Sunshine Coast, Queensland, and Coffs Coast, New South Wales) (Chapter 2). Near-shore sites had double the amount of debris items (0.08 m^{-2}) than offshore (0.04 m^{-2}) sites, with significantly higher rates of accumulation near-shore than offshore ($U = 0.000$, $p = 0.050$). Levels of debris increased between the first and second sampling periods at near-shore beaches only, indicating the possible influence of environmental conditions on the deposition and exhumation of debris items. More sampling is needed to confirm this trend. A Marine Debris Pollution Index

was developed to aid in monitoring debris pollution at surveyed sites based on mean amounts and size of collected debris items.

Off/white-clear coloured debris items dominated survey collections (39 % near-shore; 31% offshore). Hard plastic items were the most prevalent debris type at both near-shore and offshore sites (56 % and 42 %, respectively). Some differences in debris type existed between near and offshore beaches, for instance more fibrous plastic and sheet plastic were recovered at near-shore sites, and these differences were attributed to source influences. For example, near-shore sites were more heavily influenced by land-based sources of pollution ($F_{[2,60]}$ = 546.811, p = 0.021).

Plastic ingestion was studied in wedge-tailed shearwaters (Chapter 3) at offshore GBR sites and near-shore locations in southern QLD and northern NSW that were also surveyed for beach marine debris (Chapter 2). Overall on average ~13 % of late-stage wedge-tailed shearwater chicks had been fed marine debris plastic over two survey seasons with these birds most often ingesting off/white-clear coloured plastics (~40 %). Interestingly, significant differences existed between debris colour and material type on surveyed beaches compared to that fed to chicks nesting offshore suggesting a selective feeding pattern on these plastics. This trend was not apparent in late-stage chicks nesting at near-shore sites. Ingestion appeared to be more frequent in near-shore birds (~17 %), although this was not a significant pattern ($F_{[1, 11]}$ = 4.792, p = 0.065). While, the number of ingested plastic pieces per bird was significantly higher offshore (U = 40.000, p = 0.032). Marine debris ingestion did not appear to have a negative interaction on the health of surveyed late-stage chicks as indicated by their body condition (U = 1091.00, p = 0.204).

Marine debris from oceanic sources was common in the nests of brown boobies with over one-third containing this anthropogenic material (Chapter 4). Using a novel photographic technique developed for surveying the nest material of this species, differences in levels of nest marine debris items were determined. The outcomes of this technique detected that the Swain Reefs nests were considerably more contaminated (58 %) than Capricorn-Bunker nests (11 %). Hard plastic debris dominated Swain Reefs anthropogenic nest material (82 %) and beach debris (77 %) at all surveyed locations. There was a higher prevalence in nests for blue-purple coloured plastic items in Swains and Fairfax nests (28 % and 29 %, respectively). Specific debris items were chosen by brown boobies for use within nests, limiting the use of nests as a substitute for beach surveys as an indicator of environmental debris levels. The use of marine debris within the nest material of brown boobies did not appear to negatively affect the brown boobies during the sampled periods, with no birds found entangled.

A new risk matrix developed by modifying the IMO matrix (IMO, 2014) was applied to determine the level of risk marine debris posed to a region (Chapter 5). The marine debris beach survey data and seabird interaction data gathered from this research was applied to the risk matrix as a proof of concept demonstration. A traffic light colouring was used with the matrix based on marine debris interactions and amounts in in the environment. The results of the applied risk matrix from this study were 'green' and 'yellow' for seabirds in the southern GBR and nesting locations on the East Australian coastline. The yellow designation given to birds at Heron Island and those nesting in the Swain Reefs is at a tolerable risk level, but calls for actions to be taken to reduce marine debris levels when possible. The green designation given to birds at Northwest Island and Muttonbird Island, represent a more broadly acceptable risk level that requires monitoring and should be reduced further when practical. Further data is needed (i.e. more birds sampled) to provide a more accurate understanding of the risk to seabirds in the surveyed areas however.

Recommendations from this research include the need for continued monitoring of marine debris levels (and interactions) on Australian beaches to address this issue; to ascertain the effectiveness of any preventative measures; and to gauge the continued performance of current legislation aimed at mitigating or ameliorating the marine debris problem. Management strategies targeted at the marine debris issue in south-east Australia could be strengthened through enforcement of current legislation. This is especially important as increased ship traffic is anticipated throughout the region and shipping debris has been shown to be one of the common sources of marine debris in the surveyed areas.

This thesis aimed to provide a baseline on the current presence and interactions of marine debris with two seabird species common to this ecologically important area. A number of new and novel tools were developed to undertake this monitoring and can be used by others to help best inform upon this pollution threat. The data collected and presented herein will provide new insights that will aid both the management of seabirds in this region and to improve the management of marine debris.

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Acknowledgements

Thank you to those organisations that generously provided grants to my project, **Birds Queensland**, **Birdlife Australia Stuart Leslie Bird Research Award**, and the **Wildlife Preservation Society of Queensland**. Thank you to CQUniversity that provided me a Strategic Research Scholarship for my initial three-years, and the granting of high-cost student funding. This research was undertaken under CQU animal ethics approval A11/09-276 and permits QC11/045, WITK10514111, NCPI03548412, and SL101053.

Thank you to my supervisors Dr Scott Wilson and Prof Marine Campbell and to Prof Owen Nevin for their support and advice throughout my PhD experience.

Thank you to Queensland Parks and Wildlife Service crew for supporting my research by facilitating access to the Swain Reefs, for their assistance with debris surveys and for introducing me to the wonders of the GBR.

Thank you to Dr Rebecca Hendry, Dr Wayne Boyd and Dr Emma Jackson for the map assistance, generally fielding questions, and for the support and encouragement. A HUGE thank you to Ms Paola Rodriguez-Salinas, Ms Audrey Cartraud, Ms Sarah Elmeligi, Mr Kevin Erickson, Ms Kirstie Walker, Mr Russell Stewart, Bruce Stewart, Mrs Kirsty Small, The Small Family, the Felice family, Ms Jessica Fairall, Ms Chloe Boulard, Ms Kobi Ringuet, Ms Maud Mace, Ms Ashleigh Felice, Ms Jessica Scannell, Ms Tania Rodriguez-Salinas, Ms Hannah Wilson, Ms Lauren Aitkenhead, Dr Khurshida Siddiqua, Ms Zoe Laurent, Mr Mike Davison, Percy Wilson, and the Walker family for all the friendship and support in the field and/or living life in Gladstone. A big thank you to my Canadians, especially, Mrs Lisa-Dawn Brooks and my best friend, Mrs Tracie Greenberg-Gurman for all the love and support you have given me.

Thank you to my parents, Mara and John Verlis, for their unconditional love and support. Thank you to my brothers and sisters, niece and nephew: Pickles and Mordechai, Matthew, Lily and Isabelle, Andrejs, Erin and Lucas for the love and understanding over these past (now) four plus years. Thank you to my Aunts and Uncles: Ausma and Dougal; Ilga and Ojars; Mara and Andy; Vilis; and John and Pat, for the support. To my adopted Australian relatives, Don and Bev Swanton, Franklin was the most amazing gift I have been given, it truly changed my life.

List of Publications and Presentations Resulting from this Research

A number of peer-reviewed publications have resulted from this thesis, in addition to presentations at both national and international conferences. In all instances, I was the senior author and took primary responsibility for the development of research questions, research design, methods, and analysis, and the writing of all co-authored papers and presentations. For all co-authored publications, my co-author and primary supervisor, Dr Scott Wilson, contributed to the chapter through the development of ideas, research questions, methods and subsequent analysis. My co-author and secondary supervisor Prof Marnie Campbell contributed ideas on research methods. Both co-authors contributed edits and comments on the final manuscript.

Chapter 3 – Appendix A:

Verlis, K.M., Campbell, M.L. and Wilson, S.P. (2014). Marine debris is selected as nesting material by the Brown Booby (*Sula leucogaster*) within the Swain Reefs, Great Barrier Reef, Australia. *Marine Pollution Bulletin, 87*, 180-190.

Chapter 4 – Appendix B:

Verlis, K.M., Campbell, M.L. and Wilson, S.P. (2013). Ingestion of marine debris plastic by the wedge-tailed shearwater *Ardenna pacifica* in the Great Barrier Reef, Australia. *Marine Pollution Bulletin, 72*, 244-249.

Conference Presentations

Verlis, K.M., Wilson, S.P., Matthews, B. and Campbell, M.L. (2014). Seabirds and marine debris of the Great Barrier Reef, Australia. *Ocean Science Meeting*, Honolulu, HI, USA, February, 2014.

Verlis, K.M., Campbell, M.L. and Wilson, S.P. (2013). Chemical contaminants in seabirds and ingested plastic as vectors. *Society of Environmental Toxicology and Chemistry*, Melbourne, VIC., October, 2013.

Verlis, K.M., Campbell, M.L. and Wilson, S.P. (2012). What are we doing to our seabirds? How Australasian seabirds on the Great Barrier are being impacted by marine debris. *AMSA-NZMSS*, Hobart, TAS.

CHAPTER 1

Marine Debris: a Modern Contaminant, a Global Issue

1.1 Why Marine Debris is an Issue

Marine debris is one of the main threats facing oceans worldwide (UNEP, 2005) and is listed as a Key Threatening Process (KTP) by the Australian Commonwealth Government under the *Environmental Protection Biodiversity Conservation (EPBC) Act 1999* (DEWHA, 2009). There are a number of different definitions of marine debris, some of which are ensconced in legislation. The 'harmful' marine debris definition given in the Australian EPBC Act is not used in this thesis due to the limitations of not including items such as glass, paper, metal and crockery, that are permitted to be expelled over the side of the boat if more than 12 nm from land. As these items have the potential to be transported within and around the marine environment and can still cause harm to marine life (SCBD and STAP-GEF, 2012), this definition was not appropriate. In this thesis, I have used the following definition for marine debris, as it is one of the most commonly referred to definitions in the literature and is used by the United Nations Environmental Programme (UNEP):

> "A*ny persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment. Marine debris consists of items that have been made or used by people and [are] deliberately discarded into the sea or rivers or on beaches; brought indirectly to the sea with rivers, sewage, storm water or wind; or accidentally lost, including material lost at sea in bad weather" (Galgani, et al., 2010, p1).*

Marine debris is a multi-faceted issue that is continuing to increase in scope and severity. It can have far reaching repercussions on the marine and coastal environment, as well as impacts to the economy of a region, to human health, and to wildlife, including seabirds (Dixon and Dixon, 1986; Wiber, 1987; Redford, et al., 1997; Santos, et al., 2005; Arafat, et al., 2007; Sheavly and Register, 2007). A number of factors have influenced the increased occurrence of marine debris on beaches, including the mass-production and use of durable, long-lasting synthetic products, such as plastics (National Research Council, 1995; Redford, et al., 1997; UNEP, 2005; Sheavly, 2010) and long-held views of the ocean as being an easy receptacle for garbage (Laist, 1987; Karau, 1992; Butt, 2009). Despite global regulation to control the inputs of waste into the marine environment, marine debris persists and in some areas levels continue to increase (Lentz, 1987; Coe and Rogers, 1997; STAP, 2011). Over 152 parties or member states are signatories to MARPOL 73/78 representing 99 % of the world's registered shipping tonnage (IMO, 2013). However, the effectiveness of this legislation is dependent on its adoption, interpretation and enforcement at a national jurisdictional level (Coe and Rogers, 1997).

Increasing human populations and urbanization especially near coastal areas (Coe, 2000; Santos, et al., 2009), insufficient waste management strategies both on land and at sea (Gregory, 1990; Liffman and Boogaerts, 1997), and a lack of awareness or willingness of and by the public to address their role in pollution also contribute to the marine debris issue (Ten Brink, et al., 2009; GPA, 2011b). Often there are inadequate financial resources and/or technology to address different levels of this issue (i.e. especially in developing nations with insufficient infrastructure and disposal mechanisms) and a lack of enforcement of legislation that is already in place to deal with marine pollution (Coe, 2000; Ten Brink, et al., 2009; GPA, 2011b). The interconnectedness of the oceans and the ability of debris to be carried vast distances away from its point of origin (Leous and Parry, 2005; Maximenko, et al., 2012) make the issue of marine debris truly global in scope, with debris found in every ocean and on beaches of every continent (Carpenter and Smith, 1972; Gregory, 1977; Wiber, 1987; Redford, et al., 1997; UNEP, 2005; Barnes, et al., 2009).

1.2 General Threats to Humans Associated with Marine Debris

Marine debris has been shown to be hazardous to humans and their livelihoods. Terrestrial animals and humans can be harmed when medical, toxic chemical, or sewage-related waste washes ashore, and they may suffer cuts or abrasions from broken glass, or metal debris (Dixon and Dixon, 1981; Horsman, 1982; National Research Council, 1990; Wagner, 1990; Whiting, 1998; Sheavly and Register, 2007). Divers, snorkelers and swimmers can be harmed, or killed by debris that has sunk beneath the ocean surface (Pruter, 1987; Jones, 1995; Sheavly, 2005). Livelihoods can be impacted, especially when an area is reliant upon the tourism trade (Santos, et al., 2005; Ivar do Sol and Costa, 2007; Santos, et al., 2008). Tourism itself can also be the source of marine debris onto beaches from visiting beachgoers and potentially at levels that are more significant than that debris from stormwater or from oceanic sources (Oigman-Pszczol and Creed, 2007). As marine debris can also diminish the aesthetic and recreational value of an area, this necessitates money being spent on coastal clean-ups and on disposal (Santos, et al., 2005; Sheavly, 2005; Ebbesmeyer and Scigliano, 2009; Seino, et al., 2009).

Debris can pose a hazard to ships, their crew and passengers, through damage to steering and propulsion systems, clogging intake valves, and by collision with large items afloat in the sea. These types of impacts result in lost time, costly repairs and the potential for loss of life, especially if the impact occurs during the night (Talley, 2010), or during stormy seas (Coe and Rogers, 1997; Goldberg, 1997; Cho, 2005; Spengler and Costa, 2008). For example, a significant loss of life occurred in the Republic of Korea when an overcrowded public ferry capsized when discarded fishing gear wrapped around the propeller (Kiessling, 2003; Cho, 2005). Military fleets are also affected by marine debris. For example, in 2005 a Russian mini-submarine was entangled in abandoned netting some 191 m below the ocean surface (Leous and Parry, 2005).

Similarly, more than 675 shipping containers are estimated to be lost overboard every year (World Shipping Council, 2011). This figure does not account for catastrophic vessel loses, which can mean thousands of containers are lost into the sea (World Shipping Council, 2014). Fishing gear that is lost or discarded by commercial and recreational fishers can impact upon livelihoods and significantly reduce catches of commercially valuable fish and crab species; this is referred to as 'ghost fishing' (Jones, 1995; Brainard, et al., 2000; APEC, 2004; Watanabe, et al., 2004; Sheavly, 2005). These types of impacts can potentially undermine the long-term viability of carefully managed stocks (Cho, 2005). Examples of this exist in the Republic of Korea and in Thailand where reductions in fishery catches have led to ghost fishing being identified as a significant threat to livelihoods (Ten Brink, et al., 2009).

1.3 Impacts of Marine Debris on Wildlife and Ecosystem Health

Marine debris can cause physical damage and destruction of aquatic habitats, (Donohue, et al., 2001; Asoh, et al., 2004; Yoshikawa and Asoh, 2004; Wilkinson, 2008), thus posing a great threat to ecosystem health. Derelict fishing gear and large anthropogenic items can, for instance, physically destroy or smother coral, or unbalance the ecology of coral reefs (Kiessling, 2003; Asoh, et al., 2004; NOAA, 2008). The productivity of benthic communities and whole seabed ecosystems can be affected when debris settles to the seafloor by inhibiting gas exchange and by providing habitat to opportunistic organisms leading to changes in benthic biodiversity (Goldberg, 1997; Storrier and McGlashan, 2006; Johnston, et al., 2008; Gregory, 2009; Keller, et al., 2010). Intertidal organism behaviour can also be affected by debris deposition, for instance the increased presence of plastics has been shown to modify foraging behaviours in gastropods (Aloy, et al., 2011).

Non-indigenous marine species can biofoul natural materials and marine debris now provides a further substrate for these non-native species to hitchhike to new locations (Dixon and Dixon, 1981; Wiber, 1987; Carr, 1987; Gregory, 1999; Barnes, 2002; Sheavly, 2005; Lewis, et al., 2005; Gregory, 2009; Breves and Skinner, 2014); although ship hulls, ballast water and rigs still remain the more important facilitator of invasive species movement (Wanless, et al., 2010). Regardless, more than 150 multi-cellular species have been found associated with plastic debris (Barnes, 2002; STAP, 2011), with plastic potentially providing a preferential substrate, as indicated by timber and metal marine debris objects fouled to a much lesser extent (Widmer and Hennemann, 2010). Biofouling organisms include barnacles, molluscs, tube worms, hydroids, coralline algae, gastropods, ascidians, bryozoans, amphipods, and algae (Williams, et al., 2013; Breves and Skinner, 2014; Goldstein et al, 2014). An increased population of water striders (*Halobates sericeus*) in the North Pacific Tropical Gyre was the result of debris providing hard substrate for their egg laying (Goldstein, et al., 2012); and marine debris has been shown to spread the microalgae associated with red tides (Maso, et al., 2003). Events such as tsunamis can also provide substrate for species to raft upon. This is seen with the 2012 Japanese tsunami where associated debris rafted hydroids from Japan to North American waters (Choong and Calder, 2013). Marine debris items have the potential to transfer a wide range of organisms.

This transfer of organisms also extends to bacteria, and is another possible area of concern. Diverse microbial communities of bacteria have been identified on the surface of plastics (Lobelle and Cunliffe, 2011; Zettler, et al., 2013). Members of the *Vibrio* bacteria genus have been found growing preferentially on plastic debris (Zettler, 2013). If particular *Vibrio* strains are present and water quality conditions are poor disease could result. However, it is not yet known if bacteria populating debris could potentially cause disease in humans or animals (STAP, 2011; Zettler, et al., 2013), although the potential is there. For example, the potentially harmful coral pathogen *Halofolliculina* spp was recorded rafting on plastic marine debris (Goldstein, et al., 2014).

Marine debris can also pose a serious threat to marine animals through ingestion and entanglement (Fowler, 1987; Laist, 1987; Derraik, 2002; Moore, 2008; Ceccarelli, 2009; Gregory, 2009; Williams, et al., 2011). Globally, at least 663 different marine animal species have been impacted in this way (SCBD and STAP-GEF, 2012). This is a significant increase from the 1997 review that showed only 247 impacted species (Laist, 1997; Andrady, 2005), although part of this increase may be the result of improved awareness and observation of this threat. All known sea turtle species, 45 % of all marine mammal species, and 25 % of all seabird species are reported to be affected by either ingestion or entanglement in marine debris, with 80 % of impacts associated with plastic debris (Table 1.1; SCBD and STAP-GEF, 2012). In some studies, entanglement has been reported as causing more harm and/or death than ingestion (80 % for entanglements versus 5 % ingestion; SCBD and STAP-GEF, 2012). However, this may be related to entanglement being more readily recognised and reported, with ingestion only confirmed via regurgitation or necropsy.

Table 1.1: Number (and percentage) of species with records of entanglement and ingestion in marine debris and the total number of species identified worldwide*

		No. of species recorded as entangled			No. of species recorded as having ingested		
Taxa group	**Total no. of known species***	**Laist (1997)**	**SCBD and STAP-GEF (2012)**	**Gall and Thompson (2015)**	**Laist (1997)**	**SCBD and STAP-GEF (2012)**	**Gall and Thompson (2015)**
Marine Mammals	115	32 (28%)	52 (45 %)	52 (45 %)	26 (23 %)	30 (26 %)	30 (26 %)
Fish	16,754	34 (0.20%)	66 (0.39 %)	66 (0.39 %)	33 (0.20 %)	41 (0.24 %)	50 (0.30 %)
Seabirds	312	51 (16 %)	67 (21 %)	79 (25 %)	111 (36 %)	119 (38 %)	122 (39 %)
Sea Turtles	7	6 (86 %)	7 (100 %)	7 (100 %)	6 (8 %)	6 (86 %)	6 (86 %)

*Nb: Number of species from Ausubel, et al., 2010; In some instances, the numbers here may have under-reported species as this is a first census and many species are likely not recorded and/or discovered

Other organisms are also affected by entanglement and ingestion. For example, zooplankton species have been shown to indiscriminately ingest microplastics with unknown physiological outcomes and if pellets are contaminated with chemicals there is the potential for further negative outcomes (Moore, 2003, 2008; Andrady, 2004, 2005, 2011). This is of great concern as the health of both the marine food web and fisheries resources are dependent upon the primary producers and consumers such as autotrophic and algae zooplankton (Andrady, 2004, 2005). Furthermore, marine invertebrates such as lug worms, sea cucumbers, barnacles, and marine fish are known to ingest plastic particles (Teuten, et al., 2007; Graham and Thompson, 2009; Boerger, et al., 2010; Possatto, et al., 2011; Foekema, et al., 2013) and can be poisoned by toxic debris like cigarette butts (Slaughter, et al., 2011). These species can also act as a source of secondary ingestion of debris when consumed by a predator (Carpenter, et al., 1972; Blight and Burger, 1997; Moore, 2003). Other species that are known to be impacted by marine debris are summarised in Table 1.2.

Table 1.2: Species known to interact with marine debris through ingestion or entanglement

Species	Reference
Dolphins and whales	Ceccarelli, 2009; Jacobsen, et al., 2010; Denuncio, et al., 2011; Williams, et al., 2011
Dugong	Ceccarelli, 2009
Sea snakes	Udyawer, et al., 2013
Rays and sharks	Sazima, et al., 2002; Ceccarelli, 2009; Wegner and Cartamil, 2012
Pinnipeds	Lucas, 1992; Waluda and Staniland, 2013
Turtles	Fowler, 1985, 1987; Lucas, 1992; Laist, 1987, 1997; Jones, 1995; Eriksson and Burton, 2003; Williams, et al., 2011
Seabirds	Bourne and Imber, 1982; Furness, 1983; Conant, 1984; Brown, et al., 1986; Fry, et al., 1987; Ryan, 1987a; Slip, et al., 1990; Lucas, 1992; Ceccarelli, 2009; Schuyler, et al., 2012; Rodriguez, et al., 2013.

Figures that account for numbers of animals impacted by marine debris are likely underestimations, unless specific sampling has occurred, or data have been supplied from fisheries in the form of observer data. This is because only those animals mobile or buoyant enough to reach land, float, or that come to the attention of humans are accounted for within data sets (NOAA, 2008; Williams, et al., 2011); as severely impacted animals (i.e. from entanglement) would likely drown, or otherwise be concealed beneath the surface of the water once gas formed from degeneration of the corpse is dissipated. Detection is further complicated as not all wildlife is necropsied and/or the incidence of ingestion or entanglement recorded (Laist, 1987; Derraik, 2002; Ceccarelli, 2009; Gregory, 2009; Williams, et al., 2011).

As seabirds (and other marine animals) have the potential to interact with marine debris over a large geographic area, this makes the number of direct observations of interactions quite small. Additionally, without direct measures of death related to marine debris, it is difficult to discern the effect on whole populations from those deaths caused by other sources (Laist, 1987; 1997). It is suggested that the magnitude of the problem should be addressed through an analysis of the likelihood of an animal interacting with marine debris (i.e. via ingestion or entanglement) and examining trends in the populations of susceptible species (Laist, 1987). Understanding characteristics of the debris (i.e. amounts, types, distribution of debris) and behaviours of the birds can also help to inform on the likelihood of interactions occurring (Laist, 1987; 1997).

1.4 Movement, Distribution and Deposition of Debris

The nature of a debris item influences its dispersal and accumulation in the oceanic environment, and determines its fate and longevity by influencing the rate of biological and chemical decomposition (Dixon and Dixon, 1981; Andrady, 1990, 2004). Figure 1.1 illustrates the movement of marine debris through the environment.

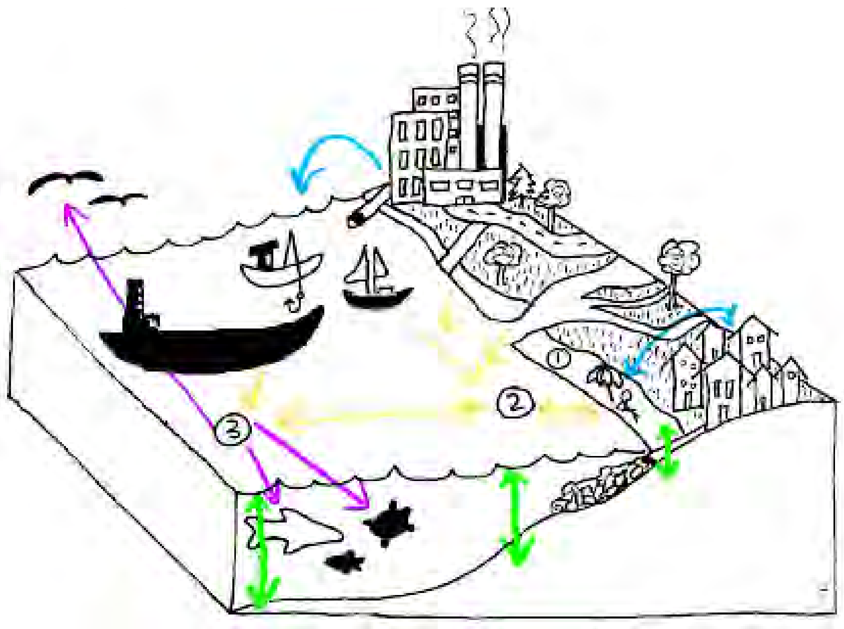


Figure 1.1: The main sources and pathways for plastic in the marine environment. (Modified from Ryan, et al., 2009). Debris items can be blown by the wind (blue arrows), transported through the water (yellow arrows), be buried in sediment, and be moved through the water column (green arrows). Ingestion of debris items may also occur by marine animals (purple arrows). All the while, debris objects are weathering and degrading within the environment (Carpenter and Smith, 1972; Gregory, 1977; Ryan, 1988; Sheavly and Register, 2007; Ryan, et al., 2009).

Seasonal effects on marine debris movement, deposition and accumulation are quite common (Pruter, 1987; Frost and Cullen 1997; Sheavly, 2010). Large storm events, such as monsoons, cyclones, heavy rain, flooding, and strong winds lead to increased amounts of debris being deposited upon beaches (Frost and Cullen, 1997; Cho, 2005; Seino, et al., 2009) and discharged into the sea from terrestrial sources. In northern Australia, large storm events and flooding are common in the summer months (the monsoon or 'wet' season), and are believed to be a source of pollution in these areas (Frost and Cullen, 1997). Annual weather patterns also influence deposition through human activities that occur on or near the marine environment. For example, beach-generated debris (Pruter, 1987; Frost and Cullen, 1997; Santos, et al., 2005; Cho, 2005) and recreational fishing activities often increase in warmer months (Slip and Burton, 1990; Huin and Croxall, 1996; Edyvane, et al., 2004). Inter-annual and seasonal variability in marine debris density and distribution is also thought to be influenced by El-Niño events that can drive changes in oceanic circulation patterns (Morishige, et al., 2007; Barnes, et al., 2009).

Furthermore, the deposition and accumulation of marine debris onto and across beaches (Taffs and Cullen, 2005; Eglinton, et al., 2006) can be influenced by:

- *Abundance of litter in adjacent coastal waters*:
    - Proximity to local land-based sources (e.g. proximity to rivers, poorly managed landfill, beach use, and urban development);
    - Offshore shipping and fishing activities;
    - Onshore recreational activities, fishing, and industrial facilities.
- *Beach dynamics*:
    - Substrate (cobbled and sandy beaches);
    - Beach aspect;
    - Onshore factors, such as rocky cliffs, dunes, and terrestrial vegetation;
    - Bathymetry;
    - Presence of offshore coral reefs and seagrass beds.

- *Oceanographic conditions*:
    - Increases in wave and wind energy;
    - Ocean circulation patterns;
    - Local offshore currents;
    - Tides;
- *Weather conditions* (heavy rain);
- *Characteristics of the debris*; and
- *Beach or ocean cleaning activities*

(Slip and Burton, 1991; Rees and Pond, 1995; Gregory, 1990; 1999; Williams and Tudor, 2001; Cheshire, et al., 2009; Ryan, et al., 2009; UNEP, 2009). As a result, different beaches and different sections of a beach accumulate debris at different rates (Taffs and Cullen, 2005; Eglinton, et al., 2006; Cheshire and Westphalen, 2007).

1.4.1 Sources and Quantities of Marine Debris

Recognition of the contribution of the different marine debris sources is needed to prevent and reduce pollution. Terrestrial- and maritime-based activities and actions are the main origins identified as creating marine debris, with an estimated 6.4 million tonnes of solid waste entering the marine environment from these sources annually (Leous and Parry, 2005; UNEP, 2005; GPA, 2011b). Some estimate that there are over 13,000 pieces of plastic debris floating on every square kilometre of ocean surface (UNEP, 2005), and in parts of the North Pacific Ocean plastic has been found to outnumber plankton 6:1 (Moore, et al., 2001).

The large majority (>80 %) of marine debris is theorised to have originated from land-based sources (Sheavly and Register, 2007; NOAA, 2008; Ten Brink, et al., 2009; US EPA, 2012), although the source of debris will vary widely depending on the geographical location of the site being surveyed and the nearest anthropogenic inputs

(Canadian Council of Ministers for the Environment, 1999). This is seen with many northern Australian beaches (an area which is sparsely populated) being more heavily impacted by fishing activities occurring offshore than by land-based pollution (Haynes, 1997; Whiting, 1998; White, 2006).

Understanding of the initial point of entry for marine debris is important for a variety of reasons. It allows for decisions to be made on prevention, reduction and control of marine debris and its associated problems (Sheavly, 2010). This empowers governments (at various levels) to address the issue through policy, regulation and in their expenditures addressing the different aspects of this pollution problem (Ten Brink, et al., 2009). It is envisaged that better management of this pollution issue will ultimately ensure that adequate funding is put towards addressing the problem, such as improvements to waste facilities and services, port facilities, education campaigns, and clean-up efforts (NOAA, 2008; Ten Brink, et al., 2009). Better management also provides for the recognition of the role of different stakeholders (e.g., manufacturing industry and other commercial entities such as merchant shipping companies) with regards to this problem. This can create pressure on these stakeholders to improve their practices and undertake measures to prevent pollution, improve their waste management protocols and facilities, and rethink packaging and equipment (Pruter, 1987; Sheavly and Register, 2007; Barnes, et al., 2009; Ryan, et al., 2009; Ten Brink, et al., 2009). For example, on commercial shipping vessels, supplying beverages in a keg instead of in individual cans or bottles could mean 30 % fewer cans are at risk of being disposed of at sea (Horsman, 1982). Measures both on land and at sea need to be considered to address marine debris pollution.

1.4.1.1 Land-Based Sources

Many terrestrial sources of marine debris have been identified and often start at street level (Table 1.3). For instance, the actions of people on land, sometimes large distances from any water body, can have a role in transmitting pollution into the marine environment (NOAA, 2008; Commonwealth of Australia, 2009; Ten Brink, et al., 2009). This close proximity of human populations and their activities to waterways increases the likelihood of waste entering into the marine environment. The majority of the world's population live within 60 km of the coast (Karau, 1992; Liffmann, et al., 1997), and as of June 2001 Australia had over 85 % of the population living within 50 km of the coast (ANZECC, 1996; Australian Bureau of Statistics, 1998; Australian Bureau of Statistics 2006) and migration to the coast expected to occur at a rate of 2 % per annum (Australian Bureau of Statistics, 2006). Since this time, more recent data has not been available. The potential for land-sourced pollution is increasing along with coastal populations.

Ports can be a considerable source of land based pollution (Table 1.3) as they have an important role in receiving and managing ship-generated wastes. Ports require adequate on-land facilities to deal with vessel garbage so that it cannot be released into the environment. Areas around ports and near-shore waters can be particularly sensitive to pollution as a result of low water exchange rates, presence of more complex ecosystems, and any resultant pollution being confined and potentially concentrated (National Oceans Office, 2001). A number of problems can be encountered with ports, but signatory nations of the *London Dumping Convention* and of *MARPOL 73/78 Annex V* are expected to provide adequate waste management facilities as part of their international obligations (Horsman, 1982; Olsen, 1994; Coe and Rogers, 1997; Ninaber, 1997). However, some South Pacific Island nations for instance, may be too small and/or not have the physical capacity to cope with their own domestic waste, in addition to those from international vessels (SPREP, 1999; Talouli, 2010). Additionally, not all South Pacific nations are signatories of *MARPOL 73/78 Annex V* (AMSA, 2014) and thus are not bound to these conventions (see Section 1.8).

Table 1.3: The main land-based sources of marine debris

Source	Reference
Effluent from municipal and industrial stormwater drains;	Goldberg, 1997; Cunningham and Wilson, 2003
Untreated sewage discharge (often associated with large storm events);	Goldberg, 1997; Cunningham and Wilson, 2003
Agricultural run-off;	Goldberg, 1997; Cunningham and Wilson, 2003
Industrial facility discharges;	Goldberg, 1997; Cunningham and Wilson, 2003
Rivers, streams, and estuaries transport from landfills and other sources;	Williams and Simmons, 1996; Cunningham and Wilson, 2003; Cho, 2009; Seino, et al., 2009
Catastrophic storm events such as tsunamis and cyclones;	NOAA, 2008
Municipal wastewater may contain a great deal of microplastic pollution from facial cleaners that contain polyethylene scrubber beads and synthetic clothes fibres;	Habib, et al., 1996 Fendall and Sewell, 2009 Browne, et al., 2011
Inadequately managed, or illegally operating garbage dumps, and other municipal waste sites;	Pruter, 1987; Frost and Cullen, 1997; Yoshikawa and Asoh 2004; NOAA, 2008; Ten Brink, et al., 2009
Insufficient recycling facilities or systems; garbage released into the environment when picked-up curb side, during transport, or from overflowing or improperly covered bins;	Pruter, 1987; Frost and Cullen, 1997; Yoshikawa and Asoh 2004; NOAA, 2008; Ten Brink, et al., 2009
Public beaches, waterfront areas, and fishing piers;	Gregory, 1990; Liffmann and Bogaerts, 1997; Liffmann, et al., 1997; ; Nollkaemper, 1997; Williams and Tudor, 2001; Sheavly and Register, 2007; Sheavly, 2010; Leous and Parry, 2005
Mismanaged industrial practices. For example, industrial plastic pellets lost during the manufacturing process, when loading, unloading, during transport, or through accidents;	vanFraneker, 1985; Wiber, 1987; Pruter, 1987; Redford, et al., 1997; Takada, et al., 2005; Sheavly, 2010; Ogata, et al., 2009; Barnes, et al., 2011
Improper use of pellets as ball-bearings to move heavy loads, or as insulation in cargo containers, and improper disposal into dumpsters;	Gregory, 1977;Pruter, 1987;; Wiber, 1987; Redford, et al., 1997; Gregory, 1999.
Land-based activities of both the shipping and fishing industries, such as at ports, shipbuilding and repair facilities, oil storage and bunkering facilities.	Coe, 2000; NOAA, 2008; Ten Brink, et al., 2009; Talouli, 2010

Ports may also require complex segregation of wastes to meet their legal obligations under *MARPOL* and other conventions, such as the *Basel Convention*, which governs movement and disposal of hazardous wastes (Basel Convention, 2011). This can have an impact on fees and the services offered by the port. The flow-on effect of this is the non-compliance by vessels (i.e., dumping of rubbish at sea) that may then occur (Olsen, 1994; Coe and Rogers, 1997; Ninaber, 1997). This had been seen in Caribbean nations that face problems related to competition to attract cruise liner tourists (Wade, 1997). Reduced waste management costs may also lower the conditions put upon cruise liners in regards to waste disposal, and may lead to contradictory pollution guidelines in relation to waste disposal at ports (Coe and Rogers, 1997; Ninaber, 1997).

Every year in Australia, more than 95 % of shipping traffic (by tonnage) is handled in just 20 of the 71 Australian ports (Ports Australia, 2014). More than 32,000 ports of call were made involving 4,875 different vessels in 2011-12, with 12,994 of these port calls involving 4,781 cargo ships originating from overseas ports (Commonwealth of Australia, 2013a). Compliance with proper disposal of waste is linked to the presence and location of waste disposal facilities, the infrastructure to deal with waste, and the perception of adequate waste management at ports by its users (Horseman, 1982; Jones, 1995; Frost and Cullen, 1997; UNEP, 2009). The proper facilities, governmental oversights, as well as community and stakeholder involvement are vital to prevent pollution into these coastal areas from this land-based source. Stronger enforcement and compliance with waste disposal legislation at all levels is needed, with a proactive response by ports to this issue. Regionally specific measures that involve government, community and businesses need to be developed to prevent and control marine debris from land-based sources (UNEP, 2009).

1.4.1.2 Sea-Based Sources

Oceanic sources of debris are those generated from the actions and activities of people at sea. This includes wastes and equipment disposed of from offshore oil and gas platforms and their associated exploration efforts, as well as aquaculture operations (NOAA, 2008; Ten Brink, et al, 2009; Table 1.4). In 2005, for example, there were 117 oil and gas platforms on the outer continental shelf of the United States that were damaged and/or lost to the environment (NOAA, 2008).

Table 1.4: Oceanic-based sources of marine debris

Source	Reference
Abandoned or derelict vessels	NOAA, 2008
Offshore materials and equipment, such as research buoys and cables (often damaged during bad weather events)	NOAA, 2008
Waste generated on-board, and the cargo and/or equipment that is either purposefully or accidentally lost from the multitude of ships at sea, including: • Yachts and pleasure crafts, • Research vessels, • Coastal and oceanic fishing boats, • Container and tanker merchant vessels, • Military vessels, • Cruise ships and ferries	Dixon and Dixon, 1981; Horseman, 1982; Andrady, 1990; Jones, 1995; Frost and Cullen, 1997; Whiting, 1998; VanFraneker and Meijboom, 2002; Kiessling, 2003; Nawadra, 2004; Leous and Parry, 2005; UNEP, 2005; NOAA, 2008; Ten Brink, et al., 2009
Aquaculture installations	NOAA, 2008; Wilkinson, 2008
Natural storm events and disasters, such as cyclones and tsunamis	NOAA, 2008; Wilkinson, 2008
Lost or discarded fishing gear from commercial or recreation fishers (*Ghost Fishing*)	Breen, et al., 1990; Jones, 1995; Brainard, et al., 2000; APEC, 2004; Watanabe, et al., 2004; Cho, 2005; Sheavly, 2005; Ten Brink, et al., 2009

Shipping provides the most environmentally sound and cost effective method for transporting goods worldwide (Butt, 2007), and has a critical role in the global economy, comprising 90 % of world trade by volume, and transporting some 5,400 million tonnes of cargo across the ocean every year via the more than 85,000 registered commercial vessels (National Oceans Office, 2001; Butt, 2007; Talouli, 2010). However, an estimated 6 to 6.5 million tonnes of solid material is discharged into the ocean from this fleet of vessels each year (Dixon and Dixon, 1981; Pruter, 1987), with 25 % of this waste originating from cruise ships (Butt, 2007). In Australian waters, approximately 13,800 tonnes of waste is thought to be generated by ships, with 4,000 tonnes of that being lost or discarded into the marine environment and 2,500 tonnes having originated from fishing vessels annually (ANZECC, 1996; Kiessling, 2005).

The composition of the vessel-originating discharge was found to be 98 % cargo-associated, and 2 % crew-generated (NAS, 1975, as cited in Pruter, 1987). This estimated proportion of plastic was much lower than that reported by Horsman (1982), who determined that 1.5 % of daily ship waste was plastic, representing 23,000 tons of plastic annually. The United States Navy determined that each person at sea generated 0.8 kg of garbage per day, with only 0.1 kg of that being plastic (National Research Council Committee on Shipborne Waste, 1995). However, these estimates likely underestimated the plastic discharge because a large proportion of ship-generated wastes are single-use plastic items like packaging which is notaccurately accounted for in discharge estimates (Horsman, 1982; Liffman and Boogaerts, 1997; Derraick, 2002; Rios, et al., 2007; Barnes, et al., 2009). As the levels of plastic production and use of plastic in everyday life increase, higher levels of plastic rubbish are to be expected. The amount of discharge from vessels can be significant if actions are not taken to manage on-board waste and cargo during transport, with items lost or discarded at sea having the potential to persist and be moved through the marine environment (Pruter, 1987; Moore, 2008; Barnes, et al., 2009; Gregory, 2009).

1.4.2 Ocean Dynamics

The main North Pacific convergence zone or gyre is located between Hawaii and California at roughly between 135°W to 155°W and 35°N and 42°N. It is often referred to as the 'Great Floating Garbage Patch' (Maximenko and Hafner, 2010) due to the vast amount of marine debris that accumulates there. These gyres consist of two accumulations (Western garbage patch) off of Japan and (Eastern garbage patch) between Hawaii and California, and are connected by a narrower band of debris north of the Hawaiian archipelago (Young, et al., 2009). Due to the dynamic nature of the gyres, estimates of its size are difficult to determine as it is constantly growing and moving, with the distribution and quantities of debris not well quantified (U.S. EPA, 2011). However, the patches are estimated to contain ~100 million tonnes of debris (Dautel, 2009). There are four other major oceanic gyres in the world (Figure 1.2).

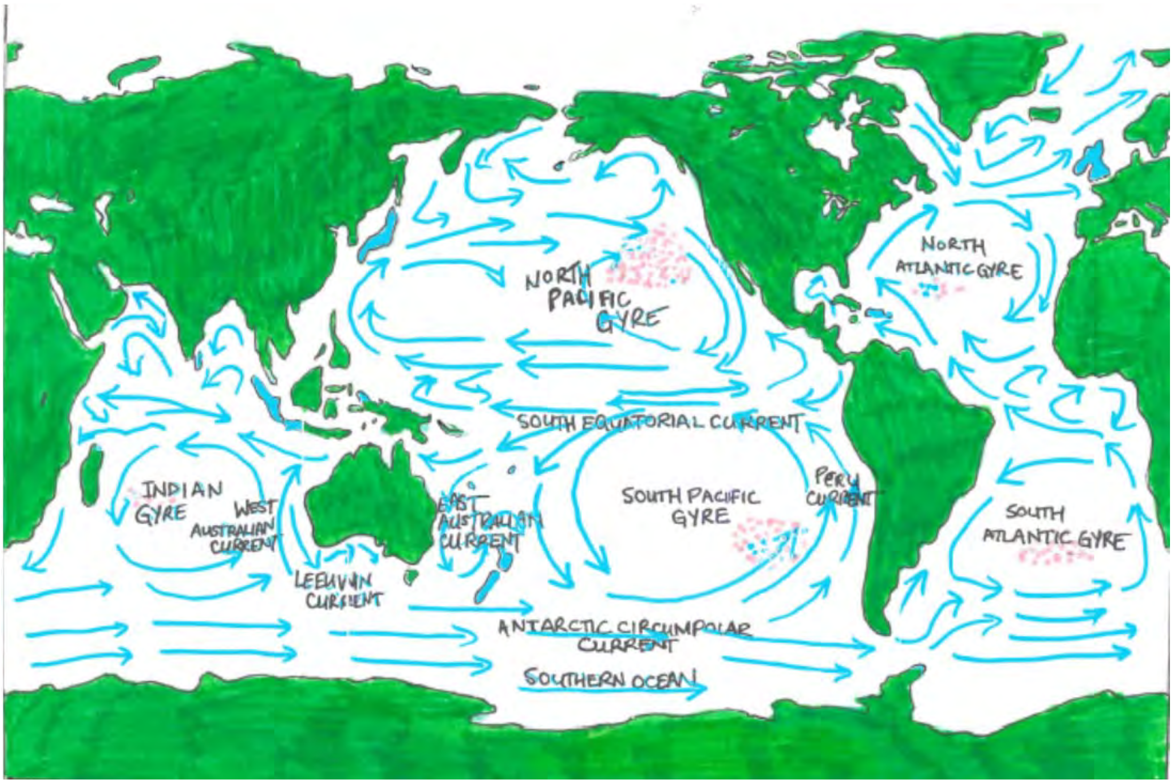


Figure 1.2: Location of the five major oceanic gyres (pink dots) and generalised surface currents (blue arrows). (Adapted from Maximenko and Niler, 2008; Seos, 2013)

In the South Pacific conditions exist that would suggest the presence of an even larger patch of garbage than that in the North. Eriksen, et al., (2013) confirmed the presence of this gyre in 2011, finding an average abundance of > 26,000 particles per km^2 in the South Pacific Gyre. This gyre has not being as noticeable as the North Pacific gyre and this is theorised to be as a result of less long-lived debris being produced in the Southern Hemisphere (Maximenko and Hafner, 2010). The surface waters of the South Pacific Ocean are generally accepted as having less pollution than the North Pacific Ocean, due to lower human populations and therefore fewer inputs (ANZECC, 1996; Gregory, 1999; Lewis, et al., 2005). This could also be a bias of the research however, with more intense research activity occurring in the northern versus the southern hemisphere, and thus accounting for the theorised smaller southern gyre. The East Australian Current (EAC), the Peru Current, South Equatorial Current and the

Antarctic Circumpolar Current act together to form the South Pacific Gyre (Figure 1.2; Suthers and Waite, 2007).

These various currents and linear oceanographic features can influence debris aggregation and movement, and can potentially transport debris long distances away from its source. In the South Pacific, the debris floating on the surface of the ocean is moved by a three-step drift mechanism. First, it is moved by Ekman drift into the tropical convergence zone between 20°S and 40°S, and is then transported east by the geostrophic currents, until it finally accumulates and remains in the eastern-central region of the subtropical gyre (Martinez, et al., 2009). Major oceanic fronts such as the Polar, Subantarctic, Subtropical and Tropical Fronts, and eddies from the East Australian Current can have an important influence on both distribution and abundance of debris. They may, for instance, act as barriers to stop the spread of materials, as well as acting to concentrate and carry items (Gregory, 1990). The Antarctic Convergence may act as a loose barrier to floating debris originating from the north, with the northward movement of ice in the Antarctic clearing debris that may be present on the sea surface (Ainley, Fraser and Spear, 1990). Along the equator is an area of divergence and upwelling and this has been shown to push debris to higher latitudes (Maximenko and Hafner, 2010).

Within Australia there are three major oceanic boundary currents: the Leeuwin Current (along the west coast), the East Australian Current (EAC) which is the largest down the east coast of Australia; and the Antarctic Circumpolar Current (Figure 1.2). Seasonality, strength and the southward extension of these currents are highly variable and their flow can influence coastal and oceanic conditions, productivity of coastal waters, as well as affect the distribution and movement of marine debris (Bowen, et al., 1996; Newton and Boshier, 2001; Suthers and Waite, 2007). The EAC eddies are largely the cause of longshore current variability off the east coast of Australia, with movement occurring inshore-offshore or north-south during the passage of a wave. Internal waves are also ecologically important as they generate down-welling behind the wave crest and can concentrate floating debris into surface aggregations (Suthers and Waite, 2007). These different currents and oceanographic features may influence debris movement and accumulation with the potential to transport debris long distances.

1.5 Plastics as Marine Debris

Plastics are consistently the most common debris type recovered by number in surveys conducted on beaches, at sea, and on the ocean floor around the world (Table 1.5; National Research Council, 1995; Coe and Rogers, 1997; Williams and Tudor, 2001; National Oceans Office, 2001; Barnes, et al., 2009; Ten Brink, et al., 2009). Marine debris surveys within Australia have also confirmed this finding with the highest proportion of recovered debris being plastic items (Haynes, 1997; Cunningham and Wilson, 2003; Edyvale, et al., 2004; Taffs and Cullen, 2005; White, 2006; Smith, 2010; Slavin, et al., 2012). A summary of 201 beaches surveyed on five continents, showed an average of 1.3 plastic items per square metre of shoreline (Bravo, et al., 2009).

This high prevalence of plastic occurs because plastic does not readily break down in the marine environment (Andrady, 1990, 2000, 2005; Gregory, 1999; Ryan, et al., 2009). Larger marine debris items become brittle, and seem to ‘disappear’ but they are breaking down into micro- and nano-sized plastic pieces. The formation of micro- and nano-plastics is an emerging area of concern. This is due to their potential to contaminate an even greater area (Browne, et al., 2011; Cole, et al., 2011), to act as vectors for chemical contaminants due to their large surface area (Mato, et al., 2001;), and the potential for them to be ingested by a wider variety of marine and terrestrial organisms (Besseling, et al., 2013; Farrell and Nelson, 2013) with unknown physiological and ecosystem effects and outcomes (Andrady, 2003, 2005, 2011; Thompson, et al., 2004; Barnes et al., 2009; Browne, et al., 2011).

There have been calls by researchers for plastic marine debris to be reclassified from a solid waste to a hazardous material (Rochman and Browne, 2013). Advocates for this change suggest this classification would give power to environmental protection agencies to restore affected habitats and to take action to prevent more debris from accumulating (Rochman and Browne, 2013). A reclassification could ultimately result in research and development initiatives into alternative polymers and production methods, and may lead to the replacement of problematic plastics with safer alternatives (STAP, 2011; Rochman and Browne, 2013). The improvement of the plastic polymer and method of production would thus involve both the industrial or virgin production pellet and the object that these pellets will ultimately be used to form as a user plastic product.

1.5.1 User and Industrial Plastics

Two distinctions can be made about marine debris plastics based on its origin; those that are industrial and those that are user plastics. Industrial plastics are the building blocks of plastic, the virgin resin pellets whereas user plastics are those items formed from those pellets into items regularly used by humans, like bottles, containers and ropes (van Franeker, 1985; Azarello and Van Vleet, 1987). There has been a switch from industrial to user plastics predominance in marine debris in the last two decades (Robards, et al., 1995; Spear, et al., 1995; Ryan, 2008), with a resultant end point of user plastics now being the most common type encountered within the marine environment. This change could be related to measures taken by plastic manufacturers to curb loss of industrial (virgin) pellets through the implementation of best management practices (Redford, et al., 1997). An example of this is *Operation Clean*

Sweep, that was developed in 1990 in cooperation with the United States Environmental Protection Agency (EPA) and the United Nations joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) (NOAA, 2008; ACC, 2012), with the aim to engage industry to keep plastic pellets out of the environment.

Plastic products are made from industrial raw resin or 'virgin' pellets (also called 'nibs', 'nurdles' or 'mermaid tears') composed of virgin polymers and are thought to be biologically inactive when produced (Moore, 2002). They come in a variety of shapes (sphere, disk, cylinder and rectangular) and colours (usually clear, off-white or white), and are between 1 to 5 mm in diameter (Morris, 1980; Robards, et al., 1995; Redford, et al., 1997; Gregory, 1999; Takada, et al., 2005). The pellets are shipped to manufacturers where they are melted down and formed into a final 'user' plastic product through the addition of additives and an injection moulding process (Dixon and Dixon, 1981; van Franeker, 1985; Ogata, et al., 2009).

A range of additives may be used, but of particular concern are the additives of colorants, softeners, matting agents, UV-stabilizers, brominated flame retardants (BFRs), bisphenol A (BPA), phthalate plasticizers and antimicrobial agents because some of these are shown to be toxic (Mato, et al., 2001; Ananthaswamy, 2001; Takada, et al., 2005; Ogata, et al., 2009; Hu, et al., 2009). Polypropylene (PP), low- and high-density polyethylene (LDPE and HDPE), polyvinyl chloride (PVC), and thermoplastic polyester (PET), are the most common forms of plastic pollution in both user and industrial plastics (Table 1.5; Pruter, 1987; Moser and Lee, 1992; Eriksson and Burton, 2003; Thompson, et al., 2004; Takada, et al., 2005; Carson, et al., 2011). Unsurprisingly, these make up 90 % of the total demand for plastic products globally (Redford, et al., 1997; Andrady and Neal, 2009).

Table 1.5: Classes of plastic commonly encountered in the marine environment

Plastic class	Acronym	Specific gravity	Percentage of global plastic production (Brien, 2007)	Products and typical origin
Polypropylene	PP	0.85-0.83	24%	Rope, bottle caps, netting
Low-density polyethylene	LDPE LLDPE	0.91-0.93	21%	Plastic bags, six pack rings, bottles, netting, straws, buckets, bottles
Poly-vinyl chloride	PVC	1.38	19%	Plastic film, bottles, cups
High-density polyethylene	HDPE	0.94	17%	Milk and juice jugs
Thermoplastic polyester	PET	1.37	7%	Plastic beverage bottles
Polystyrene	PS	1.05	6%	Plastic utensils, food containers
Nylon	PA		<3%	Netting and traps
Foamed polystyrene		1.09		Floats, bait boxes, foam cups
Cellulose acetate	CA	1.30		Cigarette filters

Reference: Shah, 2007; Andrady, 2011

1.5.2 Plastic Production and Properties

The production and demand for plastic products has increased dramatically from the 1950s, with a concomitant increase in the amount of plastic resin being produced (Figure 1.3). A conservative estimate of approximately 5-10 % increase per year is given for the amount of global plastic production expected due to demands for plastic products (Andrandy and Neal, 2009; Ebbesmeyer and Scigliano, 2009; Ogata, et al., 2009). Already, the amount of plastic produced in the first decade of this present century is more than that produced in the entire preceding century (Thompson, et al., 2009). The demand and consumption of plastics in developing nations is growing rapidly, with countries in Asia and Eastern Europe driving this increase (STEP, 2009). This ultimately means that as plastic production increases there is an increased likelihood of both industrial and user plastics being released into the environment.

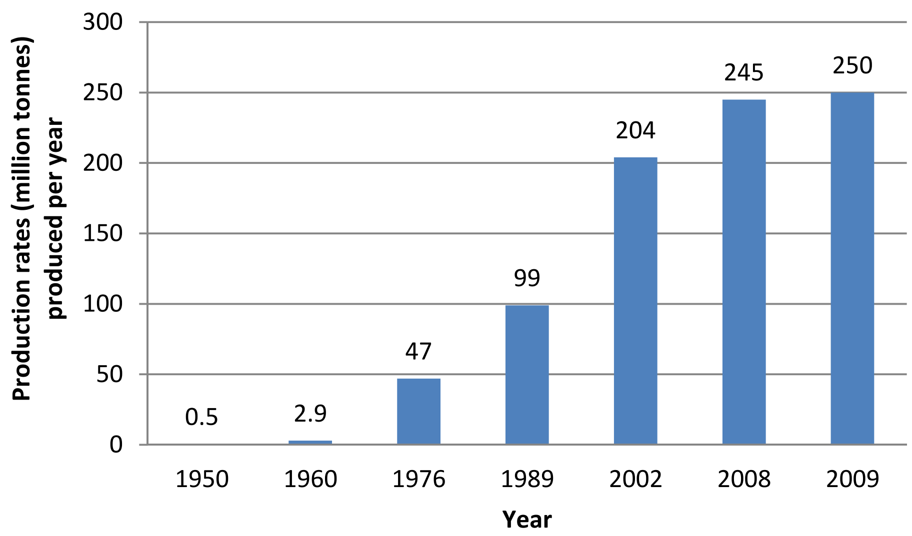


Figure 1.3: Amount of plastic production from virgin resin pellets (Robards, et al., 1997; PlasticsEurope, 2008; Andrandy and Neal, 2009; Thompson, et al., 2009; Barnes, et al., 2011; Plastics Europe, 2013).

The mass production of synthetics has only been occurring for the past 60-years, so the fate and lifespan of these plastic items in the environment is not fully known (Thompson, et al., 2004), but estimates of hundreds of years to degrade have been made (Leous and Parry, 2005). It is thought that all conventional plastics that have entered into the environment still exist today as unmineralized whole items or fragments (Barnes, et al., 2009; Andrady 2000, 2011), with mineralization meaning the complete biodegradation of a polymer in conjunction with oxygen to form carbon dioxide and water (Andrady, 2004). Therefore, plastics persist and pose a significant threat to the environment.

1.5.3 Resistance to Degradation, Persistence and Dispersal of Plastic Debris

Degradation in plastic is indicated by a reduction in tensile strength and a loss of surface area (O'Brine and Thompson, 2010) causing a state of 'embrittlement' whereby its extensibility becomes less than 5 % (Andrady, 2005). The cool temperatures, reduced sunlight and ultraviolet (UV) exposure, and the high salinity of the oceanic environment can hinder the degradation process from occurring and further contribute to debris persistence (Andrady, 1990, 2000, 2004, 2005; Gregory, 1999; Ryan, et al., 2009). Polypropylene and polyethylene based plastics, in particular, have a high resistance to aging and minimal biological degradation (Rios, et al., 2007).

Fouling of the plastics by marine organisms like algae, can cause objects to sink further into the water column (Wiber, 1987; Andrady, 2004), and increase the plastics longevity by reflecting UV B radiation and interfering with photodegradation (Andrady, 1990; 2004; Leous and Perry, 2005). The only synthetics that have been found to degrade faster in the ocean than in the air are foamed polystyrene and polyethylene six-pack rings which are treated to be more degradable (Andrady, 1990; 2005). In addition, there are no easy ways to retrieve, sort and recycle plastic debris items that have entered into the marine environment, so the relative lifetime of plastics at sea are also extended by this means (Andrady, 2005).

Plastics labelled as 'bio-degradable' can still generate microscopic plastic fragments as their composition only contains a certain percentage of the biodegradable material (Goldberg, 1997; Ryan, et al., 2009; Roy, et al., 2011). A biodegradable plastic is one that will eventually break down by way of fungi and bacteria to fully or partially mineralised carbon dioxide and water (GESAMP, 2010). However, most of these products require composting conditions and these products will not degrade under normal environmental settings (Shah, et al., 2008). A study conducted in 2007 examined the different bio-based and biodegradable bags and determined that only polyhydroxy alkanoate (PHA) bags demonstrated some ability to disintegrate when in the ocean (CIWMB, 2007).

The properties that make plastic popular, such as cheap production costs (Rios, et al., 2007), strength, durability, and light weight, are the same properties that cause it to persist and accumulate in the environment (Andrady, 1990; 2011; Rios, et al., 2007).

The buoyancy (i.e. having a density less than seawater and a specific gravity of ~1.025) allows plastics to travel across great distances, with almost 90 % of all floating marine debris identified as plastic (Gregory, 1977; Laist, 1987; Pruter, 1987; Goldberg, 1997; Derraik, 2002; Andrady, 2005; Rios, et al., 2007). The influence of specific gravity on dispersal is illustrated by two of the most commonly encountered floating plastics, polyethylene (0.79-0.97) and polypropylene (0.90) having specific gravities below that of sea water (1.028)(Dixon and Dixon, 1981; Eriksson and Burton, 2003; Andrady, 2005; 2004).

Factors influencing the ability of plastic to float are additives and salinity that affect polymer density, in addition to hydrodynamic processes like turbulence and sea surface tension (Reford, et al., 1997). Floating debris can be hazardous to marine life because of entanglement and ingestion (as discussed in section 1.2), with between 12.5 to 100 % of plastic items ingested by seabirds have the ability to float (Furness, 1983).

1.5.4 Formation of Microplastics and Nanoplastics

There are indications that as large-scale debris levels of macroplastics (items > 5 mm) are stabilizing in certain areas (Barnes, et al., 2009) and levels of virgin pellets appear to have decreased as indicated by lower levels found ingested by seabirds (Vilestra and Parga, 2002; van Franeker, 2005; Ryan, 2008). There are increasing levels of microplastics within certain areas of the marine environment (Barnes, et al., 2011; Browne, et al., 2011; Zarfl, et al., 2011). Further work is needed to determine how different plastic types degrade under different conditions and at what rate (Andrady, 2003; Ryan, et al., 2009).

Microplastics are defined as pieces, or fragments, that are less than 5 mm in diameter (Arthur, et al., 2009; Barnes, et al., 2009). They can originate from primary or secondary sources. Secondary sources are those resulting from the breakdown of larger plastic items (Gorycka, 2009; Zarfl and Matthies, 2010; Andrady, 2011; Zarfl, et al., 2011), and primary sources include virgin pellets and those coming from sewage-discharge and sewage-effluent from soap scrubber beads (Gregory, 1996), abrasive cleaning agents and processes, and from washing machines as synthetic clothing and linen shed fibres (Zubris and Richards, 2005; Browne, et al., 2011). For instance, a single polar-fleece garment can release more than 1,900 fibres per wash (Browne, et al., 2011). Interestingly, polar-fleece, made of polyethylene terephthalate (PET) was originally developed as a means to recycle plastics and keep it out of landfill (Gotro, 2011). However, in this instance this initiative may prove to have done more harm than good. Some cosmetic manufactures (i.e. Johnson and Johnson, Unilever) are now committed to phase-out the use of micro-beads in their cosmetic cleaning products by 2015 due to public pressure (Unilever, 2013).

Nanoparticles are a separate category to microplastics (measured in nanometres < 0.1µm) due to their incredibly small size, with a nanometre equal to one billionth of meter. These particles are especially challenging due to limitations in the sampling and analytical methods that are currently available to sample for these particles, and little is known about what type of debris has degraded into nano-sized fragments (Ng and Obbard, 2006; STAP, 2011; Wright, et al., 2013). Due to the very small size of nanoparticles, they could be subjected to different transport mechanisms than the relatively larger micro- and macro-plastic fragments (STAP, 2011). Studies have shown that toxicity of ingested nanoparticles can be influenced by shape, with long, rod-shaped nanoparticles being more toxic than spherules, with rods causing inflammation and cell injury in lungs of rats exposed through inhalation (Wright, et al., 2013). The long, rod-shape is thought to have a greater contact area and therefore a greater potential for interaction (Huang, et al., 2010). Further studies are needed to understand these issues associated with nano-sized plastics (STAP, 2011).

As with other forms of small plastic debris, microplastics can then either be readily ingested by a wide range of organisms, and can act as sponges, adsorbing and concentrating any hydrophobic, or persistent organic pollutants (POPs) that may be present in the area (Andrady, 2011; Browne, et al., 2011). Nanopolystyrene beads have also been shown to prevent photosynthesis and cause oxidative stress in algae (Bhattacharya, et al., 2010). Further work is required to understand the implications of micro- and nanoparticle plastic ingestion and interactions with various marine organisms (STAP, 2011).

1.6 Plastics and Chemical Contamination

Early researchers had theorised that contaminants and toxins within plastics would pose much less of a threat than either entanglement or ingestion to marine organisms (Fry, et al. 1987; Laist, 1997). In part, this conjecture was based upon the belief that chemicals would be diluted in the ocean rendering them harmless (Laist, 1997). Early researchers, Dixon and Dixon (1981) even suggested a new approach by plastic manufacturers that could include the incorporation of suitable extenders (additives) that are cheaper than base polymers as a means to lessen the impact of plastics on the environment. However, it has long been speculated that toxic materials on, or in plastics (such as additives) are potentially the more serious hazard to wildlife from plastic marine debris pollution (Carpenter, et al., 1972; Baltz and Morejohn, 1976).

Numerous investigations have demonstrated the capacity of plastics to act as vectors for chemical contaminants that may then impact on the health and wellbeing of humans, wildlife, and the environment through various interactions (Ananthaswamy, 2001; Mato, et al., 2001; Endo, et al., 2005; Teuten, 2007; Barnes, et al., 2009; Hu, et al., 2009; Ogata, et al., 2009; Zarfl and Matthies, 2010). However, few studies have been able to conclusively demonstrate harm from the chemicals that have come directly from the plastics, or that plastic is specifically the vector for chemicals. For instance, poly chlorinated biphenyls (PCBs) in the environment may gain entry into the tissues of seabirds (Ryan, et al., 1988; Teuten, et al., 2009; Yamashita, et al., 2011) through prey items just as readily as from ingested plastic items.

1.6.1 Extrinsic Source of Chemicals

Plastic pellets, user plastic fragments, and microplastics can adsorb chemical contaminants from surrounding seawater and concentrate them at significant levels. Some pellets have been found to contain concentrations that are one-million times greater than the surrounding seawater. Hydrophobic sorption is favourable as the plastic surface is non-polar and thus very hydrophobic (Endo, et al., 2005; Takada, et al., 2005). Many persistent organic pollutants, such as PCBs, and polybrominated diphenyl ethers (PBDEs) have very high water-polymer distribution coefficients ($K_{p/w}$) and thus favour adsorption to plastic (Andrady, 2011; Barnes, et al., 2009; Colabuono, et al., 2009; Teuten, et al., 2009; Hirai, et al., 2011). Chemicals with a strong affinity for organic carbon, such as polycyclic aromatic hydrocarbons (PAHs), may also attach more strongly to floating plastics (Zarfl and Matthies, 2010). The variations in concentrations absorbing onto the plastic relate to differing sorption pathways, the length of time the plastic has been in the water, and the concentration of contaminants surrounding the plastic (Barnes, et al., 2009; Colabuono, et al., 2009; Ogata, et al., 2009; Teuten, et al., 2009; Hirai, et al., 2011).

The equilibrium sorption of organic pollutants onto plastic has been shown to be approximately two orders of magnitude greater than that to natural soils and sediments (Mato, et al., 2001). Desorption of chemicals back into the water from plastics occurs at such a low rate that sediments have been shown to desorb faster

(Andrady, 2011). However, the actual sorption mechanism and the influence of things like additives and weathering to sorption behaviour is not fully known (Zarfl, et al., 2011). Many studies have determined plastics contaminated by PCBs (Carpenter, et al., 1972; Mato, et al., 2001; Endo, et al., 2005; Rios, et al., 2007; Teuten, et al., 2009; Ogata, et al., 2009; Zarfl and Matthies, 2010), as well as petroleum hydrocarbons, PBDEs, bisphenol A (BPA), and organochlorine pesticides and contamination can occur at concentrations that range from nano-grams to micrograms per gram (Teuten, et al., 2009).

A large scale global program called the 'International Pellet Watch' has been set up to monitor persistent organic pollutants (POPs), such as PCBs and dichlorodiphenyltrichloroethane (DDTs) in coastal waters (Ogata, et al., 2009). Samples of polyethylene pellets have been collected from over 30 beaches from 17 countries with the highest median concentrations of 13 PCBs occurring in the USA. PCB levels were lower in Foul Bay, Australia (< 16 ng/g-pellet) and these differences reflect regional PCB usage (Figure 1.4). Economic development can be correlated to environmental levels of some chemicals such as BPA and DDT (Teuten, et al., 2009; Thompson, et al., 2009). For instances, DDT is very high in both the western United States and Vietnam, with contamination in Vietnam being linked to its current usage of pesticides for malaria control (Ogata, et al., 2009). Levels of DDT are shown to decrease with the restriction of its use, for instance in Germany levels of DDT in breast milk has decreased by 81 % from 1969 to 1995 (Solomon and Weiss, 2002). As more compounds are banned under the Stockholm Convention, concentrations will continue to decrease (Ryan, et al., 2012).

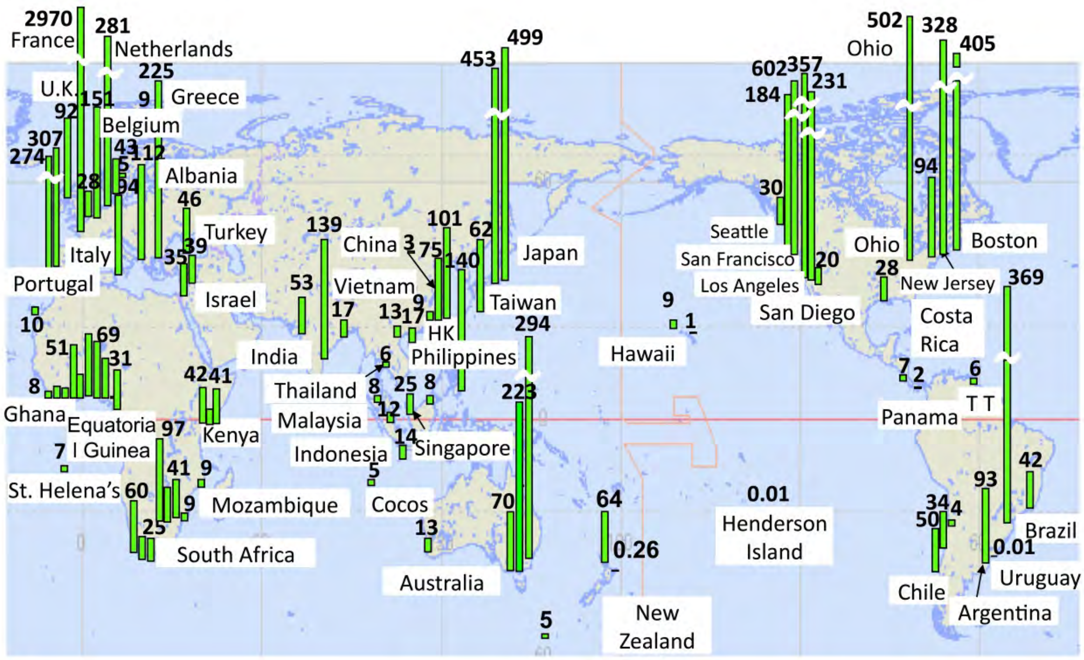


Figure 1.4: Concentration of Poly-Chlorinated Bipheynol's (PCB's) (ng/g) in beached resin pellets across the world. Bar graphs provide sum of concentrations of PCB congeners #66, 101, 110, 149, 118, 105, 153, 138, 128, 1897, 180, 170, 206 (Permission given: Takada, S., 2014 ©Pelletwatch)

Polyethylene (PE) pellets showed the highest concentrations of organic chemicals sorbed from the oceanic environment, when compared to polypropylene (PP) pellets and polyvinyl chloride (PVC) (Takada, et al., 2005; Teuten, et al., 2009). Nonylphenols (NP) however, were found at higher concentrations on PP than PE pellets. This is thought to be related to the increased number of additives used in these plastics (Takada, et al., 2005). So there is some correlation between plastic type and chemical contaminants found in association with them.

1.6.2 Intrinsic Source of Chemicals

Health risks from plastics can stem from their monomeric building blocks (e.g. BPA) which is one of over 200 known endocrine disrupting chemicals from additives (e.g. plasticizers), or from a combination of the two, (e.g. Antimicrobial polycarbonates) (Hu, et al., 2009; Teuten, et al., 2009; Halden, 2010). Environmental endocrine disruptors (EEDs) are chemicals that could interfere with and produce physiological problems in living organisms in areas of development, neurology, reproduction and immunity due to their ability to modulate the endocrine system (Talsness, et al., 2009; Oehlmann, et al., 2009). This may be accomplished through competition with endogenous steroid hormones for binding to receptors or transport proteins, or through alteration of the synthesis or metabolism of endogenous hormones that eventually influences the recruitment of transcription factors and altering gene expression (Talsness, et al., 2009). These changes are of particular concern in developing organisms because, unlike in adults where alterations in steroid hormones are transient, in developing organism the changes can be permanent (Talsness, et al., 2009).

Exposure to POPs can lead to serious health effects, such as cancers, reproductive and immune system dysfunction, birth defects, and an increased susceptibility to disease (Stockholm Convention, 2008). Most additives are bound to the plastic matrix so they usually escape rapid degradation and can persist within the plastic. As discussed in Section 1.5, the leaching and degrading of plasticisers and polymers is a complex process that is dependent on the unique chemical properties of each additive, in addition to the environmental conditions that the plastics are exposed to (Teuten, et al., 2009; Thompson, et al., 2009). Some of the common chemicals used in plastics and their potential effects on living organisms are summarized in Table 1.6.

Chemical contaminants have the ability to transfer from plastics when ingested to the organism, accumulating in tissues and causing a toxic response, as shown by studies done with PBDE, NP and PAHs (Takada, et al., 2005; Ryan, et al., 1988; van Franeker, 1985; Laist, 1987; Teuten, et al., 2009; Hutton, et al., 2008). For example, phthalates can leach out of PVC and disrupt androgen activity causing a wide range of negative health outcomes (Hu, et al., 2009). Chemical contaminants in plastic present a potential hazard to the overall health and wellbeing of wildlife that ingest them.

Table 1.6: Common chemicals used in plastics and their effects

Chemical	Use	Issue	Problem	References
Polybrominated diphenyl ethers (PBDE)	Primarily as flame retardants in wide range of products, includes textile and electronics.	Not chemically bound to polymer in which they occur, so they can escape during production, use, when disposed of and when recycled.	Found in sediment and soil, water, air, wildlife and humans. Effects involve thyroid, thyroid hormone levels, kidney morphology, liver, neurodevelopment, reproductive success and fetal teratogenicity. Have shown similar toxicokinetic behaviour as PCBs.	Law, et al., 2006; Elliott, et al., 2009; Chen and Hale, 2010
Bisphenol A (BPA)	Used in manufacturing of polycarbonate, as an intermediate in resins, in flame retardants and use as an antioxidant and stabilizing material in many plastic types such as polyvinyl chloride (PVC). Final products include paper coatings, dyes, CDs.	Moderately soluble (120-130 mg/L at pH 7) and may adsorb to sediment (Koc 314 to 1524). Has a great solubility at alkaline pH due to its disassociation constants The polymerization of BPA leaves some monomers unbound so they can be released from products and during synthesis into the air.	BPA has a low acute toxicity (1.1 mg/L to 10 mg/L in fish and invertebrates), but it has been shown to have estrogenic activity and can thus act as an EED (Environmental endocrine disruptor) at concentrations that are well below acutely toxic levels. Due to the widespread use of BPA in plastic production this presents a significant area of concern.	Staples, et al., 1998; Yamamoto and Yasuhara, 1999 ; Hu, et al., 2009; Talsness, et al., 2009; Halden, 2010; Browne, et al., 2011
Phthalates, such as Diethylhexyl phthalate (DEHP), Diisononyl phthalate (DINP)	Used as additive in plastic to increase their flexibility. Main use in softening polyvinyl chloride. Also used as additives in industrial products, including food and cosmetics, medical tubing, toys, household items.	Rapidly metabolized when incorporated into the body, but even so are found at steady state levels in the body.	An EED which has been shown to effect male reproductive system – decreased testosterone levels and sperm production, infertility.	Frederiksen et al., 2007; Hu, et al., 2009; Talsness, et al., 2009
Organochlorines (OC) includes, Dichlorodiphenyltrichloroethane (DDT) and its metabolites DDE (1,1-Dichloro-2,2-bis(p-chlorophenyl) ethylene) and DDD (Dichlorodiphenyldichloroethane)	Diverse synthetic chemicals that belong to several groups based on structure. Most used as insecticides.	Stored in body fat reserves or are lipophilic and remain in the environment for long periods of time Bioaccumulate and biomagnify up the food chain.	Toxicity can cause death directly, or acute exposure can cause reproductive impairment. Storage of OCs in fat reserves means during rapid use and depletion of fat reserves in birds during migration or other stressful conditions causes release of OCs into blood, going to brain and leading to acute poisoning.	Friend and Franson, 1999

1.7 Economics - the Costs of Marine Debris

Marine debris not only has environmental costs, potential impacts also extend to the economic realm. Some of the costs based on use and non-use values associated with marine debris inputs are identified below within a Total Economic Value (TEV) framework (Table 1.7).

Table 1.7: The use and non-use value of marine debris upon the environment

Use Value		Non-Use Value
Direct Use Value	**Indirect Use Value**	**Existence, Bequest, Option and Quasi-Option Value**
Lost revenues from tourism industry from o Loss of aesthetic value o Safety issues o Costs of clean-ups • Vessel damage • Loss or injury of commercially valuable marine life • Loss of subsistence fish and marine organisms	• Ecosystem and habitat damage • Loss of biodiversity • Harm and death to marine wildlife • Damage and smothering of coral, benthos and sand flora and fauna	Loss or damage to the aesthetics, habitat and marine organisms within a region

References: Hall, 2000; Derraik, 2002; Gilardi, et al., 2010; STAP, 2011; Williams, et al., 2011

For instance, the cost of removing debris can be high, with significant costs associated with locating and removing items to shore, and transporting the debris to waste facilities for safe disposal (Cho, 2009; STAP, 2011). A study in Shetland, UK, determined that the annual cost to the community based on marine debris was nearly $9 million USD. This valuation includes beach clean-up by council and various community groups, voluntary labour and transport costs, power station costs, harbour clean-up, costs to salmon farmers, crofters, fishing industry and lifeboat launching costs (Hall, 2000). In areas with less debris, it is expected that clean-up costs would be lower. Compensation and liability costs as a result of beach or oceanic pollution are hard to follow up. This is because the majority of debris cannot be assigned to a particular person or organization, and often labels have been lost, so the owners or shippers of the material cannot be conclusively identified (Dixon and Dixon, 1981). So the costs incurred from marine debris are borne by those affected and not by those causing the problem (STAP, 2011).

In general, oceans are considered public spaces and a common property resource, so no oceanic property rights exist. The exception to this is territorial waters or sovereign territory that extends from the low mean water to 12 nautical mile (nm), and a country's Exclusive Economic Zone (EEZ) that extends from 12 nm to 200 nm (Parish, 1972; Newton and Boshier, 2001). In Australia, the territorial waters are managed by the states, while the EEZ is managed by the Commonwealth. However, even when property rights exist, the space is common to most users and in many instances, due to sheer size it is not easily monitored or controlled. This can result in severe pollution issues, as demonstrated with marine debris and is considered a 'Tragedy of the Commons' (Coulter, 2010).

Intervention and assistance to solve this issue requires government input into pollution abatement measures, waste management, and other initiatives. Governmental intervention is needed because marine debris is a 'Tragedy of the Commons' problem that is coupled with cross-jurisdictional implications that affect a vast number of people and economies (Parish, 1972; Leous and Parry, 2005). Ofiara and Seneca (2006) promote the concept of a governmental role in curbing marine pollution through policy measures that help identify and estimate the economic losses incurred. Marine debris can also be viewed as 'Wicked Problem' in the sense that it cannot be solved once and for all, but will always pose a challenge (Jentof and Chuenpagdee, 2009). This is because of the multi-layered nature of this pollution issue, with multiple aspects needing to be addressed. In addition, even if intentional discharge is halted, the problem will still persist from accidental loses and passive (unintentional) littering by individuals. The level of pollution is also present at such a high level within the marine environment that effective ways to actually clean-up the problem simply do not exist at this point in time, with many different viewpoints existing on how to best address the issue.

There is a lack of ownership and difficulties in monitoring marine pollution, often resulting in an absence of private company participation in marine debris prevention initiatives as there are no direct economic incentives. Private companies are often involved in sponsoring clean-up efforts, but preventions are key to the solution. Preventative measures are things such as product modification and development to reduce waste at all stages of product life (Sustainability Victoria and PACIA, 2008; America's Plastics Makers, 2014). Economists refer to marine debris as an *externality* which is a consequence of an economic activity or transaction that is experienced by unrelated third parties that is not captured by market forces (Investopedia ULC, 2011) and can provide either a positive (benefit) or negative (cost) outcome (Van Kooten and Bulte, 2000).

If a dollar value or cost can be assigned to marine debris, it can help justify and promote protective measures, compensation, clean-ups and restorative-rehabilitation efforts (Ofiara and Seneca, 2006). Although assigning a true cost to marine debris can be a challenge, some studies now exist on the economic and environmental benefits gained from improved control and reduction of debris entering into the marine environment (Hall, 2000; Ofiara and Seneca, 2006; Gilardi, et al., 2010). Attempts have been made to model the impacts to commercially fished species by assigning economic values as a result of derelict gear, and costs to improve coastal beach quality (Brink, et al., 2009; Mouat, et al., 2010; Kershaw, et al., 2011).

Market Based Instruments (MBI) could have an important role in addressing marine debris if used as part of an integrated strategy (Parish, 1972; Ten Brink, et al., 2009). Examples of MBI include offering 'bounties' to fisherman to bring abandoned nets to shore where these items can then be properly disposed of at port (Ten Brink, et al., 2009). In Hawaii, there is an initiative in place that provides cash awards to fisherman based on the weight of abandoned gear they report, which has resulted in nearly 75-tonnes of debris being removed over two-years (Nuttall, 2009). A similar program operates in Korea, which over a three year period resulted in 11,000 tonnes of marine debris being purchased (Cho, 2009). The initiative in Hawaii is linked to the Nets-to-Energy Scheme that takes debris removed from the oceans, and after cutting it up, burns it at a Hydrogen-Power facility to create steam that generates electricity (NOAA, 2013). Since its inception in 2002, 800 tonnes of debris has been collected and used to create electricity (NOAA, 2013). Other MBIs also include plastic bag taxes, deposit-refund programmes on glass and plastic bottles, and fines for litter and illegal disposal of waste items (Ten Brink, et al., 2009).

Environmental and economic benefits can be achieved with waste management minimisation, through a reduction in materials, recycling and re-use policies. A major benefit of plastic recycling is the reduced need to produce new plastics, and recycling leading to a reduction of plastic in landfills and consequently within the environment (STAP, 2011). Life-Cycle Analysis (LCA) has shown that there are greater benefits to the environment from mechanical recycling than sending plastics to landfill or incinerating it for energy recovery (Sustainable Packaging Coalition, 2009). Some companies are now beginning to recognise that modern packaging can have detrimental impacts on the environment due to the single-use design, and mass production and use of their products (Sustainable Packaging Coalition, 2009). The involvement of the plastics industry is critical. Many benefits can result for industry if they are involved in increasing their capacity to recycle end-of-life polymers and potentially use the recycled materials as a raw material for new production (STAP, 2011). Plastics have many important and positive roles in modern-day society and they do have the potential to reduce human impacts on the environment. For example, plastic use has led to more light-weight vehicles that then burn less fuel, and food packaging can extend a product's shelf-life and reduce waste (Andrady and Neal, 2009).

A holistic approach to plastics that optimises their benefits and garners the greatest potential of plastic products, while reducing the impacts and costs to the environment is needed (STAP, 2011). A solution like this will require the plastic industry, national government and general consumers to work together in a regionally relevant manner. The five 'R's of reduce, reuse, recycle, redesign, recover (energy) are promoted as the means to achieve this goal (STAP, 2011). These concepts are interconnected and show that marine debris is not solely a waste management issue.

Understanding the source of litter also allows for the recognition of the role of industry to be fully recognised and understood. This in turn, can place pressure on communities and government to bring about changes (Pruter, 1987; Sheavly and Register, 2007; Barnes, et al., 2009; Ryan, et al., 2009; Ten Brink, et al., 2009). In March 2011, leaders from 54 plastics associations from 34 countries signed a declaration to combat marine debris (Global Plastics Association, 2012). This entailed six public commitments that focus on:

- *Research*: work with scientific community to better understand plastic pollution;
- *Education*: especially with young children, and working through public-private partnerships that aim to prevent marine debris;
- *Sharing of best practices*: spreading knowledge about efficient and ecological waste management practices and systems;
- *Promoting best policies*: encourage comprehensive science-based policies and existing laws to prevent marine litter;
- *Plastics recycling/recovery*: enhanced opportunities for product and energy recovery, and;

- *Preventing plastic pellet losses*: stop loss from production to transport and distribution (Global Plastics Association, 2012).

Furthermore, actions outlined by STAP (2011) attempt to encompass all parts of the product supply and value chain of plastic production and the full-life cycle of a plastic product, including extended producer responsibility (EPR). EPR can be beneficial for developing nations as it can redistribute the burden of handling end-of-life plastics from governments and those whom may be impacted by the waste, to the producers. This ensures that producers have to bear the costs associated with waste management that can lead to incentives to reduce or redesign packaging, as well as ensure that the products are recovered when they reach the end of their useful life (STAP, 2011).

Currently most responses to marine debris are end of life, rather than preventative. This means actions are merely palliative care, not solving the issue, only serving to lessen the impact on those nations and/or communities that have the will and the resources to address the issue. A paradigm shift is needed in the way that this issue is addressed globally (STAP, 2011).

1.8 Social Aspects of Marine Debris

Differences in living standards and social customs of society, population level, education, and urbanisation can influence the quantity and type of waste generated. These factors can also influence the capacity and sometimes the willingness and/or ability to deal with waste in a non-polluting way (Laska, 1989; Liffman and Boogaerts, 1997; Morrison, 1999; Coe, 2000; Barnes, et al., 2009). Of interest, is the opinion that marine debris, although quite a significant problem and far reaching is thought to be solvable because it originates from human choices and actions (Coe and Rogers, 1997; Sheavly, 2005; Ocean Conservancy, 2009). As Dixon and Dixon (1981) state, "*Pollutants [may] change with progress, but the proximate cause is unaltered*" (p295), meaning the nature or type of the pollutant may alter but we humans are still the ultimate cause of the pollution. Understanding and addressing the source through rewards and new and creative ways is needed (Laska, 1989).

Social drivers of environmental pollution in developed nations often relate to societal paradigms or way of seeing the world (Laska, 1989). Societal attitudes like apathy, convenience, or a feeling of entitlement contribute to littering behaviours (Florida Centre for Solid and Hazardous Waste, 1997; 1998; EPA NSW, 2000; Hall, 2000). Additionally, unconscious learned behaviours passed from one generation to the next, an assertion of personal freedom, or rebellion (EPA NSW, 2000; BIEC and CCPL, 2001; Spacek, 2008), a lack of education and awareness of polluting consequences, low literacy levels, (Spacek, 2008), lower socio-economic status (Santos, et al., 2005) and rural living (BIEC and CCPL, 2001; Olli, et al., 2001) have all been linked to higher incidences of pollution and litter behaviours. Conflicting studies exist however, on how these factors may contribute and if they indeed hold true. For instance some studies show higher littering rates among males while other finding no differences between the sexes (Slavin, et al., 2012). Littering behaviours, like any human behaviour, is a complex and multifaceted issue that can only be addressed (or modified) through an understanding of the multiple aspects of this behaviour (BIEC and CCPL, 2001) and how these different factors may be correlated such as education levels, cultural norms and poverty.

In the USA, littering has been attributed to government neglect and lax anti-littering laws (Spacek, 2008), and American littering attitudes are influenced by the perceived benefits to society as a result of waste management strategies (Coe and Rogers, 1997). This differs to Australia, where there has been more awareness of the role of community attitudes and individual behaviours in the occurrence of littering behaviour (BIEC and CCPL, 2001). Signs posted in public areas within Australia encouraging people to not litter and the introduction of new bins has in some instances decrease littering behaviours (BIEC and CCPL, 2001). In addition, proper disposal behaviour was found to be directly and immediately affected through engagement in awareness raising activities and education, although follow up studies did not show this behaviour was maintained into the long term (BIEC and CCPL, 2001). In Singapore strong enforcement of anti-littering legislation through imposing large fines and giving corrective work orders to those who litter has reduced the occurrence of public littering (Andrady and Neal, 2009).

Education is critical to help address this pollution problem. Younger people in particular are important targets of education campaigns as they can readily change their behaviour and influence others in their community to do the same (Storrier and McGlashan, 2006). Raising public awareness about how litter may travel through waterways and the potential impacts it can have upon livelihoods, health and the environment are seen as a major method for changing behaviours (Liffmann, et al., 1997; Hall, 2000; Storrier and McGlashan, 2006; Andrady and Neal, 2009). Introduction of measures that involve members of the community, such as through beach clean-up efforts (Rees and Pond, 1995) and paying fisherman to haul in derelict gear they find while out at sea, could bring about a moral impetus for them not to pollute in the future (NOAA, 2008; Cho, 2005, 2009), while also educating them about their role in the problem (Coe and Rogers, 1997; Sheavly, 2005; Ocean Conservancy, 2009).

Public support for recycling can be quite high in some countries like Sweden where only 1 % of waste goes to the rubbish tip (Swedish Institute, 2015). However, in countries like Australia, a lack of understanding of the recyclable product symbols, and whether a product is actually recyclable can hinder engagement (Hopewell, et al., 2009). So education has an important role to play in correct disposal.

Anti-littering campaigns that focus attention on the high prevalence of litter and the occurrence of littering within the environment have the potential to actually increase the occurrence of the behaviour (Cialdini, 2003). This is due to the conflicting impact these campaigns may have on the norms that motivate people's behaviours; that is a person's injunctive norms (their perceptions of what behaviours are approved or disapproved of) and their descriptive norms (their perceptions of what behaviours are usually performed) (Cialdini, 2003). It would be better to align these (injunctive and descriptive) norms rather than to have them compete against one another in educational campaigns (Cialdini, 2003).

To bring about a long-term reduction of marine debris that originates from land education, the adoption and enforcement of administrative and legal measures against littering; and building political commitment of nations to these measures is needed (Nollkaemper, 1992; Liffman, et al., 1997; NOAA, 2008; UNEP, 2009).

1.9 Legal Instruments for Controlling Marine Debris and Chemical Pollutants

The vastness of the ocean makes enforcement and policing of pollution an incredibly challenging task, especially with the point source of contamination not being restricted to any one particular region, nation, organization, or individual (Redford, et al., 1997; Coe, 2000; UNEP, 2005; Barnes, et al., 2009). The vast size of the ocean and the perceived abundance of oceanic resources prevented the recognition of marine debris as a threatening process until the early 1980s (Laist, 1987; Coe, 1995). This despite its presence been known since the 1960s when it was observed on oceanic waters and in sediment (Carpenter, et al, 1972; Colton, et al., 1974; Gregory, 1977**;** Shiber, 1979). Broad legal and regulatory systems that engage the major components of marine debris control both at sea and on land were necessary (Tables 1.3 and 1.4)

(Lentz, 1987; Coe and Rogers, 1997). The maritime sector is already being heavily regulated for navigation, security, and trade (Coe and Rogers, 1997) so implementation of international measures to address marine debris was perceived to be relatively straightforward.

1.9.1 International Level

The two major and specific global regulations for prevention of pollution in the marine environment are the *International Convention for the Prevention of Pollution from Ships* (MARPOL 73/78) and the *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972* (London Dumping Convention). Both MARPOL and the London Dumping Convention are administered by the United Nations' (UN) International Maritime Organization (IMO) (Lentz, 1987; Coe, 1995).

The London Dumping Convention was adopted on 29 December 1972 and entered into force on 30 August 1975 (London Dumping Convention, 2009) with over 87 states being signatories (IMO, 2014). The convention was established to control marine pollution via the dumping of wastes that could cause harm to human health, marine life and other living resources that would, damage amenities, or that could interfere with other legitimate uses of the sea (London Dumping Convention, 2009), with the protection of the marine environment being the broad objective and purpose of the London Dumping Convention (Lentz, 1987). It is composed of three annexes that address what cannot be dumped at sea (I), what requires a special permit to be dumped (II) and what only needs a general permit to be dumped (III) (London Dumping Convention, 2009).

Dumping is defined as "*any deliberate disposal at sea of wastes or other matter from vessels, aircraft, platforms or other man-made structures at sea*" (London Dumping Convention Article III (I)(a)(i); IMO, 2011b). For example, the disposal of garbage at sea by ships loaded with the sole intent to dump, exclusive of normal shipboard operations, is prohibited under Annex I (Lentz, 1987; Wolfe, 1987; Coe, 1995). Signatories are also asked to promote measures to prevent pollution of all waste types, including hydrocarbons and radioactive pollutants, wastes generated at sea by ships, sewage and garbage, and by matter originating from sea floor exploration (London Dumping Convention, 2009).

The *International Convention for the Prevention of Pollution by Ships* (MARPOL 73/78) is the main international convention for the recognition and prevention of significant and controllable sources of marine pollution through its six annexes (Lentz, 1987). The effectiveness of MARPOL is dependent on its adoption, interpretation and enforcement at the international level (Coe, 1995). As MARPOL Annex V is the only annex that directly deals with marine debris, the other annexes will not be further explored in this document.

Annex V of MAPROL 73/78 was brought into force internationally on the 31 December 1988, and on the 14 November 1990 within Australia (AMSA, 2009; IMO, 2011a). Specifically, Annex V aims to prevent pollution by garbage from ships, and expressly prohibits the "*deliberate disposal of wastes or other matters at sea*…" (IMO, 2011a), including the release of "*all plastics, including but not limited to synthetic ropes, synthetic fishing nets and plastic garbage bags*" (IMO, 2011a, p3). This encompasses all plastics that originate from any signatory countries ships, from any ships that are operating in signatory Countries waters, as well as from fixed platforms at sea, and stipulates that there be adequate waste facilities at ports and terminals (Coe, 1995).

Annex V also prohibits the dumping of items like, dunnage and floatable packing material unless the distance to land is more than 25 nm. The disposal of all other garbage, including food wastes, glass, paper products, metals, and crockery is allowed if the distance from land is greater than 12 nm (Horsman, 1982; ANZACC, 1996; AMSA, 2009). Several exceptions exist to discharging, however; with accidental loss being 'allowed' assuming all reasonable precautions to prevent the loss was made (Lentz, 1987). In 1995, Resolution MEPC.65(37) was adopted by the IMO which brought about new Regulation 9 to Annex V (effective 1 July 1997) which requires ships 400 tonnes and over, and those ships certified to carry 15 people or more, to develop and implement a garbage management plan (IMO, 1996). This plan provides written procedure for the collection, storage, processing and disposal of garbage and equipment on board. It also requires these ships to carry and use a garbage record log book that is readily available to officials to monitor compliance of correct rubbish disposal (IMO, 1996). Vessels over 7.92 m are subject to MAPROL placard requirements, while vessels over 12.19 m must have and maintain the above mentioned garbage management plan (NOAA, 2008).

Further MARPOL revisions occurred in 2010, and were designed to strengthen regulation. This introduced more extensive record keeping with the aim to stop garbage discharges from ships at sea, by addressing inadequate port reception facilities, and through the development of a port reception facilities database as part of the Global Integrated Shipping Information System (GESAMP, 2010; STAP, 2011). Further proposed changes as outlined in GESAMP (2010) include:

- The size of ship required to produce a garbage management plan was reduced to 100 gross tonnes from 400 gross tonnes;
- Extension of garbage management plans and record books to include offshore installations;
- Inclusions of procedures to reduce waste in garbage management plans;
- Recording fishing gear loss in the garbage log or ship's log with details about gear type, position of loss, etc.;

- Fishing gear loss that could pose navigational or environmental risks, such as nets or long-lines, to be reported to the flag and coastal State; and
- Inclusion of aquaculture installations that currently do not fall under international legislation, but can be a significant source of debris (Hinojosa and Thiel, 2009).

A third, but weaker legal framework that addresses the marine debris issue is the United Nations Convention on the Law of Sea (UNCLOS) that was introduced in 1982 (http://www.un.org/depts/los/convention_agreements/convention_overview_convention.htm). UNCLOS (1982) calls for the entire marine environment to be protected from all types and sources of pollution. In Article 207-208, it asks States to pass national legislation to combat pollution from rivers, estuaries and pipelines. In addition, Article 211 aims to have States reduce and prevent vessel pollution into the marine environment.

At a regional scale, the problems of marine litter in the South Pacific are addressed through the global MARPOL Annex V provisions and *The Convention for the Protection of the Natural Resources and Environment of the South Pacific Region* (http://www.unep.org/regionalseas/programmes/nonunep/pacific/instruments/default.asp). This latter convention encompasses common regional management policies that focus on waste disposal practices, identifying suitable sites for landfills and the development of port reception facilities (Gregory, 1999).

Other global frameworks that address the marine debris issue include:

- New standards by the International Organization for Standardisation (ISO): ISO 21070: Shipboard Waste Management Standard; and ISO 16304: Port Reception Facility Standard (STAP, 2011).
- The *Convention on the Conservation of Migratory Species of Wild Animals* (CMS) (http://www.cms.int/) which has adopted a specific resolution that relates to

marine debris. Specifically, Objective Two of the Strategic Plan for 2006-2014, is to ensure that migratory species benefit from the best possible conservation measures (CMS, 2011). Addressed in Target 2 are actions that mitigate the most serious threats to migratory species and obstacles to animal migration, in particular wind turbines, power lines, by-catch, oil pollution, climate change, disease, invasive species and illegal take (CMS, 2011).

- The *Convention on Biological Diversity* (CBD) (http://www.cbd.int/) has not adopted specific guidelines addressing the impact of marine debris on biodiversity. However, decision X/29 on marine and coastal biodiversity adopted at CBD COP-10 asks states and other relevant organisations to monitor the risks and impacts of human activities on marine and coastal biodiversity, mitigate those negative risks and impacts and adopt complementary measures to address and prevent significant adverse effects by unsustainable human activities (UN, 1992).

Land based sources of pollution have long been seen as regional problems requiring regional solutions; however, often the response is inadequate. There are a variety of reasons for this, but are often due to inadequate financial and technological means, and a lack of knowledge and abilities (Karau, 1992; UNEP, 2009). A global strategy to support regional approaches is needed (Nollkaemper, 1992; Karau, 1992; UNEP, 2009).

Currently the only global initiative that directly addresses the connection between terrestrial, freshwater, coastal and marine ecosystems is the United Nations GPA (Global Programme of Action) for protection of the Marine Ecosystem from Land-based Activities (http://www.gpa.unep.org/). The GPA was adopted in 1995 and developed by UNEP as a means to reduce and control land-based sources of pollution from entering into the marine environment by facilitating the duty of the State to protect and preserve the marine environment (UNEP, 2010). The main targets of the

GPA are threats to the health, biodiversity and productivity of coastal and marine environments as a result of human activities on land and propose an integrated, multi-sectoral approach that is based on actions locally, nationally, regionally and internationally (GPA, 2011). Partnership between Government, NGOs, the private and public sector and the general public to reduce and manage marine debris is encouraged (UNEP, 2014). It is unique in being the only worldwide initiative that directly addresses the connection between land, freshwater, coastal and oceanic ecosystems (UNEP, 2014).

The GPA also feeds into the UNEP-led *Global Partnership on Marine Litter* (GPML) and the *Global Partnership on Waste Management* (http://www.gpa.unep.org/index.php/global-partnership-on-marine-litter) with the GPML guided by *The Honolulu Strategy*. However, countries can choose if they wish to implement the GPA via legislation or policy as it is non-binding agreement which limits its power (UNEP, 2010).

Pertinent to chemical contaminants is the Stockholm Convention on Persistent Organic Pollutants (http://www.unep.org/roap/Activities/HarmfulSubstances/StockholmConvention/tabid/6820/Default.aspx). This global treaty was created to protect both human health and the environment from chemicals that can persist for long periods, accumulate in fatty tissues, be distributed throughout the world, and that can have adverse effects on health, or to the environment (Stockholm Convention, 2008). It was adopted in 2001, and came into effect in 2004 and is administered by UNEP. The fundamental criteria for assessing organic chemicals are their bioaccumulation potential, persistence and ability to be transported long distances (Stockholm Convention, 2008). Chemical bioaccumulation potential is derived from a bio-concentration factor, persistence is based on environmental half-lives, and the long-range transport is based on monitoring data in remote regions (GESAMP, 2010; Zarfl and Matthies, 2010).

The promulgation of international treaties and conventions is reliant on signatories creating appropriate legislation and regulations at regional and national scales. The legislation and regulations then need to be implemented and enforced appropriately.

1.9.2 Addressing Marine Debris in Australia

The Australian Commonwealth Government considers harmful marine debris to be a Key Threatening Process (KTP) under the Environmental Protection and Biodiversity Conservation Act (1999) due to the ability of marine debris to harm marine life (through both ingestion and entanglement) (DSEWP, 2011). Illustrating the importance of the marine debris issue to Australia is that of the 19 KTPs, only three have a marine focus (marine debris, by-catch of seabirds from long-line fishing, and by-catch of sea turtles from trawlers). Within the Environmental Protection and Conservation Act, the KPT is assigned a threat abatement plan that addresses marine debris (DEAG, 2011). The threat abatement plan for marine debris (Section 268) focuses primarily on prevention and mitigation measures to reduce impacts to vertebrate marine life, such as seabirds and turtles, but excludes invertebrates such as corals (EPBC, 1999). Items seen as benign to wildlife from ingestion and entanglement, such as metal and wood objects are not considered harmful marine debris and are not considered under the threat abatement plan (DEWHA, 2009; 2014). The main objectives of the marine debris threat abatement plan are to prevent the long-term incidence of harmful marine debris; remove existing marine debris from the environment; mitigate the impacts of this marine debris on wildlife and ecological communities; and monitor the quantities, origins and impacts of marine debris while assessing the effectiveness of the management strategies aimed at reducing debris (DEWHA, 2009; 2014).

Nationally, the Australian Commonwealth Government has a range of mitigation measures in-place to curb marine debris generated in Australian waters and on land (http://www.environment.gov.au/cgi-bin/sprat/public/publicgetkeythreats.pl). These include giving effect to the London Dumping Convention (1972) through the *Environment Protection (Sea Dumping) Act 1981* (Bates, 2006). Regulated and controlled by this act is the dumping of noxious and harmful wastes, such as oil and nuclear waste, by vessels at sea (White, 2007). Australia's National Programme of Action for the Protection of the Marine Environment from Land-Based Activities (NPA) brings into effect the GPA for the protection of the marine environment (Commonwealth of Australia, 2006). The NPA addresses the reduction of land-based source of marine debris pollution from the national level. Each state and territory also has legislation which gives effect to MARPOL (Table 1.8).

Table 1.8: Summary of the main legislation in Australian States and Territories which give effect to MARPOL 73/78

Legislation and Year of Implementation	State
The Marine Pollution Act, 1987	New South Wales
Protection of Marine Waters (prevention of pollution from ships) act	South Australia
Pollution of Waters by Oil and Noxious Substances Act 1987	Western Australia
Pollution of Waters by Oil and Noxious Substances Act 1987	Tasmania
Pollution of Waters by Oil and Noxious Substances Act, 1995	Victoria
Pollution of Waters Act, 1996	Queensland
Marine Pollution Act, 1999	Northern Territory

Reference: AMSA, 2009

The implementation of Annex V of the MARPOL 73/78 that meets Australia's international obligations is enacted nationally through the *Protection of Sea (Prevention of Pollution from Ships) Act 1983* administered by the Australian Maritime Safety Authority (Jones, 1995; AMSA, 2009; Commonwealth of Australia, 2011a) and is covered in the legislation of the Navigation Act 1912 (Divisions 12, 12A, 12B, 12C and 12D) that gives effect to MARPOL Annexes I, II, III, IV and VI, respectively

(Commonwealth of Australia, 2011b). Marine Orders, Part 91, Part 93, Part 94, Part 95, Part 96 and Part 97 also refer to marine pollution prevention by oil, noxious liquid substances, harmful substances in packaged form, garbage, sewage and air pollution, respectively (AMSA, 2011). Included under MARPOL legislation within Australia are a number of related enforcement provisions that are derived from UNCLOS. These items include: an extension of MARPOL to Australia's Exclusive Economic Zone (EEZ); the provision that foreign ships must provide information such as garbage log books; the ability to detain foreign ships suspected of pollution breaches; and specific powers being given to inspect ships in Australia's EEZ suspected of polluting (Commonwealth of Australia, 2011a).

The main reasons given for non-compliance with MARPOL Annex V in Australian waters has been a lack of awareness of the requirements, the attitudes of the captain and/or crew, not having adequate facilities for dealing with on-board trash, or inadequate port facilities (Jones, 1995; Frost and Cullen, 1997; Horseman, 1982). In 1992, 57 % of the vessels in Australian waters carrying observers complied with MARPOL, while in 1993, compliance dropped to 47 % (Jones, 1995). More current compliance figures would be beneficial in understanding how compliance has changed in this time period and if awareness of facilities and attitudes toward the legislation has changed.

Other measures being undertaken in Australia at both the state and national levels to curb marine debris pollution are summarised in Table 1.9.

Table 1.9: Additional Australian initiatives, regulations and legislation to prevent the occurrence of marine debris pollution

Initiative	Description	Author
State anti-littering laws	All States have some anti-littering legislation. Example: New South Wales *Protection of the Environment Operations Act, 1997* (POEO Act)	NSW Government, 2012
National Waste Policy	Mitigate impacts of marine debris through state and commonwealth projects via the Environment Protection and Heritage Council (EPHC). Promotes recycling and environmentally responsible waste management practices within Australia to control litter at its source, reduce waste, increase recycling initiatives and encourage industry responsibility.	Commonwealth of Australia, 2010; 2012
"Caring for our Country" initiative	Administered jointly by the Department of the Environment, Water, Heritage and the Arts and the Department of Agriculture, Fisheries and Forestry and provides funding for a number of community and research-based activities, like 'ghost net' clean-up projects	Commonwealth of Australia, 2011; 2012
Fishing Industry Codes of Conduct	Code of Conduct for a responsible seafood industry. Involves better gear retrieval and disposal practices on land.	Newton and Boshier, 2001; Commonwealth of Australia, 2009
National code of practice for recreational fisheries	Includes principles of behaviour aimed at minimizing marine debris.	Jones, 1995
Conservation of Antarctic Marine Living Resources (CCAMLR)	Australia is a member of CCAMLR. CCAMLR has been concerned about marine debris due to the impacts it has upon seabirds and marine mammals.	Slip and Burton, 1992; Nel and Nel, 1999; Auman, et al., 2003; Fanta, 2004
Other nationwide control measures	Development of plastic free gear; improved port facilities; and clean-up programmes.	Jones, 1995; AMSA, 2009
Indirect Measures	Container deposit legislation in South Australia and the Northern Territory; reverse-vending machines in NSW.	South Australia, 2008; NTEPA, 2014; EnviroBank, 2014

1.10 The Australian Marine Debris Situation

More than 4,000 tonnes of waste is estimated to be lost or discarded at sea within Australian waters every year, with fishing vessels discharging or losing 2,500 tonnes of gear (ANZECC, 1996). Studies conducted on the Australian coastline and surrounding waters indicate that high densities of debris exist in many areas (ANZECC, 1996; Gregory, 1999; KAB, 2013b). Studies include beaches in both rural and urban centres in New South Wales (Gregory, 1990; Frost and Cullen, 1997; Cunningham and Wilson, 2003; Smith, 2010), in South Australia (Edyvane, et al., 2004; Eglinton, et al., 2005), Western Australia (Foster-Smith, 2007; Gunn, et al., 2011), the Northern Territory (Whitling, 1998; Kiessling, 2005; White, 2006), Tasmania (Jones, 1995; Slavin, et al., 2012), the northern Great Barrier Reef (GBR) (Haynes, 1997) and in the Commonwealth Territory of the Antarctic (Slip and Burton, 1991). Surveys and findings on source are summarised in Table 1.10.

Knowledge of the Australian debris situation is important for understanding the issues surrounding marine debris and its sources and allows for the appropriate policy and conservation measures to be brought into place.

Table 1.10: Sources of marine debris in Australia

Sources	Location	Author
100 % items marine-sourced; 29% fishing sourced	Heard Island, Commonwealth Territory	Slip and Burton, 1991
100 % items marine sourced; 40% fishing sourced	Macquarie Island	Slip and Burton, 1991
Land-based sources from stormwater discharge from rivers and creeks, and from beachgoers	Six beaches in the Sydney Region, New South Wales (NSW)	Cunningham and Wilson, 2003
Source not specified, but usage categories showed, fishing debris accounted for (67 %), diving (2 %), food and drink (12 %), other (15 %), clothing (2 %)	49 sub-tidal reef locations, Northern NSW	Smith , 2010
(37.5 %), other (29.9 %), food and drink (24.6 %), Industrial (5.16 %), boating (2.90 %), domestic (2.74 %)	42 Sites in the Hunter-Central Rivers Region, Northern NSW	Smith and Edgar, 2013
Both land and marine based debris (no percentages), with fishing related debris most prevalent (35-61 %) at all locations	Reef surveys, Northern NSW	Smith, et al., 2008
Majority terrestrial sourced carried by ocean or deposited by beach-goers (no percentages given).	Northern NSW	Taffs and Cullen, 2005
30 % land (*in situ*) from beachgoers, and 70 % marine-based sources (as determined by objects ability to float), >7 % fishing related	Northern NSW	Frost and Cullen, 1997
<99 % of items marine sourced; >5 % land-sourced; 27 % fishing related	North-east Arnhem Land, Northern Territory	Kiessling and Hamilton, 2001
85% marine sourced (commercial fishing, merchant shipping and recreational boaters), 15% land-sourced.	Fog Bay, Northern Australia	Whitting, 1998
Allocation of whole debris items was 25.6 % items marine, 4.8 % terrestrial and 69.7 % common source Of the commercial fishing nets collected 98 % were foreign origin	Four sites in Northern Territory and one in northern Queensland	White, 2006
Oceanic sources, local shipping and fishing sources was surmised, but no percentages given	Offshore Cays, Near-shore Cays and Continental Islands of the far North Great Barrier Reef, Queensland	Haynes, 1997
Majority from commercial fishing industry (southern rock lobster fishery; Great Australian bight trawl fishery; southern Shark fishery)	Great Australian Bight, South Australia	Edyvane, et al., 2004
Fishing industry, and unknown (percentages not known)	Long Beach, South Australia	Eglinton, et al., 2006
Majority land sourced (77.5 %) with 22.5 % from oceanic sources	9 sites in northern, western and eastern Tasmania	Slavin et al., 2012

In Australian waters, at least 77 species of marine wildlife have been shown to be impacted via ingestion, or entanglement in plastic debris (Figure 1.5).

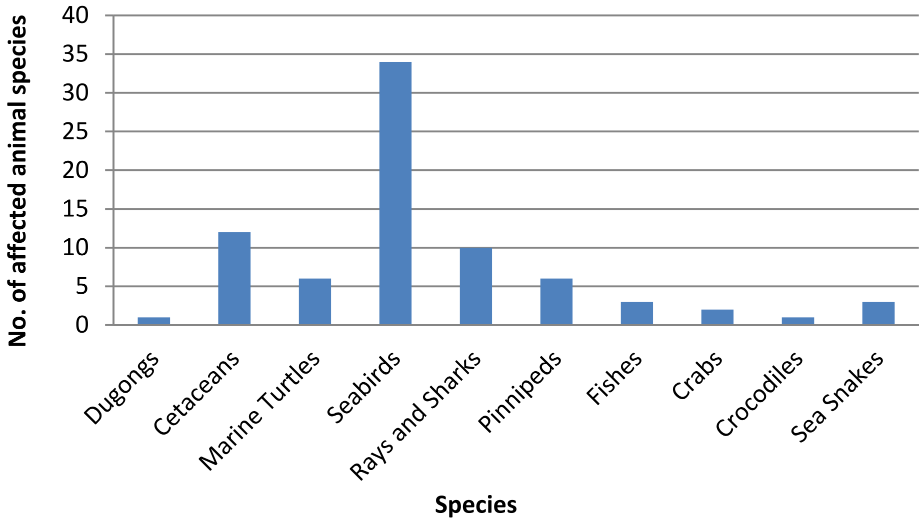


Figure 1.5: The number of animal species reportedly affected by marine debris via ingestion and/or entanglement within Australia (Ceccarelli, 2009).

Although marine debris research has occurred across Australia, there are regions that remain unstudied. Prior to the research reported in this thesis, limited data existed on the occurrence of marine debris along the southern and central Queensland coast, including the southern Great Barrier Reef (GBR). In addition, the impacts or interactions of this pollution on the breeding and nesting seabird populations of these areas are not well known. More is known about the occurrence of marine debris and its effects on bird populations in the North Pacific, but questions remain over the impacts that this debris may have locally and within the Southern Pacific Rim.

1.11 Seabirds and Marine Debris

1.11.1 Direct Interactions and Influencing Factors of Marine Debris on Seabirds

Seabirds are marine organisms that share common characteristics that allow them to participate fully in marine energy cycles (Ainley, 1980). As top predators and due to large populations, like those present in the Great Barrier Reef (GBR) (Congdon, et al., 2007), they have an important functional role in marine ecosystems. As such they can act as indicator species for marine ecosystem health as their demographics and reproductive parameters are reflected in food availability and oceanic conditions (Laist, 1987; Congdon, et al., 2007; Hutchings, et al., 2008; Elliott, et al., 2009). Seabirds also have important roles in island and reef ecology, and through nutrient transfer from pelagic and offshore regions where they feed. Some seabirds, like the wedge-tailed shearwater (*Ardenna pacifica*) also play a vital role in distributing organic matter into the soil profile through their burrowing activities (Walker, 1991; Hutchings, et al., 2008). The position of seabirds within the food web also makes them sensitive to environmental changes that include chemical pollutants (Van den Steen, et al., 2007).

Marine debris presents a serious threat to seabirds. This is indicated in the more than 56 % of all studied seabird species that have been entangled and/or have ingested plastics or other anthropogenic material (Table 1.1; Table 1.12; SCBD and STAP-GEF, 2012). Debris characteristics such as shape, durability, strength and chemical toxicity can make particular types of debris material more hazardous to seabirds (Andrady, 1990).

In the North Sea, the Convention for the Protection of the marine environment of the North-East Atlantic (OSPAR) Commission (enacted in 1972 and honoured by 15 European nations; OSPAR, 2012) have established Ecological Quality Objectives (EcoQO) as part of their commitment to create a healthy and sustainable ecosystem for present and future generations (OSPAR, 2012). One of OSPARS EcoQOs examines the weight of plastic particles in the stomachs of seabirds (OSPAR, 2012), with this amount being an ecological indication of the level of litter within the marine environment where the bird forages and nests. The EcoQO for northern fulmars (*Fulmarus glacialis*) is less than 10 % of these birds, having no more than 0.1 g of plastic in their stomachs from a sample of 50-100 birds over a five-year period at five sites along the North Sea (OSPAR Commission, 2010). Thus, seabirds can act as an important indicator that aid in understanding the extent and nature of the marine debris issue potentially within different geographical areas through the ingestion of marine debris items (GESAMP, 2010).

1.11.2 Ingestion

Ingestion of both industrial pellets, plastic fragments and other anthropogenic material, such as fishing hooks and toys, have been demonstrated in a great number of seabird species (see Table 1.11; Furness, 1983; Harrison, et al., 1983; Ryan, 1987a; Moser and Lee, 1992; Huin and Croxall, 1996; Nel and Nel, 1999). The occurrence of ingestion is thought to occur as a result of debris resembling normal prey items (Fry, et al., 1987; Ainley, et al., 1990; Moser and Lee, 1992), having prey items adhere to the debris item via bio-fouling (Connor and Smith, 1982; Day and Shaw, 1987; Ryan, 1987a), and through secondary ingestion by consuming a prey item that has already ingested plastic (Pettit, et al., 1981; Harrison, et al., 1983; Sileo, et al., 1990).

Incidental consumption of microplastics or nanoparticles of plastic could possibly occur, but it is not (yet) known to be an issue for seabirds. Feeding in areas of high contamination, like at frontal systems and convergence zones where debris becomes concentrated, is also thought to increase the risk of ingestion (Carr, 1987; Ainley, et al., 1990; Nevins, et al., 2005). Age may have an effect on ingestion, with younger birds having more plastics in their stomach than adult birds (Ryan, 1988; 1990; van Franeker and Meijboom, 2002). This may be related to chicks being fed plastics by their parents (Fry, et al., 1987; Ryan, 1988; Huin and Croxall, 1996; Bond and Lavers, 2010), from ingesting plastics or other anthropogenic material that is near to the nest from regurgitated casts, or from consuming debris that has washed ashore (Slip, et al., 1990; Huin and Croxall, 1999; Nel and Nel, 1999).

Table 1.11: Examples of the incidence of marine debris ingestion by different seabird species around the world

Species	Location	Reference
Leach's Storm petrel *(Oceanodroma leucorhoa*); Manx shearwater (*Puffinus puffinus*); northern fulmar (*Fulmaris glacialis*) Prions of genus *Pachyptila*; great skua (*Stercorarius skua*)	Gough Island, in South Atlantic Ocean	Bourne and Imber, 1982; Furness, 1985a
Great shearwater (*Puffinus gravis*); white-chinned petrel (*Procellaria aequinoctialis*); broad billed prion (*Pachyptila vittata*); white-faced storm petrel (*Pelagodroma marina*); and white-bellied storm petrel (*Fregetta grallaria*)	South Atlantic and Indian Oceans	Ryan, 2008
Southern giant petrels (*Macronectes giganteus*)	South Atlantic	Copello and Quintana, 2003
Northern fulmar	North Sea	van Franeker, et al., 2011
Northern fulmar; Storm petrels (*Hydrobates pelagicus*) Manx shearwater; storm petrel sp. *Hyrdobatidae*	Firths of Forth, and Clyde, Scotland Wales	Zonfrillo, 1985
Wandering albatross (*Diomedea exulans*); grey-headed albatrosses (*Thalassarche chrysostoma*); southern giant petrel	Bird Island, South Georgia,	Huin and Croxall, 1996
Northern fulmar; Audubon's shearwater (*Puffinus lherminieri*); Cory shearwater (*Calonectris borealis*); great Shearwater; Manx shearwater; sooty shearwater (*Puffinus griseus*); black-capped petrel (*Pterodroma hasitata*); Leach's storm-petrel; Wilson's storm-petrel (*Oceanites oceanicus*); red phalarope (*Phalaropus fulicarius*); red-necked phalarope (*Phalaropus lobatus*); long-tailed jaeger (*Stercorarius longicaudus*); parasitic jaeger (*Stercorarius parasiticus*); Pomarine jeger *(Stercorarius pomarinus*); Bonaparte's gull (*Chroicocephalus philadelphia*); laughing gull (*Leucophaeus atricilla*); Sabine's gull (*Xema sabini*); black-legged kittiwake (*Rissa tridactyla*); black tern (*Chlidonias niger*); brindled tern (*Onychoprion anaethetus*); common tern (*Sterna hirundo*).	Off the coast of North Carolina, USA	Moser and Lee, 1992
Great shearwater; northern gannet	Massachusetts, USA	Pierce, et al., 2004
Stejneger's Petrel (*Pterodroma longirostris*); sooty shearwater; black-footed albatross (*Diomedea nigripes*); fork-tailed shearwater (*Oceanodroma furcata*); Leach's storm petrel; northern fulmar; tufted puffin (*Fratercula cirrhata*); horned puffin(*Fratercula corniculata*); common murre (Uria aalge); Xantus' murrelet (*Synthliboramphus hypoleucus*); Rhinoceros auklet (*Cerorhinca monocerata*)	Off coasts of British Columbia, Canada, and Washington, Oregon, USA	Blight and Burger, 1997
Laysan albatross (*Phoebastria immutabilis*); wedge-tailed shearwater (*Ardenna pacifica*)	Midway and Oahu Islands, Hawaii, USA	Fry, et al., 1987; Sileo, et al., 1990; Auman, et al., 1997
Northern fulmar; sooty shearwater; short-tailed shearwater (*Puffinus tenuirostris*); fork-tailed shearwater; Leach's storm-petrel; black-legged kittiwake; Cassin's auklet (*Ptychoramphus aleuticus*); parakeet auklet (*Aethia psittacula*); horned puffin; tufted puffin; pelagic cormorant (Phalacrocorax pelagicus); red-faced cormorant (Phalacrocorax urile); northern phalarope (Phalaropus lobatus); mew gull (Larus canus); red-legged kittiwake (*Rissa brevirostris*); thick-billed guillemot (*Uria lomvia*); least auklet (*Aethia pusilla*); whiskered auklet (*Aethia pygmaea*); Ancient murrelet (*Sunthliboramphus antiquus*); marbled murrelet	Alaska, USA	Day, 1980; Robards, et al., 1995

(*Brachyramphus marmoratus*); Kittlitz's murrelet (*Brachyramphus breviorstris*); Pigeon guillemot (Cepphus columba); Rhinoceros auklet; horned puffin; tufted puffin.		
Crested auklet (*Aethia cristatella*); least auklet; parakeet auklet; whiskered auklet	Aleutian Islands, Alaska, USA	Bond, et al., 2010
Black-browed albatross (*Thalassarche melanophrys*); Atlantic yellow-nosed albatross (*Thalassarche chlororhynchos*); white-chinned petrel; speckled petrel (*Daption capense*); great shearwater; Manx shearwater; Atlantic fulmar (*Fulmaris glacialis*); Cory shearwater	Brazil	Colabuono, et al. , 2009; 2010
Sooty Shearwaters; short-tailed shearwaters	North Pacific	Ogi, 1990
Tahiti petrel (*Pterodroma rostrate*); Phoenix petrel (*Pterodroma alba*); Bulwer's petrel (*Bulweria bulwerii*); Christmas shearwater (*Puffinus nativitatus*); Wedge-tailed shearwater (light and dark phase); White throated storm petrel (*Nesofregetta fuiliginosa*); white-bellied storm petrel (*Oceanodroma castro*); wedge-rumped storm petrel (*Oceanodroma Tethys*); red-tailed tropicbird (Phaethon rubricauda); masked booby (*Sula dactylatra*); brown booby (*Sula leucogaster*); Sooty tern (*Sterna fuscata*); grey-backed tern (*Sterna lunata*); white tern (*Gygis alba*); black noddy (*Anous tenuirostris*); blue-grey noddy (*Procelsterna cerulea*); Juan-Fernandez petrel (*Pterodroma externa*); white-necked petrel (*Pterodroma cervicalis*); Kermadec petrel (*Pterodroma neglecta*); Herald's petrel (*Pterodroma arminjoniana*); Pycroft's petrel (*Pterodroma pycrofti*); white-winged petrel (*Pterodroma leucoptera*); collared petrel (*Pterodroma brevipes*); black-winged petrel (*Pterodroma nigripennis*); white-faced storm petrel (*Pelagrodroma marina*); Leach's storm petrel; black tern (*Childonias niger*); Pomarine jaeger (*Stercorarius pomparinus*); Long-tailed jaeger; Murphy's petrel (*Pterodroma ultima*); Mottled petrel (*Pterodroma inexpecta*); Stejneger's petrel; sooty shearwater; Buller's shearwater (*Puffinus bulleri*)	Tropical Pacific	Spear, et al., 1995
Short-tailed shearwater	Phillip Island, Victoria, Australia	Carey, 2011
Short-tailed shearwater	Tasmania, Australia	Skira, 1986
Flesh-footed shearwater (*Puffinus carneipes*)	Lord Howe Island, New South Wales	Hutton, et al., 2008
Blue Petrel (*Halobaena caerulea*)	Western and central coasts of Victoria	Brown, et al.,1986
Prion (*Pachyptila* spp.)	New Zealand	Harper and Fowler, 1987
Wandering albatross chick; white-chinned petrel chick; southern giant petrel; northern giant petrel (*Macronectes halli*)	Sub-Antarctic Marion Island	Nel and Nel, 1999
Antartctic prions (*Pachyptila desolata*)	Heard Island, Antarctica	Auman, et al., 2003
White-chinned petrel	South Africa	Ryan and Jackson, 1987
Pintado petrel (*Daption capense*)	Southern Africa coast	Ryan, 1990
Northern gannet (*Morus bassanus*)		Dickerman and Goelet, 1987

The feeding behaviour and specialization of the individual bird species may make them more or less susceptible to ingesting debris (Bourne and Imber, 1982; Ryan, 1987; Moser and Lee, 1992; Robards, et al., 1995). Many studies show that those birds that feed by diving, dipping (Day, 1980; Furness, 1983; Day, et al., 1985; Ryan, 1987a), or by scavenging behind fishing boats (Bourne and Imber, 1982; Ainley, et al., 1990) often have a higher likelihood of debris ingestion (Table 1.12).

Table 1.12: Feeding methods used by seabirds that were found to have ingested marine debris

Feeding method	Authors
Surface-seizing	Day, 1980; Bourne and Imber, 1982; Connors and Smith, 1982; Moser and Lee, 1982; Day, et al., 1985; Furness, 1985; Ryan, 1987b; Nel and Nel, 1999; Nevins, et al., 2005; Colabuono, et al., 2009
Pursuit diving	Day, 1980; Moser and Lee, 1982; Day, et al., 1985; Ryan, 1987b
Scavengers	Furness, 1984; Ainley, et al., 1990; Robards, et al., 1995; Nel and Nel, 1999; Nevins, et al., 2005; Colabuono, et al., 2009
Filter-feeding	Bourne and Imber, 1982
Diving or Dipping	Furness, 1983; Ryan, 1987a; Ryan, 1987b; Robards, et al., 1995
Pattering	Ryan, 1987b
Piracy	Ryan, 1987b

Many birds forage most actively during the day by sight, with olfaction and sound also used to a lesser extent to locate prey (Shealer, 2002). Birds have four types of retinal cones that allow them to utilise almost the entire visual spectrum and also provides them UV vision. This UV vision is used by many avian species in signalling and foraging (Cuthill, et al., 2000) and may influence ingestion of plastics as certain plastics can be absorbers of UV light.

Diet may also be an influencing factor, with those birds that feed on squid, fish eggs, and pelagic crustaceans (Day, 1980, 1985; Moser and Lee, 1992) having an increased incidence of ingestion compared to those that feed on more active prey such as fish where the bird is actively hunting. This difference is most likely attributed to the active hunting attuning the birds to prey movement and hence reducing the chances of capturing inactive plastic and ingesting it (Ainley, et al., 1990; Moser and Lee, 1992). Although, fish-eating species are thought to be excellent sentinel species for assessing the effects of chemical contaminants that biomagnify with ingested plastic being a potential vector for these chemicals (Grasman, et al., 2000).

Ingestion can be damaging to seabirds for many reasons. It may cause obstruction in the digestive tract leading to feelings of satiety that can lead to reduced foraging and a reduction in body condition that is needed for migration and successful reproduction (OSPAR, 2008). In extreme cases, birds may die through starvation (Fry, et al., 1987; Ryan, 1987b; Auman, et al., 1997; OSPAR, 2008). The lowered propensity of chicks to regurgitate indigestible material puts them at an even greater risk than adults. Ingested marine debris could impact on body condition by physically preventing a full feeding and proper proventricular contraction, which is an important cue to stimulate hunger that may cause decreased chick feeding activity (Hutton, et al., 2008).

Ingestion may also lead to ulceration or perforation of organs (Fry, et al., 1987; Ryan, 1987b; Slip, et al., 1990). The nature of the ingested material can influence its impact on the bird. For example, birds that ingest metal objects, such as fishing hooks, are at a greater risk of organ damage (Huin and Croxall, 1996). However, demonstrating these effects at statistically significant levels has been difficult (Day, 1980; Ryan, 1987a) due to small sample sizes, and the difficulties encountered in detecting impacted birds. In addition, there are complications of studying seabirds that are often only accessible on land when nesting (Connor and Smith, 1982; Furness, 1985). These factors may mask the impacts and occurrence of ingestion. It is also very difficult to make broad statements about ingestion, as variation exists between species and potentially within species that forage in different environments because of the wide variety of influencing environmental factors (Slip, et al., 1990; Nevins, et al., 2005).

1.11.3 Entanglement

As introduced in Section 1.10 above, a further interaction with plastic marine debris is entanglement of seabirds within it. The incidence of entanglement is likely under reported. This could be a result of the inherent problems that exist in the detection of entanglement with biases also existing in its sampling and reporting (Laist, 1997; Ceccareli, 2009). When a seabird becomes entangled it can lead to loss or breakage of appendages and/or infection, strangulation, reduced foraging due to drag, and animals may become caught on fixed objects leading to starvation and/or drowning (Laist, 1987; 1997; Eriksson and Burton, 2003; Ceccarelli, 2009; Votier, et al., 2011). Entanglement may be influenced by the behaviour of the bird; for instance, birds that scavenge and plunge-dive to feed (Laist, 1997), those that forage in the wake of fishing vessels, near garbage dumps on the coast, or within oceanic convergence zones where debris accumulates, tended to have a higher incidence of entanglement (Carr, 1987; Laist, 1997; Huin and Cruxall, 1996; Azarello and Van Vleet, 1997). Use of debris as nesting material may also increase the entanglement risk for chicks and adults (Laist, 1997; Bond and Lavers, 2010; Votier, et al., 2011). Like ingestion, the nature of the material will influence its ability to cause harm, with items such as monofilament fishing line and rope being more hazardous than fragments of plastic (Andrady, 1990; Votier, et al., 2011). The incidences of entanglement in different seabird species in different locations around the world are given in Table 1.13.

Table 1.13: Reported incidences of entanglement in seabirds

Species	Incident(s)	Location	Author(s)
Macaroni penguin (*Eudyptes chrysolophus*)	Plastic bottle top ring.	Marion Island, Sub-Antarctic	Nel and Nel, 1999
Northern giant petrel (*Macronectes halli*)	Toothfish hooks attached to each other by a single piece of fishing line.		
Southern giant petrel (*Macronectus giganteus*)	Toothfish hook with 7 cm of fishing line still attached to it.		
Sub-Antarctic skua			

(*Catharacta Antarctica*)	Monofilament snood sticking out its beak.		
Not specified	Five reports of entanglements in seabirds two of which involved fishing gear.	Marion Island, Sub-Antarctic	Cooper and Huyser, 1995
Northern gannet (*Morus bassanus*)	Chicks have been seen entangled but no further details recorded. Live and dead birds found entangled in fishing gear. 34 entangled birds. All occurred around their bills, involving rope plastics.	St. Mary, Funk and Bonaventure Islands, Canada Helgoland, German Bight Northeast Atlantic	Bond, et al., 2012 Schrey and Vauk, 1987 Rodriguez, et al., 2013
Black-browed albatross (*Thalassarche melanophrys*) Northern giant petrel (*Macronectus giganteus*)	Hook embedded in its throat. Line and hook attached to wing.	Bird Island, South Georgia	Huin and Croxall, 1996
Australasian gannet (*Morus serrator*)	7.5 % of recovered banded birds were found entangled in discarded fishing and lobster gear.	Port Phillip Bay, Victoria	Norman, et al., (1995a,b)
43 different species, including those of the genus *Anas, Catharacta, Halobaena, Daption, Macronectes, Pelecanus, Phalacrocorax, Puffinus, Egretta, Morus, Larus, Sterna*	293 records of entanglement interactions, with both fishing gear and debris.	Across Australia	Ceccarelli, 2009
Australian pelican (*Pelecanus conspicillatus*)	Recorded entangled in fishing line or caught on fish hooks.	Across Australia	Machado, 2007
Fairy penguin (*Eudyptula minor*), shearwater (*Puffinus* sp.), pied cormorants (*Phalacrocorax varius*), pied oyster catcher (*Haematopus longirostris*), little tern (*Sternula albifrons*), black currawong (*Strepera fuliginosa*)	10 birds found entangled in fishing gear lines and gillnets over 18-month period.	Tasmania	Jones, 1994
Masked booby (*Sula dactylatra*)	Immature bird entangled within net.	Northwestern Hawaiian Islands	Conant, 1984
Kelp gulls (*Larus dominicanus*)	27 gulls found entangled with monofilament line	Northern Patagonia, southwestern Atlantic	Yorio et al., 2014

Fishing gear (both lost and active) appears to be especially dangerous to seabirds, with this gear often seen as the source of entanglement that can then lead to drowning of the seabird. This could be related to behaviours that may lead to increased interactions between fishing vessels and seabirds, where birds scavenge behind vessels or are attracted by bait. The presence of discarded fishing gear within the nesting habitat may also increase the entanglement risk to chicks (Bond, et al., 2012).

1.11.4 Marine Debris Use in Nest Material

The use of marine debris in nesting material has been observed in a number of seabird breeding colonies around the world (Nel and Nel, 1999; Phillips, et al., 2010; Votier, et al., 2011; Bond, et al., 2012; Rodriguez, et al., 2013). Surveying nesting debris is a non-destructive technique that can indicate the types and amounts of marine debris that is available within the foraging range, as well as the level of interaction between the potential sources of debris and the seabird species (Nel and Nel, 1999). Northern gannets (*Morus bassanus*), double-crested cormorants (*Phalacrocorax auritus*), kittiwakes (*Rissa tridactyla*) and brown boobies (*Sula leucogaster*) have been known to use debris in their nesting material (Podolosky and Kress 1989; Marchant and Higgins, 1990; Montevecchi, 1991; Laist, 1997).

Northern gannets have been entangled in nest material (Montevecchi, 1991), with the majority being nestlings (Votier, et al., 2011; Rodriguez, et al., 2013). Fishing industry related debris, like that associated with the long-line fishing industry, have been found in association with nests of wandering albatross (*Diomedea exulans*) and giant petrels (*Macronectes giganteus*) on Marion Island, Bird Island, and South Georgia, but these are thought to be associated with ingestion and regurgitated pellets and are not used as nesting material *per se* (Huin and Croxall, 1996; Nel and Nel, 1999; Phillips, et al., 2010). Non-fishing related debris was more commonly seen to be used in the nests of the grey-headed albatrosses (*Diomedea chrysostoma*) and southern giant petrels (*Macronectus giganteus*), which had 25 and 44 % of fishing related gear, respectively, within their nests (Nel and Nel, 1999). This differed from a study by Phillips et al. (2010) at Bird Island, which found higher rates of fishing gear around the nests of wandering albatross (85 %), black-browed albatross (71 %), giant petrels (67 %) and grey-headed albatross (70 %).

Bond et al. (2012) recorded the amount of anthropogenic debris in Eastern Canada at Cape St Marys, Funk Island and Bonaventure Island. Their study found that the amounts of fishing gear incorporated into nests in different colonies was positively correlated with the amount of gillnet fishing occurring in adjacent waters (Bond et al., 2012). Fisheries debris was also found in nearly all northern gannet nests in Grassholm, UK (Votier, et al., 2011). This suggests selection by the birds for long, filamentous nest material (Bond, et al., 2012). The filamentous debris in nests can cause entanglement around chick's legs or wings leading to death (Votier, et al., 2011). Other sulides, apart from the gannet, have been known to become entangled in marine debris at nesting sites (Norman, et al., 1995a). Seabirds appear to choose marine debris that is similar to the natural items they usually use to build their nests, with fishing industry related debris most common type utilized.

1.12 Measuring Marine Debris

1.12.1 Techniques for Quantifying and Surveying Marine Debris

A number of different survey types are available for quantifying and categorising marine debris; these include beach shoreline, benthic, water column, sea surface, and aerial debris surveys (Dixon and Dixon, 1981; Ribic, et al., 1992; Rees and Pond, 1995; Mace, 2012). Plastic pollution can also be monitored in seabirds and other marine organisms that accumulate small plastics within their gut and through entanglement studies (Ryan, et al., 2009). The technique chosen is often based on the part of the marine environment to be sampled, the resources and expertise available to the researchers, and the aim(s) of the study. Numerous positives and negatives exist for the different survey methods and must be considered when deciding on a particular survey method, and these will be discussed below. How different studies are conducted in regards to the technique used, the units of measure, and how results are expressed, has made comparison difficult and is an area that needs to be addressed, as comparability between studies is important for drawing meaningful conclusions (Cheshire, et al., 2009; Ryan, et al., 2009; UNEP 2009). The primary methods for surveying for marine debris are as follows:

1.12.1.1 Shoreline-Based Surveys

Using shoreline surveys to monitor marine debris is the most commonly used technique for evaluating the marine debris present in surrounding waters, as well as what is on the beach itself (Dixon and Dixon, 1981; Slip and Burton, 1991; Ribic, et al., 1992; Rees and Pond, 1995; Cheshire, et al., 2009). This is a favoured method because it is inexpensive, it is relatively easy to undertake, and large areas can be surveyed by inexperienced researchers and volunteers, under most weather conditions (Ribic and Johnson, 1990; Ribic, et al., 1992; Rees and Pond, 1995).

Shoreline surveys may give a distorted picture of marine debris composition because of the varying fate of materials at sea (Dixon and Dixon, 1981) and the potential for very mobile debris items, to have originated from either land or at sea, which can complicate the understanding of source (Dixon and Dixon, 1981; Tudor, et al., 2002; Ryan et al., 2009). Despite these limitations it is still considered the most appropriate method to allow for large sample areas to be surveyed (Rees and Pond, 1995), with sampling constraints thought to be readily overcome (Ryan, et al., 2009).

A number of geographical, geomorphological, ecological and socio-economic factors need to be taken into consideration, including wind direction and beach orientation, and these factors recorded when choosing a location because these factors can influence the deposition, retention and source of the debris. Recognition of these factors and potential bias that these factors may have on marine debris distribution and its sources should be recorded.

A variety of methodologies exist for undertaking beach surveys, and this is the type of survey used in this research project. These surveys are further discussed in Chapter 2, Section 2.1.

1.12.1.2 Sea-Based Surveys

Marine debris surveys can be conducted to determine the amounts and distribution of debris on the sea surface, to a certain depth of the water column, and on the sea floor. Surveying of floating objects or those very close to the surface are accomplished by using a net trawling system (smaller items), through direct observations off a boat (larger items), or looking for aggregations of litter via aerial surveys (Dixon and Dixon, 1981; Cuomo, et al., 1988; Rees and Jones, 1995; Matsumura and Nasu, 1997; Thiel, et al., 2003).

1.13 Design of this Research Project

Marine debris and plastics in particular are a significant pollution issue occurring on a global scale. The terms 'marine debris' and 'debris' used in this thesis refer to items that are of anthropogenic origin only, and will be used interchangeably when describing this pollutant. Understanding the marine debris issue locally and how it is impacting on wildlife can create pathways to improve the issue. As such this thesis examines the issue of marine debris in a region of eastern Australia and has used two seabird species as sentinels. This thesis was developed to examine the relationship between the amount of debris found on surveyed beaches (Chapter 2) and that ingested by the wedge-tailed shearwater (Chapter 3), and the amount of marine debris found on beaches and that used as nesting material by the brown booby (Chapter 4). To assist in quantifying these loads a Marine Debris Pollution Index was created. Additionally, in Chapter 4, the development of a novel technique to survey marine debris in nest material of the brown booby is presented. This is the first study to examine marine debris loads in the southern GBR and the first to examine interactions with marine life, and specifically, seabirds, in the southern GBR. The final chapter synthesises the findings, and presents a novel risk matrix tool that can be used by managers to determine the potential interaction of marine debris upon the environment (Chapter 5). Data gathered in Chapters 2, 3 and 4 are used to demonstrate how this risk matrix tool may work and a further case-study from the North Sea using northern fulmar ingestion data and nearby debris surveys is given as a test case. This chapter concludes with recommendations in regards to further research and preventative measures for marine debris in the region.

1.13.1 Aims and Objectives of this Research Project

The overarching aim of this research project was to ascertain the potential ecological interaction that marine debris has on nesting seabirds within the southern GBR. Adding to this aim was an investigation of how these interactions may differ between those birds nesting in offshore locations to those nesting near-shore. Offshore sites refer to islands within the Capricorn-Bunker group of islands in the southern GBR, while near-shore sites are those that are on the mainland of Australia and Mudjimba Island (Figure 1.10). For the purposes of this study, the discussion around potential harm from marine debris is based on selected species (Section 1.13) with the term interaction regarded as any ingestion, entanglement or use at any level. An overview of the thesis chapters are outlined below.

Chapter 1: Provided an overview of the marine debris issue and its impacts, and provided the background for the relevance of this research project. The importance of understanding the levels of marine debris in an area provides important information needed to respond appropriately to this pollution threat.

Chapter 2: Quantified the occurrence and qualified the characteristics (i.e. types and sources) of marine debris recovered from offshore southern GBR Islands and select near-shore beaches along the subtropical East Australian coastline.

- The surveyed beaches were chosen at or near to the nesting sites of wedge-tailed shearwaters to provide an indication of the pollution levels present within the nearby marine environment;
- This chapter tested the null hypotheses (H_{I}, H_{II}, H_{III}, H_{IV}) that the type and source of marine debris detected at beaches were not significantly different between offshore and near-shore beaches.

Chapter 3: Investigated the occurrence of marine debris ingestion in wedge-tailed shearwaters nesting at locations near-shore and offshore on the east coast of Australia.

- It was predicted that offshore islands wedge-tailed shearwaters will be less polluted than near-shore wedge-tailed shearwaters that are exposed to more polluted areas.
- The well-being of surveyed populations through morphometric measures and a correlation between ingestion and body condition was determined.
- The null hypotheses tested (H_{VI}, H_{VII}, H_{VIII}, H_{IX}, H_{X}, H_{XI}) were that the level of ingestion and therefore pollution does not differ between offshore and near -shore wedge-tailed shearwater populations.

Chapter 4: Examined the use of marine debris (i.e. amount and type) in the nest material of the brown booby. This was accomplished by:

- Determining if there was a relationship between marine debris found in the brown booby nest and that found in beach surveys in the area.
- With the null hypotheses tested (H_{XII}, H_{XIII}, H_{XIV}, H_{XV}, H_{XVI}) being that the level of usage of marine debris in nests did not differ significantly from the surrounding natural environment.

Chapter 5: Provided a synthesis of the information gained from chapters 2, 3 and 4, and the modification and application of a risk matrix to examine interactions of the specified seabird species with marine debris. As a result of the outcomes from the risk matrix, a number of recommendations were offered to address the marine debris issue. In addition, limitations of this research were discussed, research gaps identified and future research directions proposed .

The final Sections of this chapter (1.13 and 1.14) provide an overview of the seabird species used in this thesis to examine the potential marine debris interactions, and give descriptions of survey sites on the east coast of Australia.

1.14 Species of Interest

The Capricorn-Bunker group of islands in the southern Great Barrier Reef (GBR) is an important breeding and nesting area for a number of internationally important seabird populations (Hutchings, et al., 2008), including the largest nesting population of wedge-tailed shearwater in the Pacific Ocean (Hutchings, et al., 2008), and the brown booby (*Sula leucogaster*). Wedge-tailed shearwaters also use islands further south on the east coast at Mudjimba Island, QLD, and at Muttonbird Island, NSW (see Section 1.15). Wedge-tailed shearwaters and brown boobies from these populations are the focal species of this research project for ingestion of marine debris and use in nesting material, respectively. A visual explanation of the chosen species is given in Figure1.6.

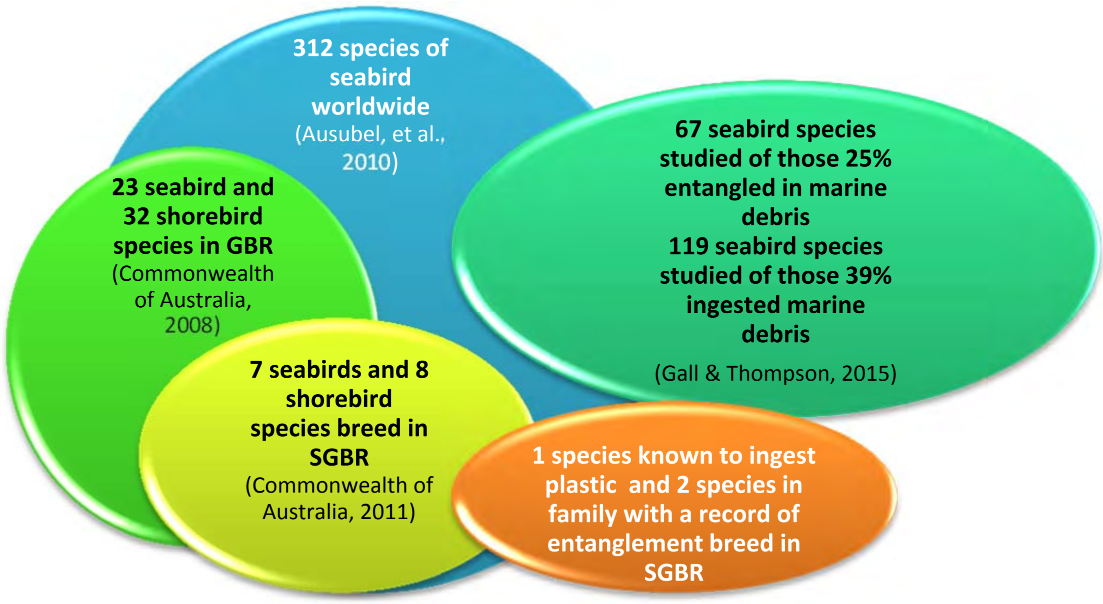


Figure 1.6: Bubble Diagram of species selection rationale

1.14.1 Wedge-Tailed Shearwater (*Ardenna pacifica*)

Wedge-tailed shearwaters are 41 to 46 cm in length, with a wingspan of 97 to 104 cm (Figure 1.7; Coleman, 1997). They are a pelagic seabird that occurs in both tropical and subtropical Pacific and Indian Oceans over a wide-range of marine habitats (Marchant and Higgins, 1990; Pelagicos, 2005). Most populations are considered migratory and are protected by the Japan-Australia Migratory Bird Agreement (JAMBA), China-Australia Migratory Bird Agreement (CAMBA), and Republic of Korea-Australia Migratory Bird Agreement (ROKAMBA) (Crowley, et al., 2008; Commonwealth of Australia, 2009). They exhibit a colonial breeding distribution and are usually nocturnal at their colonies displaying strong site fidelity (Marchant and Higgins, 1990).

The sexes appear alike and exhibit no seasonal variation in plumage (Marchant and Higgins, 1990), however two colour phases, light and dark, exist. Dark phase birds are sooty brown all over, while light phase birds have white underparts (Pelagicos, 2005; Crowley, et al., 2008). This species is not known to breed until at least four years of age (Marchant and Higgins, 1990; Pelagicos, 2005; Crowley, et al., 2008), and is thought to be monogamous; although failures in breeding may cause 'divorce' (Marchant and Higgins, 1990; Pelagicos, 2005; Crowley, 2008).

Figure 1.7: Wedge-tailed shearwater late-stage chick in *Pisonia* forest, Heron Island, GBR

Wedge-tailed shearwaters belong to the order of Procellariiformes, which are the order most commonly found to have ingested plastic (Day, 1980; Ryan, 1987b;

Moser and Lee, 1992; Colabuono, et al., 2009). The first study to show ingested plastic by wedge-tailed shearwaters was Fry, et al. (1987) in the Hawaiian Islands of Midway Atoll and Oahu. Since then, a number of studies have shown the incidence of ingestion in wedge-tailed shearwaters specifically, and have indicated a risk for transference of plastic to its chicks (see Chapter 3).

Wedge-tailed shearwaters are generally pelagic feeders, and retain indigestible materials in their gizzard only regurgitating from their proventriculus to feed their young (Figure 1.8). Thus, wedge-tailed shearwaters would integrate within their body levels of pollution they encounter in the ocean (OSPAR, 2008). As wedge-tailed shearwaters are known to forage to feed their chicks well within 100 km of nesting sites (Cecere, et al., 2013; McDuie, per comm.) the levels of plastic ingestion seen in chicks and those adults returning to feed chicks, likely reflect nearby marine debris levels. This species also undertakes longer distances for self-provisioning (Peck and Congdon, 2005). Their diet consists of mainly small fish (goat fish (*Mullidae* sp.), mackerel skad (*Decapterus macarellus*), flying fish (*Exocoetidae* sp.)) and cephalopods that live in warmer waters, with most items taken from the sea surface (Harrison, et al., 1983; Baduini, 2002). A study by Catry, et al. (2009) in the western Indian Ocean, showed that wedge-tailed shearwaters exploited relatively unproductive oceanic waters, with their at-sea distribution largely matching that of the skipjack (*Katsuwonus pelamis*) and yellow fin tuna (*Thunnus albacares*). This emphasises the importance of their association with subsurface predators, and not necessarily an association with physical oceanographic features, like convergence zones, that many enhance primary productivity. They breed throughout the GBR and Coral Sea through the austral spring and summer. One egg is laid in a sand burrow with both parents attending the young (Coleman, 1997).

Like other shearwaters and petrels, wedge-tailed shearwaters have a stomach morphology that may restrict the ability of these birds to regurgitate indigestible items, such as plastics, due to a narrow U-shaped isthmus between the proventriculus and gizzard where plastics and other hard, indigestible items tend to accumulate (Figure 1.8) (Furness, 1985; Ryan and Jackson, 1986; Ryan, 1987b; van Franeker and Meijboom, 2002). For this reason some studies have only made use of dead birds, or have killed birds for determination of plastic stomach contents (Ryan and Jackson, 1986; Ryan and Fraser, 1987). However, studies done by Sileo et al. (1990), Fry et al. (1987) and Hutton et al (2008) have all used a stomach flushing protocol on live wedge-tailed shearwaters and found plastics remains therein.

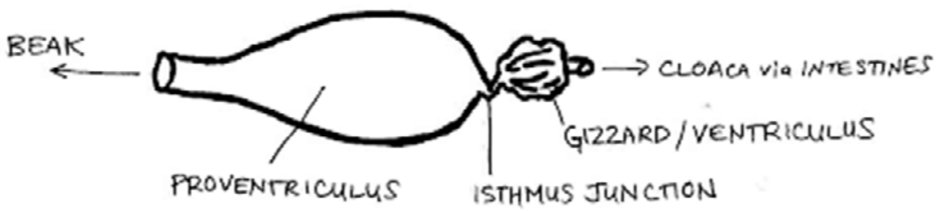


Figure 1.8: Schematic diagram of the wedge-tailed shearwater stomach

Hence, the wedge-tailed shearwater was selected for the ingestion component of this research because it is known to ingest plastics, is part of an order known for plastic ingestion, and it is the only nesting Procellariiform in the southern GBR with very large populations (see Chapter 3).

1.14.2 Brown Booby (*Sula leucogaster*)

Adult brown boobies are 65-75 cm in length, with a wingspan of 130-150 cm, and weighing 750-1500 g (Coles and Pierce, 2003; Marchant and Higgins, 1990). On average, females are slightly smaller than males, with no seasonal difference in plumage (Figure 1.9). They have narrow wings and bodies that are specially adapted for plunge-diving and are known to feed upon squid and a variety of small fish

(Marchant and Higgins, 1990). Similarly to wedge-tailed shearwaters they are also known for locating pelagic schools of fish due to their feeding in aggregations with these species (Coles and Pierce, 2003). Brown boobies are colonial seabirds, and are named in part due to their lack of fear of man and clumsiness on land (Marchant and Higgins, 1990).

Figure 1.9: Brown booby on nest at Thomas Cay, Swain Reefs, GBR

Brown boobies have a sustained monogamous pairing with both parents incubating and tending the chicks for an average of 41 days. Most chicks are able to fly by 105 days after hatching. One parent is usually in attendance during the day and both parents return to the nest at night (Marchant and Higgins, 1990). Birds will either leave early in the morning to hunt for prey, or will roost on the beach throughout the day, with those out hunting returning to rest periodically (Batianoff and Cornelius, 2005). Communal roosting occurs day or night on suitable surfaces, including artificial structures (Marchant and Higgins, 1990). Both parents feed the chick by incomplete regurgitation directly from their throat, up to twice daily (Marchant and Higgins, 1990; Coles and Pierce, 2003).

Brown boobies nest on the ground, often in low grass or a scrape (Coles and Pierce, 2003; Hutchings, et al., 2008). Nesting material can vary from nothing on vegetated cays to substantial amounts of natural materials and anthropogenic marine debris (Marchant and Higgins, 1990; See Chapter 4; Appendix D: Verlis, et al., 2014). Cays that are used for nesting by the brown boobies can sometimes be as low as 1 m above high tide, and can be submerged by storm-waves (Marchant and Higgins, 1990). This has implications for chick survival and population numbers during stormy periods.

Brown boobies are found in tropical waters of all the major oceans and are found between the latitudes of 38°N and 30°S (Marchant and Higgins, 1990). Breeding occurs mainly on tropical islands away from the continental coastlines. Within Australia, brown boobies nest on the Bunker group of islands and in the Swain Reefs (Marchant and Higgins, 1990). Nesting can occur throughout the year with peak activity occurring in Northern Queensland during November and December (Batianoff and Cornelius, 2005) and in March-April and June-October in the Coral Sea (Marchant and Higgins, 1990).

The diet of brown boobies consists of flying fish and cephalopods, such as squid (Marchant and Higgins, 1990; Shealer, 2002). They feed in both shallow and deep waters, and may be dependent on subduction zones where more marine life is present (Marchant and Higgins, 1990). Brown boobies fly low (< 30 m) to the sea and look ahead for their prey, then either plunge dive or horizontal pursuit-plunge dive to capture their prey (Marchant and Higgins, 1990). Increased foraging activity has been linked to turbid waters and high winds (Shealer, 2002). Food may also be obtained by aerial piracy, or by diving into the bow-wave of ships to capture prey (Marchant and Higgins, 1990). Ingestion of marine debris is not thought to be an issue for brown boobies with no studies showing ingestion of plastic (n = 5) (Spears, et al., 1995) and antedotal evidence from research undertaken in the Swain Reefs had hundreds of brown boobies regurgitated and saw no evidence of primary plastics ingestion (Paul O'Neill, 2012-2013, pers. comm.). Brown boobies are offshore feeders and part of the order Suliformes (formerly Pelecaniformes), known for entanglement in marine debris (Conant, 1984; Laist, 1987; Coles and Pierce, 2003). Thus marine debris has the potential to interact with this species through alteration of their habitat and by entanglement.

As marine debris is known to be used as nest material by Brown boobies, and the large populations found nesting within the southern GBR. This species was chosen to investigate the use of marine debris within nest material in the southern GBR (see Chapter 4).

1.15 East Coast Seabird Sites of Interest

1.15.1 The Great Barrier Reef

The Great Barrier Reef (GBR) was the first coral reef system to become a World Heritage Area in 1981, and has been a marine park since 1975 (Commonwealth of Australia, 2013). It extends from north of Fraser Island to the top of Cape York, and encompasses over 600 continental islands, 300 coral cays, and intertidal zones that are protected under Queensland State and Commonwealth Government legislation (GBRMPA, 2011). It stretches parallel to the North-Eastern Australian coastline for nearly 2,000 km on the edge of the continental shelf (Mather and Bennett, 1994). No other area on the planet contains such great biological diversity, with the reef containing many different habitats, such as coral reef, seagrass and mangroves and supports many different populations of rare and endangered plant and animal species (GBRMPA, 2011). Many globally significant fauna groups are found within the GBR, including over 4,000 species of molluscs, and 1,500 fish species. Globally important breeding colonies of marine turtles and seabirds are also found with the GBR (GBRMPA, 2011), which includes the Capricorn-Bunker group of islands and the Swain Reefs in the southern zone of the GBR (Commonwealth of Australia, 2013).

The Great Barrier Reef Marine Park Authority (GBRMPA) manages the conservation and use of the Great Barrier Reef Marine Park (GBRMP). The management strategy involves regulating activities within the marine park through statutory zoning in order to improve the GBR's health and resilience, while providing for a range of ecologically sustainable recreational, commercial and research opportunities and traditional activities (GBRMPA, 2013). There are nine main zones of use within the park: General Use (light blue) zone; habitat Protection (dark blue) zone; conservation Park (yellow) zone; buffer (olive green) zone; scientific research (orange) zone; marine national park (green) zone; and preservation (pink) zone (Appendix A and B, GBRMPA, 2011c,d). The majority of cays accessed for this research study were either pink zones or green zones, and East and West Fairfax Islands are both pink zones.

The Great Barrier Reef World Heritage Area (GBRWHA) encompasses the whole of the land and water masses up to the high-tide mark on the continental landmass from just north of Fraser Island to Cape York. While the Great Barrier Reef Marine Park (GBRMP), and the Commonwealth Marine Area extends beyond the GBR Region into the Torres Strait, Coral Sea and into the south of the region. Within the GBR region a subset of the marine park is protected and managed by GBRMPA. Outside the region, the Director of the National Parks as part of the Commonwealth marine reserves network is responsible for the Commonwealth marine area (Commonwealth of Australia, 2013).

No previous marine debris studies have been conducted in this area and limited data exists for the other sites described below. Due to the importance of these areas for nesting seabird populations (and other important flora and fauna) the presence and interactions of marine debris on nesting seabirds within these areas warrants further investigation. Sites were therefore selected based on presence or nearness to the wedge-tailed shearwater and brown booby nesting locations. These included, the Capricorn-Bunker Group of Islands, the Swain Reefs, Mudjimba Island on the Sunshine Coast, QLD and Muttonbird Island, at Coffs Harbour, NSW. These were the only nesting sites in relatively close proximity to each other where near-shore and offshore debris influences could be tested. Despite the longitudinal differences, the study was designed to assess influences of both land and oceanic marine debris sources equally.

1.15.1.1 The Capricorn-Bunker Group of Islands

The Capricorn-Bunker group of islands is found at the very southern tip of the Great Barrier Reef (GBR), approximately 80 km north-east of Gladstone, Queensland, and along the Tropic of Capricorn (Dyer, et al., 2005) (Figure 1.10). The group encompasses 20 reefs and 16 coral cay islands composed of sandy calcareous skeletal debris from reef organisms (Mather and Bennett, 1994; The State of Queensland, 2013). These islands within the Capricorn-Bunker group at the southern end of the GBR, and they represent the largest cluster of permanently vegetated coral cays within Australia (Batianoff, et al., 2009). The Capricornia Cays National Park and the Capricornia Cays National Park (Scientific) are managed by Queensland Parks and Wildlife Service (QPWS), with adjacent waters managed by GBRMPA (QPWS, 2000).

The vegetated cays of Heron, Wilson, North West, Tryon, Lady Musgrave and Masthead Islands are dominated by forests of *Pisonia grandis* with some *Pipturus argenteus*, *Ficus opposita*, and *Celtis paniculata*, strand vegetation of *Pandanus tectoris*, *Argusia argentea*, *Scaevola taccada* and *Casuarina equisetifolia*, and herbs and grasses of *Sporobolus virginicus*, *Ipomoea pes-capre*, and *Lepturus repens* (Cribbs and Cribbs, 1985; Dyer, et al., 2005). The *Pisonia* forests are less developed on Wreck, Erskine, West Hoskyn and West Fairfax Islands, and the *Pisonia* forest on Tryon Island had previously been decimated by a large scale infestation of insects (Dyer, et al., 2005) but has now recovered, although access remains restricted. Camping is permitted on three of the islands in the Capricornia Cays National Park (Northwest, Masthead and Lady Musgrave Islands), with a resort owned by Delware North, and research station owned by the University of Queensland present on Heron Island (The State of Queensland, 2013) and a research station owned by the University of Sydney on One Tree Island.

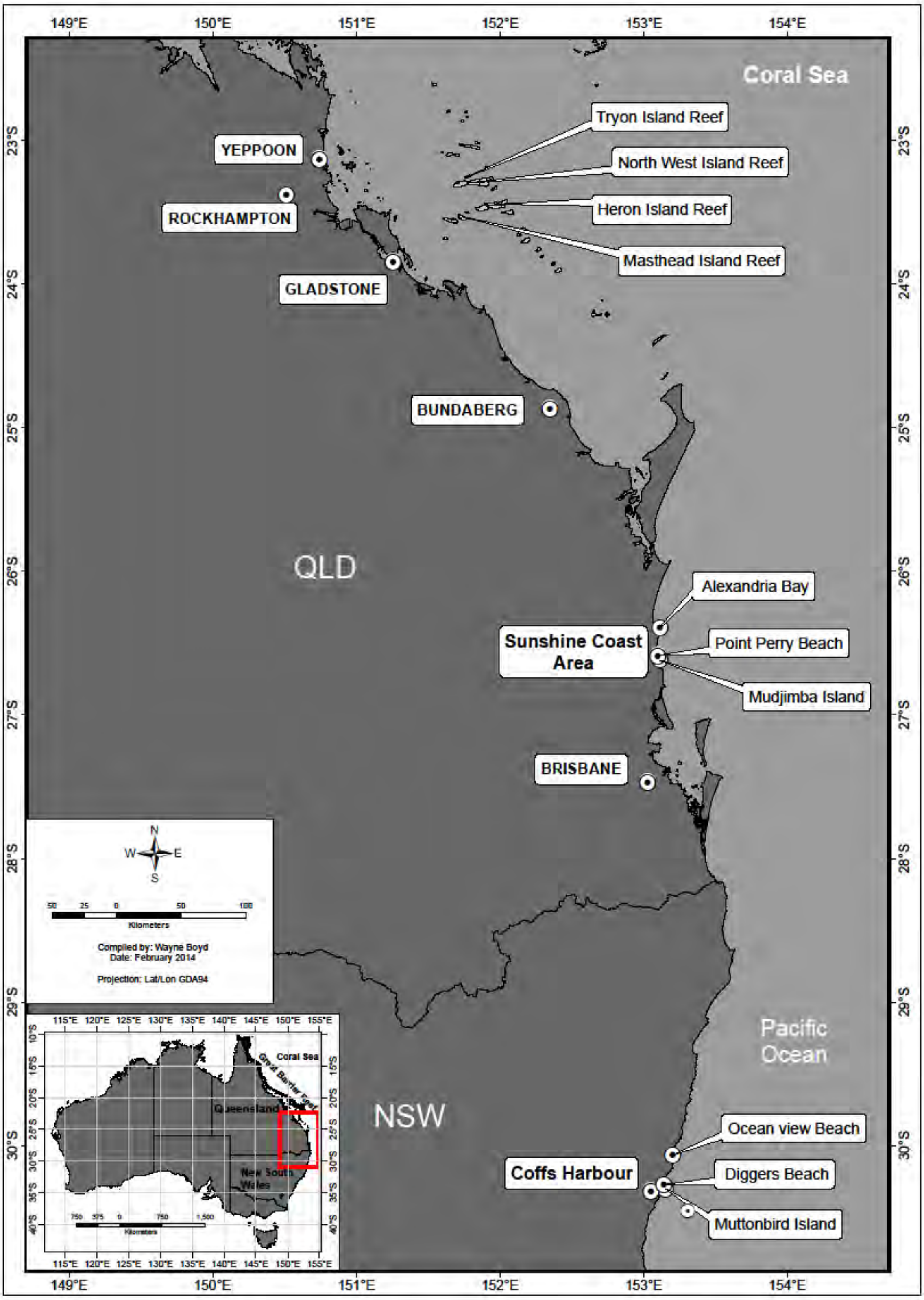


Figure 1.10: Location of sites accessed for this research study in the Capricorn Bunker Group of Islands and along the East Coast of Australia

The GBR is an important seabird breeding area for over 20 different seabird species (Hutchings, et al., 2008). The Capricorn-Bunker Group of islands is of particular importance as it holds both nationally and internationally significant seabird breeding populations, and contains approximately 75 % of the total seabird biomass of the GBR (Congdon, et al., 2007; Hutchings, et al., 2008). The largest breeding colonies of wedge-tailed shearwaters in the Pacific Ocean with approximately 500,000 birds are found on these 13 islands (Hutchings, et al., 2008). Heron Island alone hosts approximately 13,000 wedge-tailed shearwaters between September and May each year (Dyer, et al., 2005), and Northwest Island has the largest population on the East Coast of Australia (Dyer and Hill, 1992; Hemson and McDougall, 2013). In the Bunker group of islands there are estimates of nearly 5,000 breeding brown boobies (Australian Government Department of the Environment, 2013). In recent years, declines in certain seabird species, such as wedge-tailed shearwater and brown booby have occurred within the area. This has been attributed to changing climatic factors like rising sea temperatures, which have had significant impacts on foraging success and reproductive output (Smithers, et al., 2003; Peck, et al., 2004; Congdon, et al., 2007). It is not known what influence marine debris may be having on this decline.

1.15.1.2 The Swain Reefs

The Swain Reefs are located on the southern edge of the GBR and within the Great Barrier Reef Marine Park (Figure 1.11). Managed by the GBRMPA and Queensland Parks and Wildlife, they are composed of a series of small cays and approximately 370 patch reefs (Birdlife, 2013). It is an Important Bird Area (IBA) due to the occurrence of over 1 % of the global population of breeding roseate terns (*Sterna dougalii*), in addition to other tern species, brown and masked boobies (*Sula dactylatra*) and lesser frigate birds (*Fregata ariel*). Overall the land mass encompasses an area of 9 ha. There are nine cays that consistently support both breeding and non-breeding seabirds, these include Bacchi Cay (0.5 ha), Bylund Cay (0.6 ha), Bell Cay (1.5 ha), Distant Cay (0.25 ha), Gannet Cay (1.7 ha), Frigate Cay (2 ha), Riptide Cay (0.25 ha), Price Cay (1.6 ha), Thomas Cay (1 ha) (Birdllife, 2013). Only Price and Bell Cay are vegetated with grass and herbs.

1.15.2 Mudjimba Island, Sunshine Coast

Mudjimba Island, or Old Woman Island (26°37’08S, 153°05’31E) is on Gubbi Gubbi land and named from an Aboriginal legend. It is located approximately 1 km off of the coast of Mudjimba near Coolum on the Sunshine Coast of Southern QLD (Figure 1.10). It is one of the only nesting locations for wedge-tailed shearwaters in Queensland near to the mainland. When last surveyed in the 1997/98 breeding season, the island had between 1,500 to 2,000 breeding pairs and 2,700 burrows with a breeding success rate of 84 % (Dyer, 2000). The island encompasses an area of approximately 1.1 ha and has a sandstone base with a central vegetated area (Dyer, 2000). Access is difficult, but it is a popular surf spot.

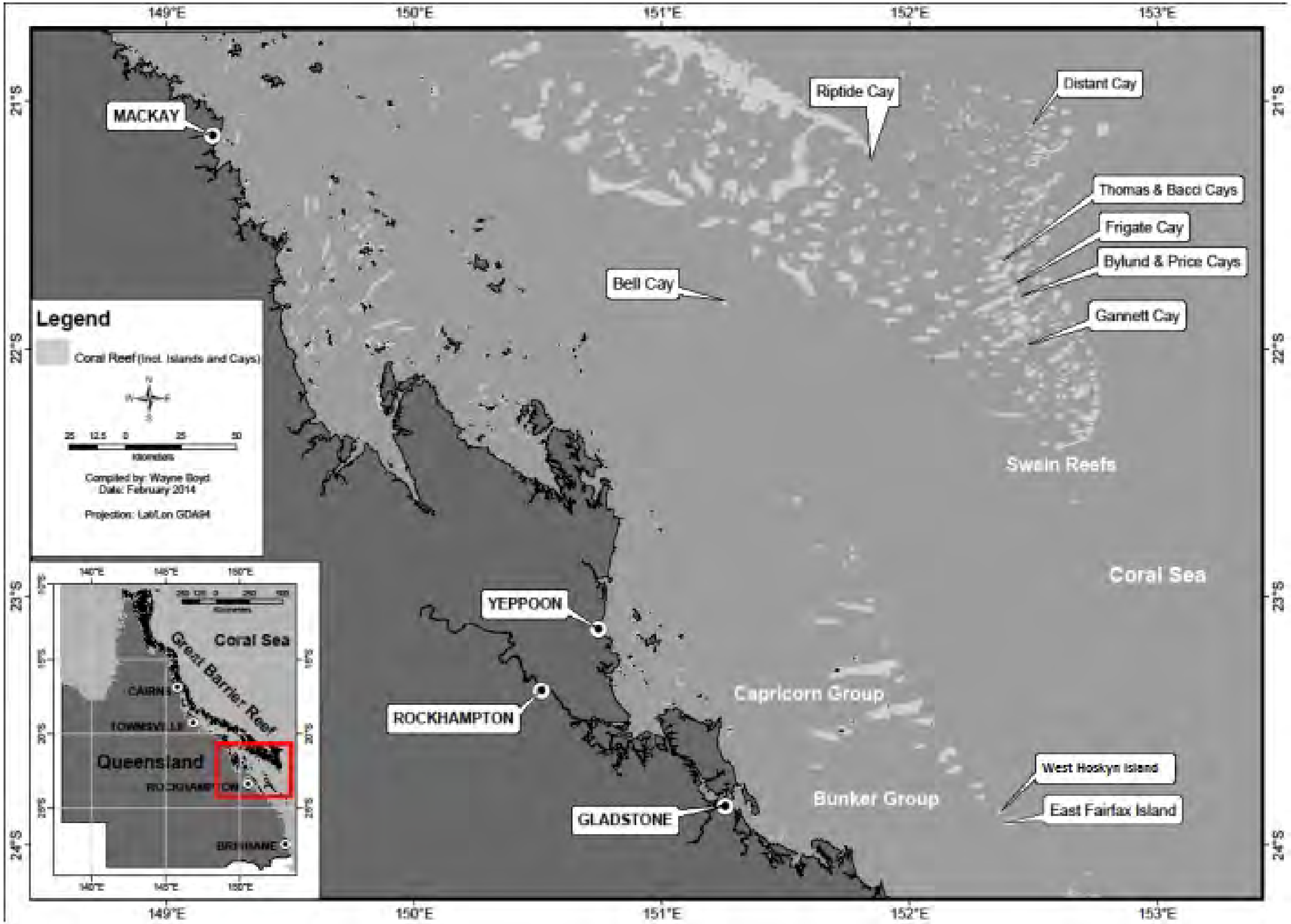


Figure 1.11: Locations of surveyed brown booby nests and shoreline beach marine debris surveys accessed for this research study

1.15.3 Muttonbird Island, Coffs Harbour

Muttonbird Island Nature Reserve, or Gidany Mirrlari, (30°18’19.04”S 153°09’04.84”E) is a colony for thousands of wedge-tailed shearwaters in Coffs Harbour, Northern NSW (Figure 1.10), with an estimated 12,400 nesting pairs (Floyd and Swanson, 1981). It is managed by the NSW National Parks and Wildlife Service, and is connected to land and the Coffs Harbour International Marina via a breakwater and marks the southern boundary of the Solitary Islands Marine Park (Office of Environment and Heritage, NSW Government, 2013). It is 8 ha in size and is located at the mouth of the local marina and fishing port (Invasive Animals CRC, 2009). Vegetation consists of low-growing grasses and herbs that dominate the southern and central portions of the island, with the northern edge having *Lantana camara*, *Cupaniopsis anacardioides* and *Chrysanthemoides monilifera*. Human disturbances are present due to the presence of the walking trail, and a number of possible predators to the nesting wedge-tailed shearwaters, like rodents and lizards exist due to the connection to the mainland. However, a baiting program is used to control the rat and mice populations on the island (Invasive Animals CRC, 2009). An understanding of the threats to this nesting population, including that from marine debris, would benefit the conservation and protection of this species.

CHAPTER 2

Shoreline Marine Debris Surveys Conducted at Offshore and Near-Shore Wedge-Tailed Shearwater Nesting Sites on the East Australian Coast

2.1 Introduction

Marine debris surveys allow for the quantification of debris, and an understanding of the extent and nature of this pervasive pollution problem at the surveyed locations. The information gained from surveys can be used to examine potential threats or impacts in the marine and coastal environment (Ribic and Johnson, 1990; Cheshire and Westphalen, 2007; Spengler and Costa, 2008; Smith, 2010; US EPA, 2012). Surveys provide vital information (e.g., the source of debris) that can be used by management to improve tactical objectives in the field and inform strategic directions such as policies and legislation (Dixon and Dixon, 1981; Rees and Pond, 1995; Smith, 2010; Nevins, et al., 2011). Furthermore, understanding the marine debris issues allows for the development and improvement of educational and preventative initiatives, which can help to solve or ameliorate this global issue.

Although the data gained from surveys are useful, comparing survey outcomes is difficult as different methods and survey types are used among various regions and studies. At present no global survey methodology, classification system, or reporting template is used and this has been attributed in part to the varied nature and uses of beach surveys (Earll, et al., 2000; de Araujo and Costa, 2006), the variable location of debris on beaches due to different physical processes, and the variability of types, quantities and sources of debris (Earll, et al., 2000). In addition, the different objectives of the researcher will often dictate the survey technique utilised, the size of objects collected and the categorisation of recovered debris items (Pruter, 1987). This lack of consensus and varying objectives can confound marine debris survey comparisons and may limit the analysis of spatial and temporal trends (ANZECC, 1996; Kiessling, 2003; Cheshire and Westphale, 2007). There is recognition in the literature and within management agencies that the lack of comparability needs to be addressed to enable temporal and spatial studies so that meaningful conclusions about the full extent of the marine debris pollution issue can be drawn (de Araujo and Costa, 2006; Cheshire, et al., 2009; Ryan, et al., 2009).

The United Nations Environment Programme (UNEP) has developed a classification system with suggested survey methodology (Cheshire, et al., 2009); however, its implementation is sporadic (Cheshire, et al., 2009). Within Australia, a national marine debris database has been created, and suggestions have been given by the Australian Government for conducting marine debris surveys (Cheshire and Westphalen, 2007). However, different collection methods are currently utilised by different community and research groups; with the community group surveys often relying heavily on participation by the public and school groups (Commonwealth of Australia, 2009; Clean-Up Australia, 2014; Tangaroa Blue, 2014).

The persistence and retention of debris items will depend on the nature of the debris material, substrate types, the physical environmental conditions, the beach slope, and the rates of both biological and chemical decomposition of the material (Dixon and Dixon, 1981). All these different elements can influence the amounts and types of debris that collects on a beach, and should be considered when deciding upon the technique to be used to survey for marine debris for each location and survey period. This research project will utilise accumulation shoreline/beach surveys as a way to quantify and qualify the marine debris recovered at selected sites. This in turn will be used as a proxy to represent the level of marine debris in the nearby marine environment.

2.1.1 Standing Stock or Baseline Surveys

The initial collection of debris is considered a standing stock of debris and provides a baseline against which future surveys can be compared. In this instance, all debris items in the specified transect area are collected and no rate of deposition of debris can be determined (Opfer, et al., 2012; Lippiatt, et al., 2013). A standing-stock provides a snapshot of the debris situation at that particular point in time and provides an indication of the debris amounts and types (Lippiatt, et al., 2013) but it does not have a temporal component unless multiple time-series surveys occur.

Alternatively, if these surveys occur over a number of sampling seasons, they may reflect the longer-term inputs (from land and ocean sources) and removals of debris items (burial, degradation, remobilisation from waves and wind) on a particular beach (Cheshire, et al., 2009; Ryan, et al., 2009; Lippiatt, et al., 2013). The results from the standing stock survey are limited and biased however, as variations from events like storms and changing activity levels on the beach cannot be accounted for and these factors may alter the amounts and types of recovered marine debris (Ryan and Moloney, 1990; Ryan, et al., 2009; Lippiatt, et al., 2013). Longer term studies (e.g., longitudinal surveys) may statistically account for these stochastic events to a certain extent. Yet, standing stock surveys are seen as being less powerful tools for gathering data on marine debris occurrence as no data exist on deposition, or how long items have been present in the survey area (Ryan, et al., 2009). As such, accumulation (or temporal) surveys are often considered and implemented.

2.1.2 Temporal/Accumulation Debris Surveys

To avoid the problems associated with standing stock surveys, regular debris surveys are undertaken. These measure the rate of debris accumulation on a beach over time and provide an index of trends in the marine debris loads in adjacent waters (Ribic and Johnson, 1990; Ryan, et al., 2009). These surveys (like standing stock surveys) can also provide information on material types and material characteristics such as weight of recovered items (Opfer, et al., 2012). These types of surveys can also eliminate some of the biases associated with differential removal of items from beach dynamics and beach cleaning activities undertaken by visitors (Ryan, et al., 2009). They also serve the additional benefit of removing the items from the natural environment; as plastic marine debris is considered harmful to wildlife. However, a great deal more effort is required to undertake these surveys compared to standing stock surveys as they involve the actual collection of items, and they need to occur routinely at sites to track any debris trends (Sheavly, 2010).

The interval time between debris surveys can influence the accumulation rate. Surveys may occur at daily, monthly, quarterly, or annually depending on the aims of the survey, available resources, and if background data exist to perform a power analysis to determine the frequency of survey effort needed for a particular site (e.g. Sheavly, 2010; Ryan, et al. 2009; Lippiatt, et al., 2013). Consideration also needs to be given to the spatial variability in debris upon the beach, and the desired detection level of changes in debris load to help inform the amount of sampling effort (Lippiatt, et al., 2013). Some researchers have suggested that more frequent surveying is needed as longer time periods between surveys may lead to an underestimation of debris levels (Ribic, et al., 1992; Eriksson et al., 2013; Smith and Markic, 2013). However, longer intervals may be preferable as it may act to reduce the variability in accumulation rates (Ryan, et al., 2009). There are, for example, a number of surveys that have occurred at intervals of six months or a year (e.g., KAB, 2013b; Storrier, et al., 2007). Further work is needed to understand the impact of sampling interval time on estimations of accumulation rate, but ultimately the decision needs to be made on a site by site basis.

Certain assumptions are made when using beach surveys to indicate marine debris pollution in the adjacent sea. The first is that the debris at time *t* (the first sampling period) is not the same as it is at the second sampling period (*t+1*), with this being accomplished by clearing the beach of all (surface) debris after each survey (Ribic and Johnson, 1990). The second assumption is that the amount of debris that is floating in an unknown part of the ocean is related to the amount of debris collected at the beach with this oceanic area remaining the same between surveys (Ribic and Johnson, 1990). This second assumption is important when trying to draw conclusions about the effects of mitigation measures as the removal of all visible debris allows for any potential changes in debris to be determined and removes some of the bias of items left over from previous surveys that may be recounted (Ribic and Johnson, 1990; Rees and Pond, 1995). Although buried items may be exhumed between surveys and this may be incorrectly identified as new. This is a recognised limitation of this method (Ribic, et al., 1992).

Changes in composition of marine debris through inputs and removals, and any changes in amounts and distribution can be determined by monitoring the same beach over a long period of time (Ryan and Moloney, 1990; Willoughby, et al., 1997). This type of regular, comprehensive temporal survey requires a great deal more time, effort and resources (Sheavly and Register, 2007).

Further limitations to accumulation (and standing stock) beach surveys are that they may give a distorted picture of marine debris composition. This is due to the varying fate of materials in the ocean with not all debris items reaching the shore (e.g., debris can be caught up in coral, or sink), the nature of the debris item (e.g., paper readily degrades, metal items may sink) and the removal and deposition of items by beachgoers and wind/wave action potentially influence the nature and amounts of marine debris present on the shoreline (Dixon and Dixon, 1981; de Araujo, et al., 2006; Ryan, et al., 2009; Lippiatt, et al., 2013). In addition, initial clean-ups may not remove all debris items, so accurate accumulation rates may be under-estimated until a number of surveys have occurred (Ryan, et al., 2009).

However, shoreline accumulation surveys are still considered the most appropriate method to allow for large sample areas to be surveyed (Rees and Pond, 1995). Constraints to sampling are thought to be readily overcome, with many of the factors that influence litter input and removal being relatively constant and not significantly impacting the results of surveying over time (Ryan, et al., 2009). In addition, these surveys can be supplemented by drift experiments in the open ocean and in waterways to determine debris movement, and the accumulation and deposition characteristics of an area (Ribic, et al., 1992; Wilson and Randall, 2005; Maximenko, et al., 2012).

2.1.3 Marine Debris Classification and Quantification

After marine debris is collected, surveyors may undertake a number of different actions depending on their objectives. For example, some surveyors count and report the number of items (Keep Australia Beautiful, 2014), others record the item types with an overall weight (Clean-Up Australia, 2014b), while others undertake a more extensive classification of collected debris items and include all of these things (Jang, et al., 2014; this study). The classification system used for the collected debris items requires a good balance between resolution and efficiency (Lippiatt, et al., 2013). Cheshire, et al. (2009) suggested a two-tiered hierarchy that first identifies the composition of the material (i.e., glass, plastic) and then classifies by type (i.e., bottle, net). In Cheshire's et al (2009) system, 10 different material classes were identified with 77 discrete litter types.

In regards to quantification of the debris, both counts and weights should be recorded for all items, and weights should be taken only after debris items have been dried as moisture content can be a source of error (Cheshire, et al., 2009). It is important to relate dry weights to individual items, as the scale of the potential impact can be heavily influenced by this assessment. For example, 5 kg comprising 10,000 plastic bags presents a very different problem than one large 5 kg debris item. Counts are important as a quantitative indicator of debris items and their relative importance as a debris item. Problems can arise however, if items that are in the same class are significantly different in terms of size or weight, as this can reduce the meaning of the counts as a measure of these items (Cheshire, et al., 2009). For example, a fishing net that is < 1 m^2 versus one that is 1000 m^2: obviously the larger fish net would have a greater potential impact on the environment. Despite these limitations, the collection and the subsequent classification of marine debris items is an important tool; especially when the aim of a study is to understand potential marine debris impacts. One way to standardise these risks is to use a pollution index.

2.1.4 Marine Debris Pollution Index

The effective management of marine debris includes measurement of the levels in the environment, and a pollution index can be a tool that can help to rapidly inform upon this threat. A marine pollution index is a rating that evaluates the overall status of beach pollution, by measuring marine debris as an indicator of beach cleanliness. The simple grading can be readily understood by community members, and used for education and management activities. Any actions undertaken to address the marine pollution issue can also be measured with the index over the long term (Alkalay, et al., 2007). Pollution indicesmay consider the number of items per a defined area have previously been undertaken (e.g. Corbin and Singh, 1993) and assign a 'cleanliness' score based on this amount of debris. Some like Alkalay, et al., (2007) are simple in design (Table 2.1). Others like the index developed by Earll, et al., (2000) examined different categories of recovered debris types and the number of those items (Table 2.2) and assign a 'cleanliness' rating based on these factors.

Table 2.1: Clean Coast index beach cleanliness assessment (Alkalay et al., 2007)

Coast Index	Very clean	Clean	Moderate	Dirty	Extremely dirty
	0 – 0.1 items m^{-2}	0.1-0.25 items m^{-2}	0.25 – 0.5 items m^{-2}	0.25 – 1 items m^{-2}	> 1 items m^{-2}

The downside of these types of indices is that they are based purely on abundances. Earll, et al., (2007) also attributes source, but it does not truly account for size in the index. Further to this, beach managers have often put a great deal of confidence into award systems (e.g., Blue Flag) that assess a number of criteria that go far beyond those measured in pollution indices, and that also account for presence/absence of infrastructure such as restrooms (Nelson, et al., 2000).

Table 2.2: Litter Categories and grading scheme (Earll, et al., 2000)

Category	Type	A (Very good)	B (Good)	C (Fair)	D (Poor)
Sewage-related debris	General	0	1-5	6-14	15+
	Cotton buds	0-9	10-49	50-99	100+
Gross Litter	(e.g., furniture, pallets, tyres)	0	1-5	6-14	15+
General Litter	(e.g., drink can, food packaging)	0-49	50-499	500-999	1000+
Harmful Litter	Broken glass	0	1-4	5-9	10+
	Other (e.g., medical waste, used nappies)	0	1-4	5-9	10+
Accumulations	Number	0	1-4	5-9	10+
Oil	(Includes mineral and vegetable oil)	Absent	Trace	Nuisance	Objectionable
Faeces	Dog	0	1-5	6-24	25+

The derivation of a beach pollution factor is also based on the findings of a number of studies (e.g., Dinius, 1981; Morgan, 1996, as cited in Tudor and Williams, 2003) that have found links between the perception of water quality and the presence of pollution that was visible upon the associated beach. This is also linked to work by Cialdini (2003) that shows that people are more likely to litter in already polluted areas. Marine debris is known to have both direct and indirect social and economic consequences to beach users and beach communities (Chapter 1, Section 1.6 and 1.7), with aesthetics being a significant contributor to these issues. One researcher has gone so far as to say that the greatest impacts associated with marine debris may not be to wildlife, but to economic losses (Windom, 1992), which includes human health impacts.

Aesthetics are considered to be a subjective and intangible concept that deals with the perception of beauty and ugliness (Tudor and Williams, 2003). If marine debris is present on a beach the aesthetic value (or beach appeal) can be reduced (Pruter, 1987; Ballance, et al., 2000; de Araujo and da Costa, 2007). Consequently, people will avoid certain beaches if the appearance is unacceptable to them (Williams, et al., 2003). Thus a new Marine Debris Pollution Index was developed in this thesis through an expansion of the 'Clean Coast Index' (Alkalay, et al., 2007) and a modification of the litter characterisation approach (Earll et al., 2000) that takes into account visual pollution. The premise (or assumption) of this Marine Debris Pollution Index is that smaller objects at low density will be less offensive than larger objects even if the larger items occur at low densities, because of the visibility of the item and the perceived space that the items are taking up on the beach. As such, the Marine Debris Pollution Index will provide a more robust assessment that takes into account size as well as abundance of debris items.

2.2 Aims and Hypotheses

Shoreline accumulation surveys were undertaken to determine the pollution (marine debris) types and amounts found on beaches at both offshore and near-shore locations near to and/or at nesting sites of the wedge-tailed shearwater. It was anticipated that near-shore locations would be more polluted than offshore sites, due to the majority (80 %) of marine debris often being attributed to land-based sources of pollution (Coe, 2000). Yet, this hypothesis had not been tested in the southern Great

Barrier Reef (GBR), specifically within the Capricorn Bunker group of islands. To achieve this in the southern GBR the following null hypotheses were tested:

- **HYPOTHESIS H_I**: Marine debris will only be present at very low levels on the beaches of offshore and near-shore surveyed sites;
- **HYPOTHESIS H_{II}**: No variation will exist between the amount and type of marine debris between and within near-shore and offshore sites (spatially and temporally);
- **HYPOTHESIS H_{III}**: No variation will exist within and between beach zones at near-shore and offshore beaches; and
- **HYPOTHESIS H_{IV}**: The source of marine debris will not differ significantly between near-shore and offshore sites.

Additionally, a Marine Debris Pollution Index was developed for the surveyed areas to help inform upon this pollution threat to the surveyed areas. The development, use and limitations of this index will be discussed.

2.3 Methods

2.3.1 Site Selection

All sites were chosen due to their close proximity to and/or at the nesting locations of the wedge-tailed shearwater (Figure 1.10). Shoreline beach marine debris surveys were undertaken to inform upon the environmental levels of this pollutant in the environment near to this nesting seabird. The amounts and types of marine debris recovered in these surveys will be used in Chapter 3 and Chapter 5 to discuss how and if the environmental loads influenced upon the occurrence of marine debris ingestion in this species in the surveyed areas.

This study surveyed beaches at three offshore islands in the Capricorn-Bunker Group of islands in the Great Barrier Reef (GBR) marine park, one near-shore beach in southern Queensland (QLD), and two near-shore beaches in northern New South Wales

(NSW) providing a total of six sample locations (Figure 1.10). All were areas where wedge-tailed shearwaters nest. Initially, a second southern QLD beach was planned and was conducted at Point Perry beach. Finding suitable beaches in southern QLD was difficult due to the vast size and/or regular cleaning activities occurring at most all beaches in this popular tourist destination. Point Perry was significantly smaller than the other surveyed beaches and was not included in the overall analysis due to the data being a significant outlier. On offshore Islands, the windward side was surveyed as this is been shown to accumulate more regional sources of debris and more debris overall, while leeward shows more local recreational sourced items (Debrot, et al., 1999). The leeward side of Northwest Island was also surveyed for comparative purposes, and this is discussed in Section 2.4.1, but is not reported in the overall results. This was because the windward side has been shown.

Surveys occurred over two different time periods. At offshore locations surveys were conducted in December 2012 and then in May 2013, and at near-shore locations in November 2012 and April 2013; providing a five-month deposition period for analysis. Summarized in Table 2.3 are the coordinates of the islands and beaches that were surveyed, with the basic site descriptions provided in (Table 2.4).

Table 2.3: Coordinates of the beaches surveyed for marine debris

Site Name	Coordinates
Offshore sites	
North West Island, QLD	S23°18’08.7” | E151°42’13.4”
Heron Island, QLD	S23°44’23.3” | E151°91’14.4”
Tryon Island, QLD	S23°14’55.4” | E151°46’44.5”
Near-shore sites	
Diggers Beach, NSW	S30°16’33.3” | E153°08’35.5”
Ocean View Beach, NSW	S30°03’58.8” | E153°12’09.1”
Alexandria Bay, QLD	S26°23’23.2” | E153°06’51.5”

The Capricorn Bunker Group of Islands are located east of Gladstone, Queensland in the southern GBR (Chapter 1, Section 1.14.1). This area is characterised by well-developed platform reefs that are quite uniform in zonation and fauna. These reefs are separated by moderately deep water with many of these reefs associated with vegetated sand cays/islands (Hopley, 1982; Veron, 1996).

The offshore sites of Heron and Northwest Islands are commonly accessed by people through the presence of a resort and research station (Heron), and campsite (leeward side of Northwest), while access to Tryon is restricted. All offshore sites were chosen due to the presence of nesting wedge-tailed shearwaters, while near-shore sites were chosen due to the close proximity to wedge-tailed shearwater nest sites. No actual nest site themselves were surveyed near-shore. The nearest suitable site to nesting wedge-tailed shearwater was selected, with beach selection including an assessment of slope, beach length, occurrence of formal cleaning activities and accessibility. The windward beaches of the three sites in the Capricorn Bunker islands were surveyed for marine debris (Figure 1.10).

All near-shore beaches had human visitation. Alexandria Bay, QLD, is part of the Noosa Headlands Park and is a popular nudist beach that can be accessed only by foot off the park trail (or by boat). Diggers Beach is located in Coffs Harbour, NSW, near a number of resorts, and has two nearby creeks. Ocean View Beach is a suburban beach located in Mulloway, NSW (Chapter 1 Section 1.14).

Table 2.4: Site descriptions for offshore and near-shore beach study sites

Site Name	Location	Beach Slope	Beach Length (m)*	Avg. Beach Width (m)	Substratum type and uniformity	Back of Beach
Tryon Island	Offshore	7°/12.2 %	~ 700	24.7	70 % sand 10 % reef rock 20 % vegetation	Natural: small dunes; *Pisonia grandis*, *Pandanus tectorius*, *Casuarina equisetifolia, Argusia argentea*
Heron Island	Offshore	11°/18.7 %	~ 700	9.8	90 % sand 10 % reef rock	Jetty, and research station; Natural: dunes, *Pandanus tectorius*, *Casuarina equisetifolia, Argusia argentea*
Northwest Island windward	Offshore	7°/10.7 %	~ 1600	30.0	80 % sand 15 % reef rock 5 % coral rubble	Natural: low dunes; *Pandanus tectorius*, *Argusia argentea, Casuarina equisetifolia*
Northwest Island leeward	Offshore	12.7°/23 %	~ 1600	18.9	65 % sand 20 % coral rubble 15 % reef rock	Campground; Natural: minor dunes, *Argusia argentea*, *Pandanus tectorius*, *Casuarina equisetifolia*
Diggers Beach	Near-shore	6° /10.5 %	800	43.9	100 % sand	Parking lot, park, resort; Natural: tall dunes
Ocean View Beach	Near-shore	5.2°/9 %	900	36.7	100 % sand	Minor residential, park; Natural: low dunes
Alexandria Bay	Near-shore	7° /12.3 %	1200	41.0	100 % sand	Natural: high dunes; *Casuarina equisetifolia*

*Near-shore site beach lengths from (Short, 2006; Short, 2007), offshore site beach lengths determined from GoogleEarth

2.3.2 Survey Design

2.3.2.1 Transect Set-Up

Transect position on the beaches were based on an assessment of each individual beach and its physical characteristics. Geological features, such as rocky outcrops were avoided as they represent a different shore type with different wave energies and influences on deposition. Transects were started ~10 m away from the headland, or ~10 m from natural outcrops, or human-made structures such as beach entry stairs.

Details describing the surveyed beaches were recorded, and included:

- Total beach length: determined from GoogleEarth Satellite Images, or from text if available;
- Beach slope: measured with a clinometer;
- Substratum composition: by observation and percent allocation;
- Composition of beach back (i.e., natural, human use); and
- Details of the presence of terrestrial vegetation; nearby towns; presence of storm-water pipes/drains; offshore reefs and seagrass meadows; and the accessibility of the beach to humans.

To ensure that the same location could be resampled at subsequent survey times, the GPS coordinates were taken at the start of each transect. On each beach, 50 m belt transects were spaced as to sample the two ends and middle of each beach (east/south, central, west/north zones), with three replicate 50 m transects run in each of those zones (for a total of nine transects run on each beach). On Northwest Island, both leeward and windward surveys occurred resulting in a total of 18-transects sampled (nine windward, nine leeward). The distance between zones was a minimum of at least 30 m, with gaps of 5 m between each of the three 50 m belt transects within a zone (Figure 2.1). For logistical reasons, at certain beaches the distance between transects was adjusted to suit the size of the beach. For instance, larger beaches required larger distances between zones (so >30 m) to properly represent the three zones. To overcome the differentials in sample effort of surveyed areas, the data were standardised at each beach to the amount of debris items collected per m^2.

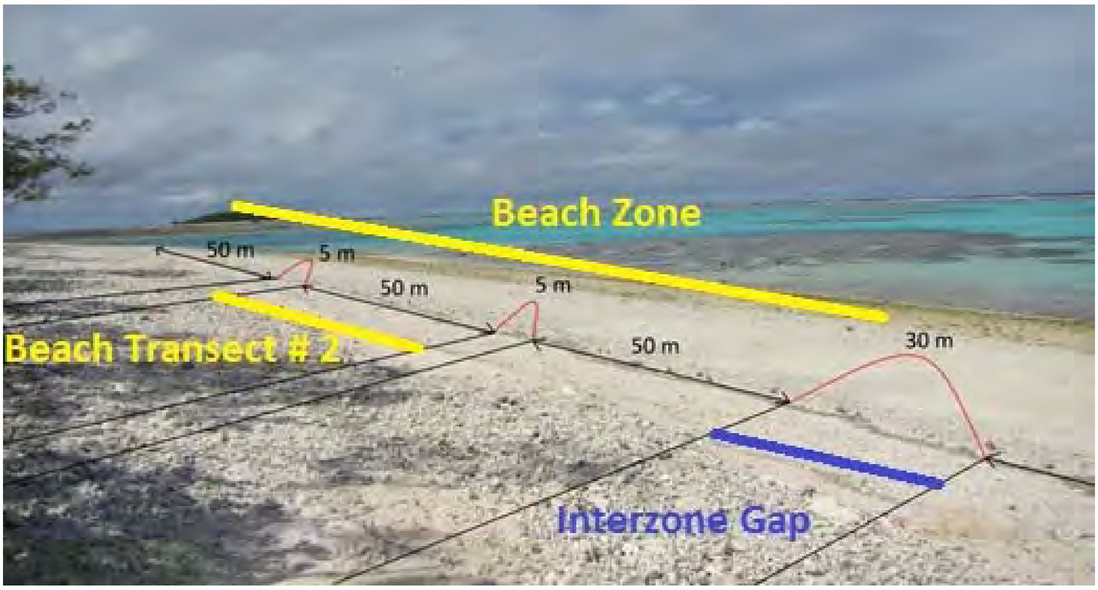


Figure 2.1: Illustration of transect length and spacing on surveyed beaches

Collection of beach marine debris occurred twice at all surveyed beaches. These measurements allowed for an accumulation rate to be calculated and statistical comparisons to be made between offshore and near-shore beach locations.

2.3.2.2 Debris Collection

Debris was collected by at least two people whenever possible by walking along the length (of each 50 m) and width (10 m) of the transect. The transect area included the area from the front dunes down to the low water mark with the transect run at the highest or most recent strandline (Figure 2.1). On each transect, all surface debris detected was collected into a single bag, which was labelled with the location, zone, transect number and collection date. Items too heavy to lift or too cumbersome to remove were recorded *in situ*, with the transect location, number of item(s), and measurements of height, width and length recorded. The item itself was labelled using a permanent marker, to note the date it was detected and its location in the survey to ensure that it was not resampled in subsequent surveys. Photographs were taken of identifying marks on these items.

The minimum size of debris collected was 1 cm and was of a minimum size collected by other studies (e.g., Corbin and Singh, 1993; Debrot, et al., 1999). This is slightly smaller than that used by White (2006) and the NOAA guidelines (Lippiatt, et al., 2013), but encompassed some of the smaller debris items present on the sampled beaches. These smaller sizes were set as they could potentially pose an ingestion hazard to seabirds, and it also ensured a more comprehensive collection.

2.3.2.3 Debris Sorting

All collected debris items were brought back to CQUniversity, Gladstone, QLD, and were sorted using the method described by Cheshire et al., (2009) in the UNEP marine debris collection guidelines. Collected items were first air dried at room temperature, and then classed according to their major material type (e.g. wood, metal, cloth, paper-cardboard, glass-ceramic-masonry, rubber, plastics, and other), with plastics further subdivided into hard, sheet, rope, medical, foamed and fibrous plastic. Fibrous plastics included items such as cigarette butts and stuffed animal poly-fill, and medical plastic included items such as Band-Aids and syringes. Foamed plastic were items like polystyrene, while rope plastic included ropes, monofilament line, ribbons and strapping. Sheet plastics were soft plastic items, such as cling wrap, confectionary wrappers and soft packaging, and hard plastic included any 'hard' items like bottles, buckets and toothbrushes.

Items were then identified by what they actually were (e.g., bottle, straw) with the weight (using a AandD GF-10K balance, accurate to 0.01 g), longest length (using metal ruler accurate to 0.1 cm), colour and any other distinguishing feature for each item being recorded. Additionally, the area of debris objects for a site was determined, by multiplying the longest two dimensions of the objects (whatever they may be, length, width, or height). For items such as flat fragments of material that may have only had one measure recorded, the longest length was used again as the second measure to determine area. Distinguishable fragments were classed as items from which they fragmented, for example a bottle cap fragment was categorised as a bottle cap. Fragments of debris (plastic, glass, metal) that were less than five cm, or greater than five cm and could not be identified to its original intact object were first grouped by colour (when applicable), counted and then weighed together. The categorisation of debris material type and enumeration of debris amounts was undertaken because it is acknowledged as a helpful tool in determining sources and the effectiveness of things such as legislation and preventative initiatives in reducing debris amounts and/or types of debris in the environment (Williams, et al., 2003).

Colour was determined using a modified coding system that is described in Appendix D: Verlis et al., 2014) that used eight colours: blue-purple, off/white-clear, green, orange-brown, grey-silver, pink-red, yellow and natural (to designate unpainted/unstained processed wood items). Colour was recorded as it can aid in item identification, sourcing and potentially is a contributing factor to interaction with wildlife.

2.3.2.4 Source of Marine Debris Items

Sourcing of debris items has been identified as an important tool in reducing marine debris pollution (Williams, et al., 2003). A matrix scoring technique used by Whiting (1998), and described in more detail by Tudor and Williams (2004), was utilised to determine the source of recovered marine debris items. Determining the source can be a challenge due to the very mobile nature of many debris items, many of which have the potential to have originated from numerous sources on land or at sea (Dixon and

Dixon, 1981; Tudor, et al., 2002). Percentage allocation (Earll et al 1999) was used to identify debris that had originated from ships. This method attributes a percentage score to the likelihood of a debris item originating from a particular source (e.g., a foreign-labelled can of insecticide would not be an item brought by beachgoers, so the probability score assigned to the can from the land – beach tourism source would be 'very unlikely') (Table 2.3).

The matrix scoring process is based on three main factors:

1. Correct identification of an item;
2. The items function, so the primary use of an item, or if an item has been modified for a secondary purpose (for example, a water bottle cut in half to be used as a bailer); and
3. The quantity (for instance large amounts of a particular item or types of items could indicate a deliberate dumping event or imply regular inputs of items) (Williams, et al., 2003).

Additionally, further aids to determine the source of debris were the consideration of factors such as labels and markings found on items, approximate distance to each source, seasonal wind and current patterns, presence and amount of fouling, and human activity occurring within the area (Williams, et al., 2003; Tudor and Williams, 2004). This technique was chosen as it allowed for debris items to be designated as originating from more than one source, and allowed for items to be weighted towards a more likely source. In instances of unidentifiable items, or common items, they would for example be given the same score for all sources.

No 'zero' was assigned for this data set, as it was decided that no one source could with absolute certainty be discounted as being from that origin. Each debris item was first assigned a score (see Table 2.5) for each potential source (Land-beach tourism; Stormwater; Commercial shipping; Commercial fishing; Recreational boating/fishing).

Using the calculations described in (Tudor and Williams, 2004), the mean for each source type is then derived for each site.

Table 2.5: Probability scoring for use with sourcing debris items

Probability of item originating from a particular source	Score
Very unlikely	0.25
Unlikely	1
Possible	2
Likely	4
Very likely	16

Some subjectivity is involved in this approach with assigning the likelihood of a source. Attributing source has been called a common sense activity that is applied to collected items (Williams, et al., 2003). However, the ability to apply a proportional allocation to an item with multiple possible sources helps to reduce this subjectivity. Not assigning a zero score could restrict the accuracy of this grading system, as in very few instances, a particular item could be sourced with utmost certainty to one particular source. Nonetheless, as the large majority of items cannot be accurately sourced to one location, then this approach is deemed the most appropriate methodology to follow.

2.3.2.5 Extension of a Marine Debris Pollution Index

A Marine Debris Pollution Index based on debris amounts and the size of debris items was developed. The Clean Coast Index scale (Alkalay, et al., 2007) was used for the beach cleanliness categories, and the marine debris size categories were developed based on a visual trialling of different debris object dimensions. A graded number system from high to low was applied to each respective measure so that a single number 'traffic light' colour code (green, yellow, red) could be generated for a surveyed beach. Numbering was created by adding the y-axis row number to the x-axis column number. The more numerous and/or large the item, the greater the perceived visual impact and this is reflected in the yellow and/or red colour coding, while less numerous and smaller items are coded green (Table 2.6).

Table 2.6: Marine debris pollution index

Mean Debris Size		Beach cleanliness				
		Very clean (0 - 0.10 m^2)	**Clean (0.11 – 0.25 m^2)**	**Moderate (0.26 – 0.50 m^2)**	**Dirty (0.51 – 1.0 m^2)**	**Very dirty (> 1.0 m^2)**
		5	*4*	*3*	*2*	*1*
1 - ≤ 25 cm^2	*4*	9	8	7	6	5
25.1 – 900 cm^2	*3*	8	7	6	5	4
> 900 – 3600 cm^2	*2*	7	6	5	4	3
>3600 cm^2	*1*	6	5	4	3	2

The limitation of this Marine Debris Pollution Index is that different material types may be small, but offensive, even in small amounts (e.g., syringe, used condoms). This index would be further improved by considering perhaps a third variable of material type (similar to Earll, et al., (2000).

2.3.2.6 Data Analysis

Statistical analyses were undertaken using SPSS statistical package (version 20.0.01). For all statistical tests run, significance was represented by $p < 0.05$ (Brown, 1986). All debris data used in parametric tests were first checked for heterogeneity using the Levene statistic and normality by running a Shapiro-Wilk's test (Gastwirth, et al., 2009). Data that had unequal variance was log transformed and re-checked to see if the assumptions were met. If the assumptions were not met the original (non-transformed data) was analysed using non-parametric tests (i.e., Mann-Whitney U-test and Kruskal-Wallis H-Test).

The mean (± standard error [S.E.]) for the greatest size, weight and amount of each debris item collected in transect were determined at both offshore and near-shore sites. The percentage occurrence of different material types, items and colours of debris items were also determined for each sample period. A chi-square analysis (χ^2) was used to determine if differences existed between colours of debris recovered offshore compared to those recovered at near-shore sites, using near-shore sites as the expected values. A comparison of the percentage of plastic to non-plastic items at near-shore and offshore sites was undertaken using a non-parametric Mann-Whitney U-test.

The number of debris items found per metre square (m^{-2}) was determined by dividing the total number of debris items collected by the total surveyed transect area for each site. The weight of items per square metre was calculated in a similar manner. An accumulation rate per day was calculated for both offshore and near-shore beaches by using the total number of items from the second collection divided by the number of days between first and second collection. Sourced items (Section 2.4.5) had the mean contribution of each source (±S.E.) determined for offshore and near-shore sites.

A one-way ANOVA was used to determine significant differences between marine debris prevalence, accumulation rate, and the mean size and weight of debris items found within near-shore and offshore survey locations, and at different sampling periods. A Mann-Whitney U test was used to determine if differences in amounts of plastic to non-plastic items was significant. A one-way ANOVA was also used to identify any statistically significant differences between debris amounts (items/m^2) collected within offshore (three Capricorn Bunker sites) and near-shore (three sites, one site on the Sunshine Coast and two at Coffs Harbour) sites and during the different sampling times. It was also used to compare the marine debris source and location between and within the offshore and near-shore sites. A Kruskal-Wallis H test was used to determine any differences between the amount of debris in the different beach zones at near-shore and offshore sites.

A Spearman rank correlation and a linear regression were used to look at slope and beach length and examine any relationship with the amount of debris between near-shore and offshore sites, and within near-shore and offshore sites. A Shannon-

Weiner Diversity Index was used to compare the diversity of debris type categories between sites and locations. This test gave an indication of how common particular debris items were in relation to other debris item types on the whole of the surveyed beach. A Kruskal Wallis H-Test was then performed to determine if differences existed between the diversity of marine debris at offshore and near-shore sites.

2.4 Results

2.4.1 Comparison of Leeward and Windward side of Northwest Island

To verify that the windward side of the islands in the southern GBR collect more marine debris, both sides of Northwest Island were surveyed. The windward side had significantly more debris recovered at both survey times ($U = 2.000$, $p = 0.010$), and had a much higher daily accumulation rate (1.2 items/day; $F_{[1,34]} = 2.840$, $p < 0.001$).

The mean weight and length of debris items were quite similar in the December 2012 survey, but the leeward beach had a greater mean length (~17 cm compared to ~10 cm) of recovered debris items in May 2013 (although this was not significant, $U = 2.000$, $p = 1.000$; Table 2.7).

Table 2.7: Summary of marine debris comparisons at Northwest Island

Time	Site	Mean length ± S.E. (cm)	Mean weight ± S.E. (g)	Mean area ± S.E. (cm²)	Weight (g) items per m²	No. items per m²	Total debris items in transect	Accumulation rate (items/day)
Dec 2012	Leeward Northwest	8.1±1.0	21.1±8.0	47.9±13.1	0.4	0.02	86	-
	Windward Northwest	8.6±0.7	26.3±8.4	62.2±11.5	1.2	0.05	237	-
May 2013	Leeward Northwest	16.7±7.1	23.2±10.3	76.0±27.6	0.2	0.01	38	0.3
	Windward Northwest	9.96±1.2	22.5±7.4	40.3±8.4	0.9	0.04	175	1.2

The diversity of material appeared greater on the leeward side of Northwest Island, at both surveyed time periods, but not significantly so (Table 2.8, $U = 0.000$, $p = 0.121$).

Table 2.8: Shannon-Weiner Diversity Index for marine debris collected at leeward and windward Northwest Island

Site	2012	2013	Mean
Leeward Northwest	2.0	1.9	1.9
Windward Northwest	0.6	1.3	0.9

The central zone of the beach consistently had the lowest levels of debris on both the windward and leeward sides. The windward side had more debris collected from its more easterly end, but this was not significant ($H_{[2]}$ = 0.458, p = 0.795). On the leeward side slightly more debris was recovered on the east transect (Table 2.9).

Table 2.9: Zone marine debris item totals for the leeward and windward sides of Northwest Island

Time	Site	East Zone Total	Central Zone Total	West Zone Total
Dec 2012	Leeward Northwest	33	17	32
	Windward Northwest	94	67	77
May 2013	Leeward Northwest	19	6	13
	Windward Northwest	89	56	30

Hard plastic items were the most common debris item recovered on both sides although more hard plastic was recovered on the windward side. More sheet and fibrous plastic, metal and glass-ceramic recovered was retrieved from the leeward side (Figure 2.2). These differences in material types between sides was found to be significant ($\chi^2_{[12]}$ = 77767.047, p < 0.001).

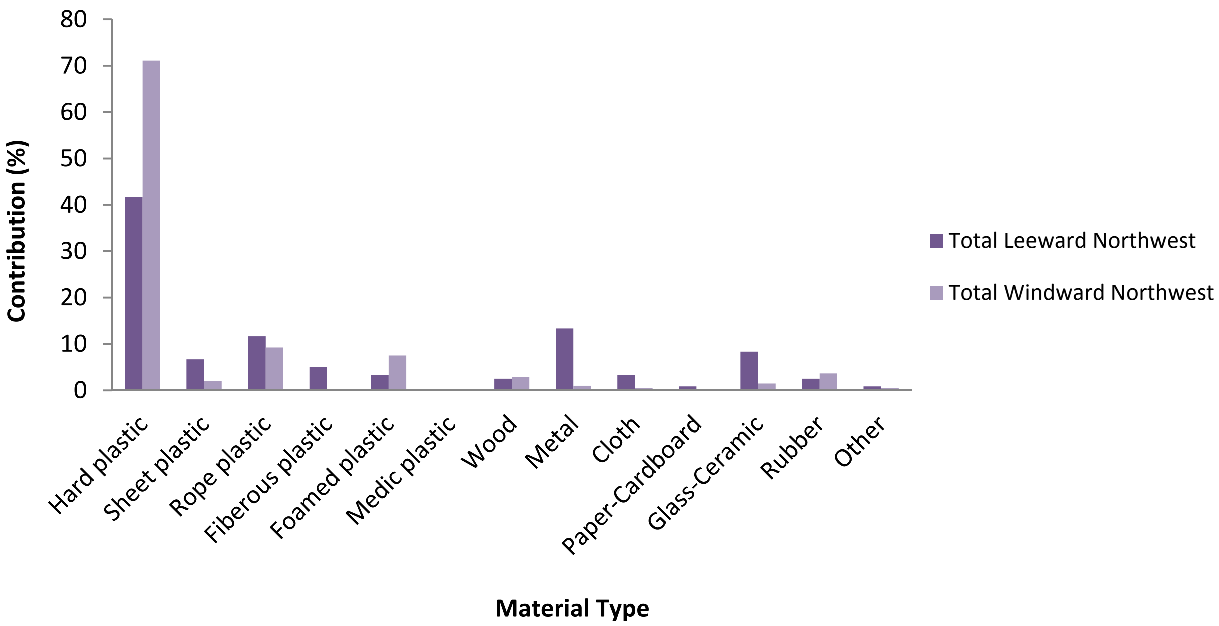


Figure 2.2: Total material types recovered from the leeward and windward sides of Northwest Island from both survey time periods

The colour of debris objects was quite similar between the sides of Northwest Island with blue-purple and off/white-clear items the most common colour (Figure 2.3). More orange-brown, grey-silver and red-pink items were recovered on the leeward-side (Figure 2.3). These differences in colour was found to be significant between windward and leeward sides of the Island ($\chi^2_{[8]} = 19.233$, $p = 0.014$).

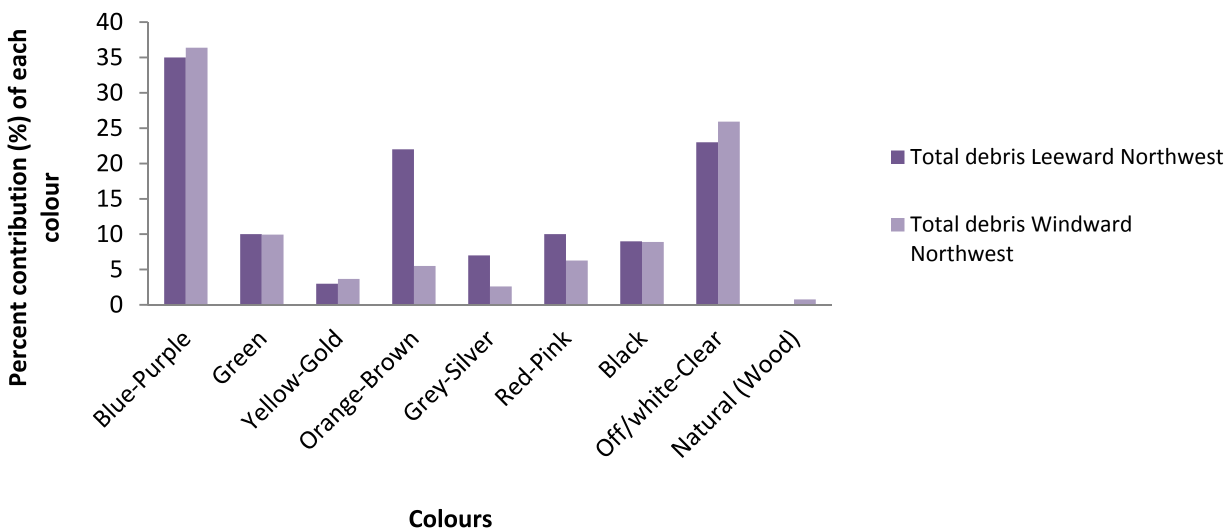


Figure 2.3: Overall colours of debris objects (%) recovered from the leeward and windward sides of Northwest Island

There were higher levels of beach tourism debris on the leeward side of Northwest Island, and overall more land-sourced pollution (44 %) on the leeward side. The windward side had more oceanic sourced debris (62 %; Figure 2.4). Although this difference in source was overall not significant ($F_{[1,8]} = 0.000$, $p = 1.000$), with sources on both sides being strongly correlated (Pearson correlation $R_2 = 0.834$, $n = 5$, $p = 0.079$) to each other.

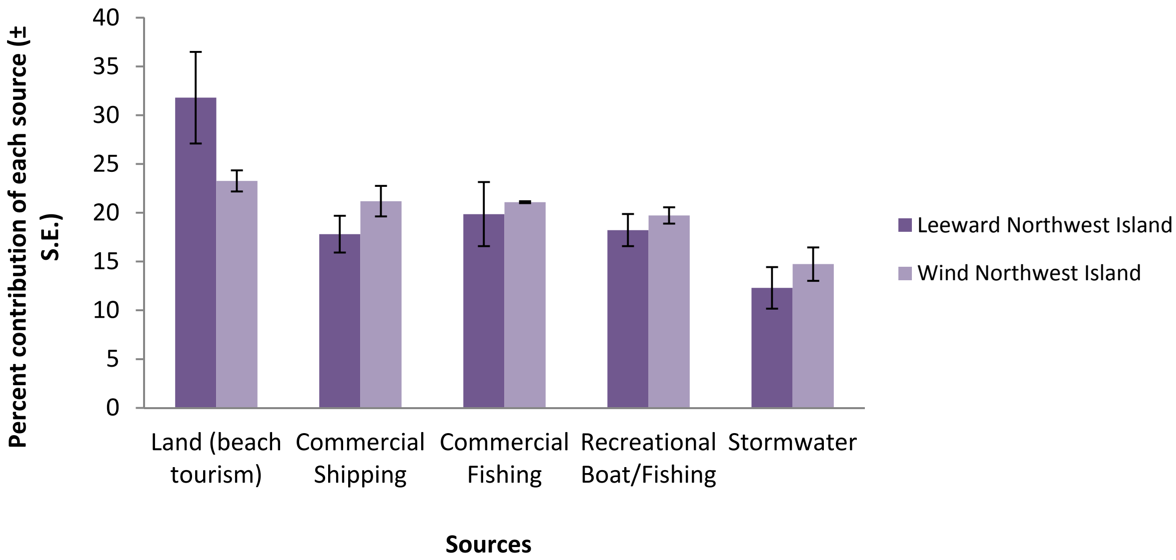


Figure 2.4: Sources of marine debris on leeward and windward sides of Northwest Island

2.4.2 Amounts of Recovered Marine Debris

Debris was found at all surveyed beaches (n = 6), both offshore and near-shore. The quantity of debris was variable among locations, with offshore sites having lower levels of debris (ranging from 0.03 to 0.05 items m^{-2}), then at near-shore sites (range from 0.03 to 0.07 items m^{-2}). Significantly more items were recovered per square kilometre at near-shore compared to offshore sites ($U = 5.500$, $p = 0.042$; Figure 2.5).Accumulation rates were thus significantly lower at offshore sites (ranged from 0.9 to 1.2 items day^{-1}) then at near-shore sites (ranging from 2.1 to 4.7 items day^{-2} ; $U = 0.000$, $p = 0.050$; Tables 2.10 and 2.11). The major findings from marine debris surveys conducted at offshore and near-shore sites at both survey time periods is summarised in Tables 2.10 and 2.11.

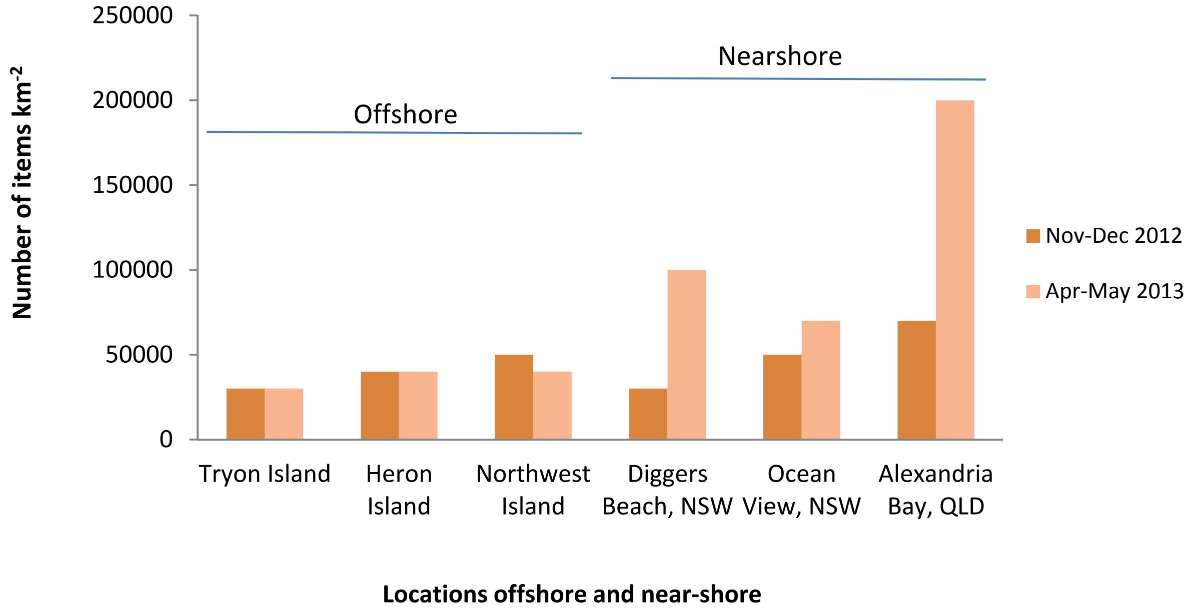


Figure 2.5: Total number of marine debris items per km^2 on offshore and near-shore beaches at two surveyed time periods

Different trends in debris levels were observed temporally in near-shore and offshore locations with near-shore locations having significantly greater amounts of debris recovered from the second survey rather than at the first survey time ($F_{[1,52]}$ = 10.563, p = 0.002; Figure 2.5). Debris levels were quite similar between offshore surveys (553 and 478 items) with just slightly more debris collected in the first survey time (this difference was not significant U = 326.000, p = 0.505; Table 2.10).

There was also a significant difference in the debris amounts between near-shore locations ($F_{[2,16]}$ = 8.197, p = 0.011). Post-hoc analysis showed that Alexandria Bay and Diggers Beach had significantly different (p = 0.023) debris levels. At near-shore locations, Alexandria Bay had the greatest number of debris items m^{-2} at both survey times (Table 2.11). These were significant different with the second sample being significantly greater than the first ($F_{[2,16]}$ = 9.197, p = 0.011). The lowest debris levels near-shore were at Diggers Beach, NSW, in November 2012 (0.03 items m^{-2}) and at Ocean View Beach, NSW, in May 2013 (0.07 items m^{-2}) (Table 2.11).

The amount of debris recovered amongst offshore sites was significantly different ($F_{[2,51]} = 3.928$, $p = 0.026$), with a post-hoc analysis showing a significant difference in debris amounts between Northwest Island and Tryon Island ($p = 0.033$). This is supported with the greatest number of items m^{-2} offshore recovered at Northwest Island (0.05 items m^{-2}) in December 2012, and tied with Heron in May, 2013 with 0.04 items m^{-2}, and the lowest amount of debris retrieved at Tryon Island at both survey times(Table 2.10).

The beach characteristics of slope, length and width were examined for correlations with the amount of debris deposited per m^2 (refer to Table 2.4). The only strong correlations were beach length at near-shore sites, which were moderately significant ($R^2 = 0.6157$, $p = 0.038$). Offshore sites had a moderate but not significant correlation, with debris amounts and beach length ($R^2 = 0.4733$, $p = 0.188$). No significant correlations were found at either offshore or near-shore sites in regards to beach slope ($R^2 = 0.0056$ and $R^2 = 0.3018$, respectively), or beach width ($R^2 = 0.0197$, and $R^2 = 0.0297$, respectively).

Table 2.10: Summary of offshore marine debris survey findings

	Site Name*	Mean length* ± S.E. (cm)	Mean weight ± S.E. (g)	Mean Area ± S.E. (cm²)	Weight (g) of items per m²	No. of items per m²	Total debris items in transect	Accumulation rate (items/day)
December 2012	Tryon Island	15.5±1.8	42.6±19.6	129.2±20.1	1.3	0.03	130	-
	Heron Island	9.7±1.4	63.6±33.0	205.8±80.7	2.5	0.04	186	-
	Northwest Island	8.6±0.7	26.3±8.4	62.2±11.5	1.2	0.05	237	-
	Overall mean for Dec 2012	10.6±0.71	43.3±12.5	126.3±27.9	1.6	0.04	553	
May 2013	Tryon Island	26.9±6.2	30.3±6.1	1438.1±1303.8	0.8	0.03	138	0.9
	Heron Island	12.7±2.7	17.3±12.8	136.6±12.8	0.6	0.04	165	1.1
	Northwest Island	9.96±1.2	22.5±7.4	40.3±8.4	0.9	0.04	175	1.2
	Overall mean for May 2013	15.8±2.1	22.9±3.7	477.1±376.6	0.7	0.04	478	1.1
	Overall mean for all offshore sites/times	13.0±1.0	34.0±7.0	288.9±175.2	1.2	0.04	1031	

*All presented island data was collected from the windward side, and longest length of debris item was measured

Table 2.11: Summary of near-shore marine debris survey findings

	Site Name	Mean length* ±S.E. (cm)	Mean weight ±S.E. (g)	Mean Area ±S.E. (cm²)	Weight (g) of items per m²	No. of items per m²	Total debris items in transect	Accumulation rate (items/day)
November 2012	Diggers Beach, NSW	10.8±0.89	23.3±7.2	124.3±30.3	0.7	0.03	143	-
	Ocean View Beach, NSW	16.1±1.8	49.6±21.9	224.8±70.0	2.3	0.05	223	-
	Alexandria Bay, QLD	7.0±0.5	10.7±3.2	65.4±13.0	0.7	0.07	317	-
	Overall mean for Nov 2012	10.8±0.7	26.0±7.2	129.8±24.7	1.2	0.05	683	
April 2013	Diggers Beach, NSW	9.8±1.3	25.4±9.2	74.1±11.7	2.1	0.1	471	3.1
	Ocean View Beach, NSW	10.6±0.9	15.7±5.1	115.8±19.7	0.1	0.07	318	2.1
	Alexandria Bay, NSW	9.6±0.9	6.2±1.2	65.4±9.1	0.9	0.2	738	4.7
	Overall mean for Apr 2013	9.9±0.6	13.9±2.8	78.6±7.0	1.3	0.1	1527	3.3
	Overall mean for all near-shore sites/times	10.2±0.5	18.0±3.0	94.4±3.0	1.3	0.08	2210	

*Longest length of recovered debris item

2.4.3 Characteristics of Recovered Marine Debris

There was a significant difference in the diversity of marine debris materials recovered between near-shore and offshore sites ($U = 0.000$, $p = 0.043$). Diggers Beach had the greatest diversity of debris item types recovered compared to all other near-shore sites (Table 2.12). Offshore sites had the greatest diversity of material at Tryon Island in May 2013. Although these differences were not significantly different to other sites ($H_{[2]} = 3.603$, $p = 0.165$, and $H_{[2]} = 1.397$, $p = 0.497$, respectively).

Table 2.12: Shannon-Weiner Index for marine debris items collected from offshore and near-shore sites

Offshore Sites	**2012**	**2013**	**Mean**
Heron	1.3	1.8	1.5
Tryon	1.2	1.9	1.5
Northwest	0.6	1.3	0.9
Overall Offshore Mean			1.3
Near-shore Sites	**2012**	**2013**	**Mean**
Alexandria Bay	1.9	1.7	1.8
Ocean View	1.9	1.8	1.8
Diggers	2.1	2.0	2.0
Overall Near-shore Mean			1.9

Both near-shore and offshore debris types from both survey periods were pooled and showed that there were significantly more plastic items (> 70 %) recovered than non-plastic items ($U = 6.00$, $p = 0.032$; Figure 2.6). When considered individually, significantly more plastic than non-plastic items (73 % and 21 %, respectively) were recovered at offshore sites ($U = 0.000$, $p = 0.002$), and at near-shore sites (78 and 18 %, respectively, $U = 6.000$, $p = 0.032$).

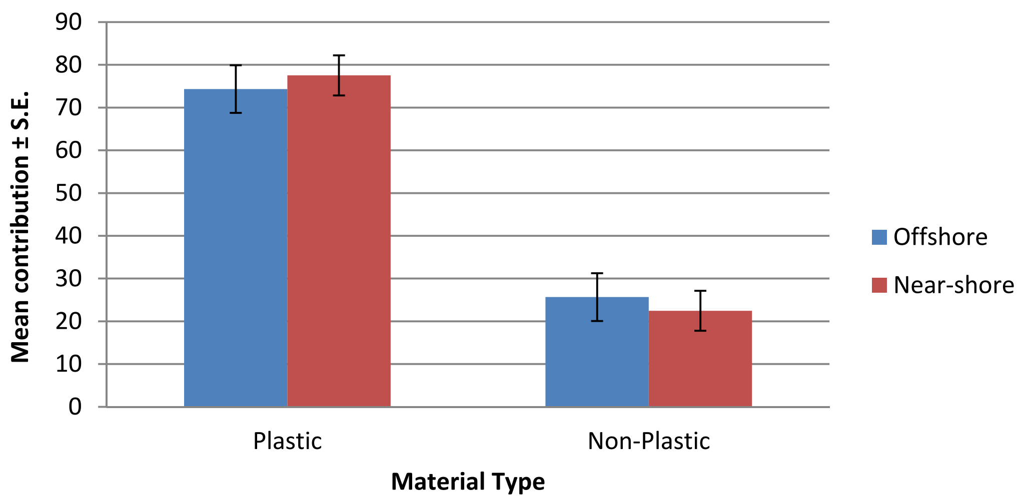


Figure 2.6: Comparison of plastic and non-plastic marine debris items on offshore and near-shore beaches

At both offshore and near-shore locations, hard plastic items were overwhelmingly the most common debris material type recovered (56 and 42 %, respectively). A significant difference in material types recovered offshore compared to near-shore was found ($X^2_{[12]} = 68.187$, $p < 0.001$), Figure 2.7). Debris items of foamed plastic (~10 %), metal (~5 %) and glass-ceramic (~6 %) were present at higher levels at offshore sites. This differed from near-shore sites that had higher levels of fibrous (e.g., cigarette butts, ~14 %) and sheet plastic items (e.g., bags and wrappers, ~13 %; Figure 2.7). Medical plastic and 'other' items were the least common marine debris material type from both near-shore and offshore locations (Figure 2.7).

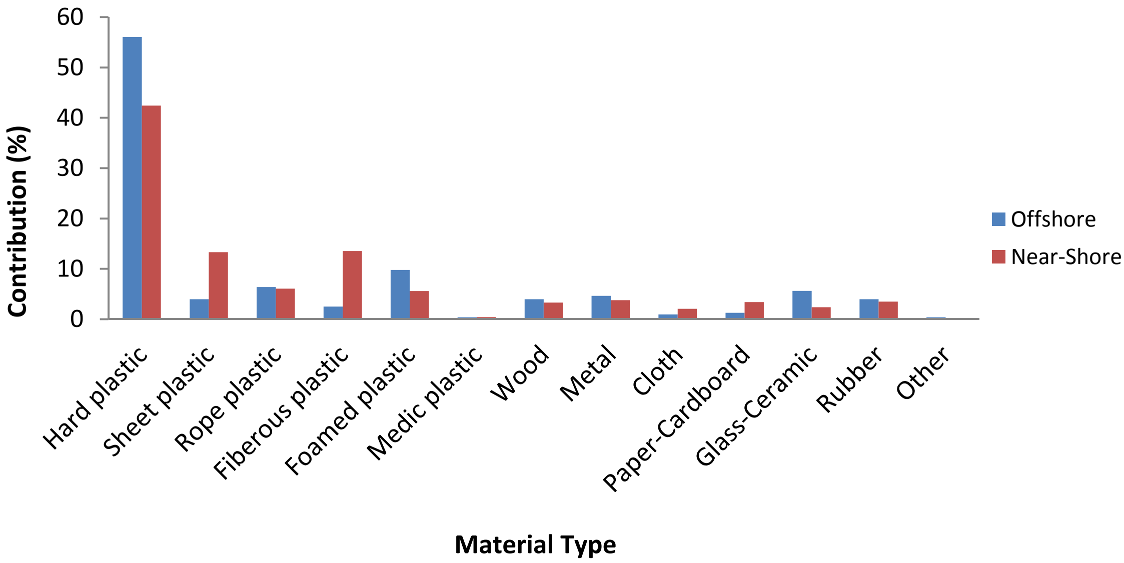


Figure 2.7: Comparison of total marine debris material type from offshore and near-shore sites (includes both survey times)

Colours of debris items were not found to be significantly different between offshore and near-shore locations overall ($\chi^2_{[8]} = 7.993$, p = 0.434), or at either sampling time period (Nov/Dec $F_{[1,52]} = 0.964$, p = 0.331; Apr/May $F_{[1,52]} = 0.151$, p = 0.699). Off/white-clear debris items were the most prevalent colour on both offshore and near-shore beaches, (~31 % and 39 %, respectively). There were more blue-purple (~24 %) and black (~9 %) coloured debris items recovered from offshore sites (Figure 2.8). Natural (wood) coloured items were the least common debris item colour at both offshore and near-shore sites. Colours at near-shore sites were not significantly different amongst locations ($F_{[2,51]} = 0.105$, p = 0.901) or between survey times ($F_{[1,52]} =$ 0.009, p = 0.926); and considering offshore sites separately, also showed no significant difference in colours between survey times ($F_{[1.52]} = 0.964$, p = 0.331) or within offshore locations ($F_{[2,51]} = 0.346$, p = 0.709).

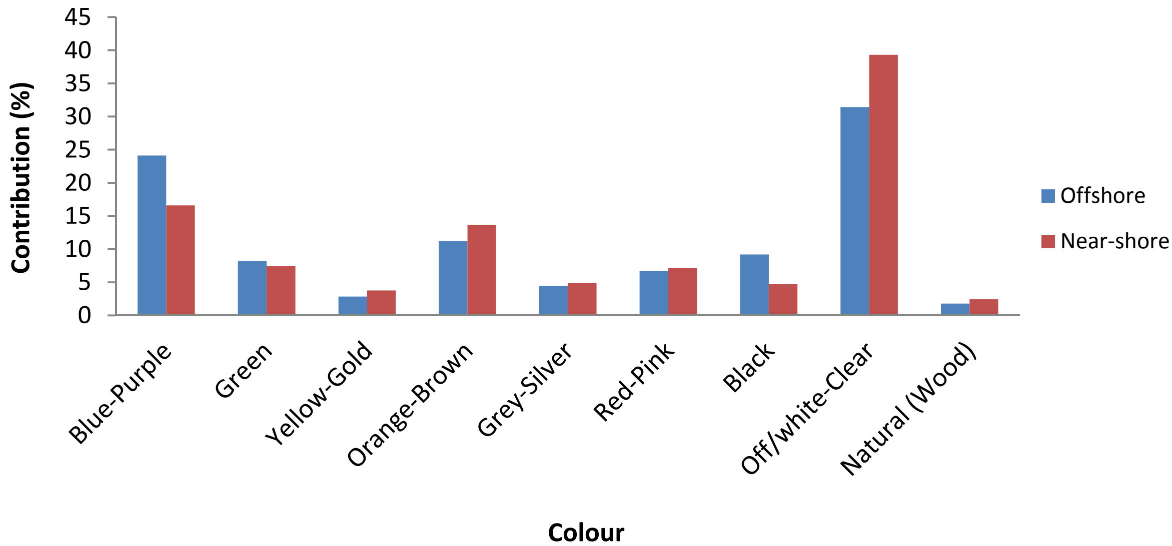


Figure 2.8: Comparison of the colour of the total marine debris items on offshore and near-shore beaches (includes both survey times)

Heron Island had the heaviest mean weight (~64 g) of items, mean area (~206 cm^2) and greatest mean weight of items per square metre (~3 g m^{-2}) of all the offshore sites in December 2012. This changed in May 2013, with Tryon Island having the largest mean length (~27 cm), mean area (1438 cm^2) and heaviest mean weight of debris items (~30 g) (Table 2.10). Northwest Island had the lightest weight of debris during both survey periods (~62 and 40 g, respectively). In the near-shore the greatest mean size and weight of debris was at Ocean View Beach in November 2012 (~16 cm and 50 g) (Table 2.11). The smallest mean size items were found at Alexandria Bay at both survey times, although the overall sizes were quite similar between near-shore sites.

2.4.4 Zonal Differences in Marine Debris

There was a significant difference in the amounts of marine debris found in beach zones between near-shore and offshore locations ($F_{[1,16]} = 6.621$, $p = 0.020$). There were also significant differences within offshore ($F_{[2,51]} = 3.856$, $p = 0.035$) and near-shore ($F_{[2,51]} = 5.625$, $p = 0.06$) sites for marine debris amounts. At offshore sites, a post-hoc analysis shows a significant difference between the central and west zones ($p = 0.046$). Trends at Heron Island for instance, illustrate that significantly more debris was recovered in the western zone ($F_{[2,15]} = 27.472$, $p < 0.001$; Table 2.13). While, the east end of the beach had higher levels of debris at Tryon and Northwest Islands. All of the near-shore sites had higher loads present in the southern beach zone (Table 2.13), with lowest amounts in the north zone at both Alexandria Bay and Ocean View beach. A post-hoc analysis shows a significant difference in debris amounts between northern and southern zones ($p = 0.006$).

Table 2.13: The total debris items in each zone for both offshore and near-shore sites

Offshore Sites	**East Zone Total**	**Central Zone Total**	**West Zone Total**
Tryon Island	116	81	71
Heron Island	53	54	244
Northwest Island	183	123	106
Near-Shore Sites	**South Zone Total**	**Central Zone Total**	**North Zone Total**
Diggers Beach	359	102	153
Ocean View Beach	266	153	122
Alexandria Bay	515	355	185

NB: 3 transects per zone for a total of 9 transects run per site

A univariate analysis showed that near-shore sites had no relationship between zone and location ($F_{[4,51]} = 0.710$, $p = 0.590$) or between zone and time ($F_{[2,51]} = 1.560$, $p = 0.224$). This differed at offshore sites, which had a significant relationship between location and zone amounts ($F_{[4,51]} = 6.671$, $p = 0.001$), but no significant relationship existed between zone and time of surveys ($F_{[2, 51]} = 0.199$, $p = 0.821$).

2.4.5 Sources of Marine Debris

Overall, near-shore sites had over half of all debris originating from land-based sources (55 %), and this differed significantly to offshore sites that had more debris originating from oceanic-based sources (~60 %; Figure 2.9; $F_{[2,60]} = 546.811$, $p = 0.021$). Land (beach tourism) was the most common individual source of marine debris items on both near-shore and offshore sites (Figure 2.9).

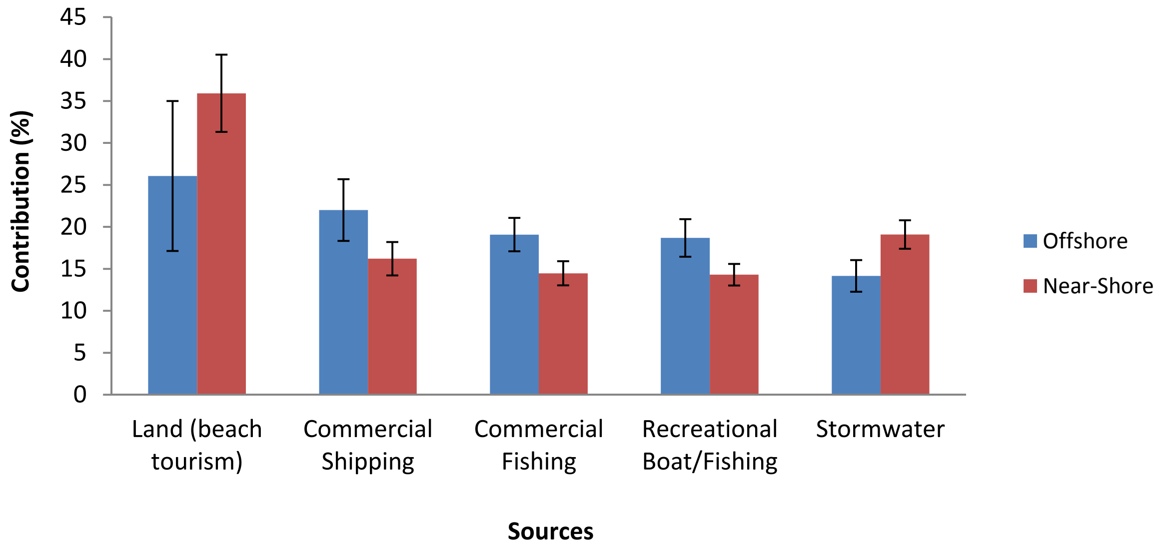


Figure 2.9: The mean contribution (%) of marine debris for each source at offshore and near-shore locations. Bars represent standard error (S.E.) of marine debris at offshore and near-shore locations

On offshore sites, Tryon Island had the lowest proportion of land (beach tourism) sourced debris, with commercial shipping having the greatest influence. This differed to Heron Island that was dominated by land (beach tourism) (Figure 2.10a). The differences in land and ocean-sourced debris was significantly different at offshore sites ($F_{[1,13]}$ = 0.975, p = 0.001), but when each source was compared separately, there was no significant difference detected ($H_{[4]}$ = 3.557, p = 0.469). This differed to near-shore sites that had a significant difference in both overall oceanic to land-sourced debris (Mann-Whitney U-test = 6.000, p = 0.013) and also for each debris source considered separately ($H_{[4]}$ = 15.953, p = 0.03). Land (beach tourism) related debris was the most common source at near-shore sites (Figure 2.10b), with Diggers beach having the highest levels of both land beach-tourism and stormwater related debris.

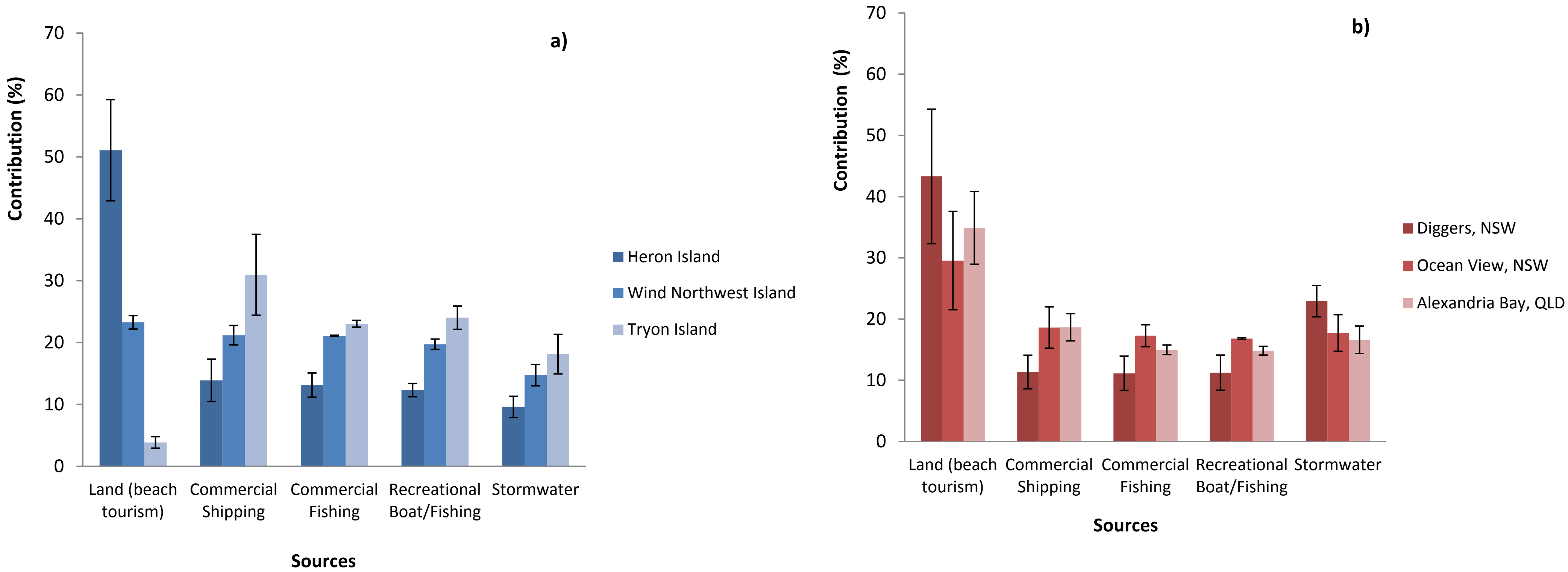


Figure 2.10: Contribution (%) to source of marine debris at individual a) offshore; and b) near-shore (± S.E.) sites

2.4.6 The application of a Marine Pollution Index

The marine debris counts and size data at each site for each sample time was imputed into the Marine Debris Pollution Index (Table 2.6) and a score given. All reported surveyed sites in this project in Nov/Dec 2012 had low levels of pollution, with a Pollution Index Score of 'Green 8' (Table 2.14). This changed in the April/May 2013 sampling period, with Tryon Island, Diggers Beach and Alexandria Bay decreasing to a score of 'Green 7' indicating a higher level of marine debris pollution (Table 2.14).

Table 2.14: Marine Debris Pollution Index score applied to surveyed sites at both survey periods

	Nov/Dec 2012			Apr/May 2013		
Site	**Debris m^{-2}**	**Mean item Area (cm^2)**	**Pollution Index Score**	**Debris m^{-2}**	**Mean item Area (cm^2)**	**Pollution Index Score**
Tryon Island	0.03	129.2±20.1	**8**	0.03	1438.1±1303.8	**7**
Heron Island	0.04	205.8±80.7	**8**	0.04	136.6±12.8	**8**
Wind Northwest Island	0.05	62.2±11.5	**8**	0.04	40.3±8.4	**8**
Lee Northwest Island	0.02	47.9±13.1	**8**	0.01	76.0±27.6	**8**
Diggers Beach, NSW	0.03	124.3±30.3	**8**	0.11	74.1±11.7	**7**
Ocean View Beach, NSW	0.05	224.8±70.0	**8**	0.07	115.8±19.7	**8**
Alexandria Bay, QLD	0.07	65.4±13.0	**8**	0.20	65.4±9.1	**7**

2.5 Discussion

This study aimed to determine differences in marine debris pollution between near-shore and offshore wedge-tailed shearwater nesting sites. This included an examination of the amounts, types and sources of marine debris and any trends in abundance between near-shore beaches and offshore island locations. This study provides evidence that marine debris pollution is present on beaches near important nesting sites of the wedge-tailed shearwater on the East Australian coastline. This chapter also introduces a new, relatively simple, and easy to use method to quantify shoreline pollution.

Comparison of Northwest Island Windward and Leeward Beaches

An investigation of leeward versus windward debris accumulation on Northwest Island in the Capricorn Bunker Group of Islands showed that there were significant debris differences. This confirms that the windward side of the island is more likely to accumulate debris and hence justifies the sampling strategy outlined in this chapter. Although both sides of Northwest Island have comparable back of the beach vegetation and dunes habitats, the leeward side has low impact campground facilities, with associated drop-toilet facilities. No such facility exists on the windward side of the island. The leeward side is also where recreational vessels access the island, and where commercial fishing vessels may drop anchor to shelter for the evening in protection of the surrounding reef. Hence, the leeward side of the island is exposed to more potential sources of debris.

The greater diversity of material (Table 2.7) and significantly different material types and colour of items recovered on the leeward side is therefore, likely due to the presence of camping and higher visitation. This is supported by the presence of particular items such as cigarette butts, metal items and glass beer bottles recovered on the leeward beach (Figure 2.2) that were either absent or in lower densities on the windward beach. Although overall source of items was not shown to be significantly different between the different beach sides, more leeward side items are attributed to land-based sources (44 %).

It is well established that windward and down-drift beaches experience greater deposition than leeward beaches (Gregory, 1990; 1999; Williams and Tudor, 2001). Thus, the differences between the marine debris amounts on the leeward and windward beaches of Northwest Island in May 2013 was expected, and demonstrates the influence of prevailing winds, nearby currents, and exposure to source as driving factors in the debris deposition (Table 2.10). This highlights the importance of understanding factors that influence debris deposition when choosing a sampling site, and how these factors can influence the interpretation of results, with regards to abundance and source.

HYPOTHESIS H_I: Marine debris will only be present at very low levels on the beaches of offshore and near-shore surveyed sites.

Marine debris was present at all surveyed locations but only at low levels and hence H_I is supported. The average amounts recorded at the three near-shore sites (0.08 items m^{-2}) were similar to levels at beaches around the more populous Sydney, NSW, region (0.1 items m^{-2}, n = 6) (Cunningham and Wilson, 2003), and were higher than levels previously reported for beaches in northern NSW (0.003 to 0.01 items m^{-2}; Frost and Cullen, 1997; Taffs and Cullen, 2005). The level of debris recorded at offshore sites (0.04 items m^{-2}) was lower than levels seen in the nearby coastal area of Gladstone, QLD, (0.09 items m^{-2}) (Wilson, 2012), but were slightly higher to the levels reported in the more remote Swain Reefs, southern GBR (0.01 items m^{-2}) (Appendix D: Verlis, et al., 2014) and were greater than levels in the northern GBR (0.005 items m^{-2}; Haynes, 1997).

In a more global context, the amounts recorded offshore in this survey were similar to those recorded on Russian beaches (0.02 items m^{-2}), but Russian debris was present at greater weights (12.8 g m^{-2}; Kusui and Noda, 2003) than at offshore (1.2 g m^{-2}) sites in this study. Japanese beaches had higher levels of debris (3.63 items m^{-2}; Kusui and Noda, 2003) and at much greater weights (24.0 g m^{-2}). While beaches in the Thousand Islands in Jakarta Bay, Indonesia, had an overall debris load of 6.9 items m^{-2}, making these beaches more polluted than both near-shore and offshore sites in this study. In Mumbai, India, extremely high debris levels were recorded (11.6 items m^{-2} and 3.24 g m^{-2}) (Jayasiri, et al., 2013). Thus the surveyed beaches in this study are relatively clean in comparison to many of the beaches at other global locations.

Cleaner Australian beaches may be a reflection of the smaller Australian population size and thus reduced inputs compared to Japanese, Indonesian and Indian beaches that have much greater population densities and potential sources from both land and at sea. Additionally, although Australia is a big country and is reliant on shipping, generally the shipping traffic is coming directly to Australia and there is not a lot of indirect shipping traffic. This differs to major shipping hubs in southeast Asia for instance, like Singapore and Hong Kong (Azmi, et al., 2015) that have more shipping traffic both direct and indirect passing-by and this can also contribute to higher debris loads originating from oceanic sources in these areas.

The Marine Debris Pollution Index developed in this project adds an additional dimension that combines the monitoring of changes to debris amounts on beaches with the mean area (cm^2) of recovered debris items. With minor adjustments the index could be ground-truthed for beach user perceptions around what amount and type of debris would cause a beach user to stop using a beach, or to complain to council or other beach managers. This index could be a useful tool for councils and environmental managers of these spaces as it would provide insight into the social dimensions of the issue and provide information about community expectations and reactions to beach cleanliness. The Condom Equivalent Index created by Nelson, et al., (2000), for instance, is based on a visual perception and response to pollution. This could be further developed and applied at time of debris sourcing to provide a social dimension to the debris findings and give an aesthetic grading.

Application of the Marine Debris Pollution Index at Diggers Beach and Alexandria Bay give index scores that increased into the 'green 7' grade zone during the second survey time. This information could be used by managers to justify undertaking actions to remediate sites as a result of the differing scores/colours. Particular actions could be undertaken (i.e., beach closures, or clean-ups) and measures to reduce debris loads could be investigated or initiated (i.e., introduction of gross pollutant traps on stormwater drains at Diggers Beach, NSW). The presence of breeding grounds (i.e., endangered or vulnerable species, or species that are protected under international agreements such as JAMBA or ROKAMA), if the beach is part of a protected area (i.e., national park, RAMSAR), level of beach usage (i.e., high or low) and accessibility of a shoreline should be considered to determine the most appropriate responses and the time-line of action.

At Tryon, the change from a ‘green 8’ to a ‘green 7’ grade is due to the presence of a large shipwrecked boat in the sample transect that increased the overall area for debris items at this site at this time. This shipwreck was likely moved out to sea during Cyclone Oswald, and eventually made land at this island (Table 2.10). This site provides an example of why an understanding of debris type and source is an important component of the analysis of the grading system and what the appropriate action is to be taken.

In general, a move from green to yellow could indicate the need for increased monitoring and removal of debris; a move from yellow to red could indicate that the site be cleaned, closed and an investigation into source. A move from green to red would require immediate action be taken with an investigation into source and clean-up of site. A move red to green, or yellow to green could be used as a learning exercise with an investigation undertaken to ascertain what led to the reduction so that perhaps these successful reductive measures could be applied to other sites.

HYPOTHESIS H_{II}: No variation will exist between the amount and type of marine debris between and within near-shore and offshore sites (spatially and temporally).

The significantly greater amounts of debris (Mann-Whitney U-test = 5.500, $p = 0.042$) and differences in debris material ($X^2_{[12]} = 68.187$, $p < 0.001$) recovered near-shore versus offshore was anticipated due to more potential sources and the greater amount of litter and litter types that are generated at near-shore sites due to the population densities in these areas. This finding refutes H_{II}.

It has been suggested that debris diversity and cleanliness of a beach are correlated and that the less diversity in recovered debris items, the cleaner the beach (Earll, et al., 1999). Offshore the diversity of items was significantly lower than that at near-shore sites ($U = 0.000$, $p = 0.043$), and the near-shore beaches were more polluted. So in that sense this pattern of higher diversity in recovered debris items and higher pollution levels does hold true. On an individual beach scale this pattern did not appear to be the case however, as Tryon Island had the least amount of debris and had one of the highest diversity indices (Table 2.12). The Earll et al., (1999) study was based on studies of coastal beaches not offshore islands sites with less exposure to land-based sources of debris, so the findings from that study may not hold true for some individual island sites. Although Heron Island, arguably acts like a land-based site due to the high human visitation and presence of significant degree of infrastructure.

Within near-shore beaches, spatial and temporal differences in debris amounts existed but variations at offshore locations were only significant at a spatial scale, not at a temporal scale. Thus, only near-shore sites refuted H_{II}, with offshore sites supporting this hypothesis.

The significantly higher debris amounts recovered near-shore during the second survey in April 2013 ($F_{[1,52]} = 10.563$, $p = 0.002$) (Table 2.8) was unexpected. Generally the first clean of a beach will show the greatest amount of debris with subsequent surveys reflecting those debris items deposited (or exposed) during that time between surveys (Ribic and Johnson, 1990). The time between surveys (or time for deposition) is less than the first collection time, where the site may never have been cleaned previously and hence reflects a starting datum that are based on deposition periods of years to decades (or longer). Consequently, these differences could be due, in part, to the influence of seasonal weather patterns and storm activity that occurred between sampling times.

The November to April sampling period is the wet season in Central and Southern Queensland (Batianoff, et al., 2009), which brings a greater prevalence of monsoon conditions such as rain, higher winds and flood events. The wet season weather patterns could act to increase the likelihood that land sourced debris was brought to the coast, especially with flood events. Large storm events, have been shown to increase debris levels through intensified wind and wave action (Vauk and Schrey, 1987; Golik and Gertner, 1992; Frost and Cullen, 1997; De Araujo and Costa, 2006; Smith and Markic, 2013) and through an increase in storm water discharge and river run off (Pruter, 1987; Gregory, 1991; Cunningham and Wilson, 2003; Ocean Conservancy, 2010). Flooding in Queensland and New South Wales occurred in January 2013 as a consequence of Cyclone Oswald (many affected areas set new January rainfall records) and hence this pattern of debris deposition and potentially exhumation (although this was not measured) at the surveyed sites could be related to the observed wet season weather patterns experienced at the near-shore sites. Comparatively Cyclone Oswald was quite weak as a Category one. However, cyclones are expected to increase in strength and severity (i.e., more Category 4 and 5 cyclones) with climate change such as increasing sea surface temperature (Webster, et al., 2005) this could have implications to debris mobilisation and deposition on both near-shore and offshore study sites in the future.

At Alexandria Bay in particular, there was significantly more debris recovered in April 2013 ($F_{[1,16]} = 8.197$, $p = 0.011$) and this could be related to the Sunshine Coast being especially impacted by Cyclone Oswald, with winds of 125 km/h and more than 150 mm of rain that lead to over 70 road closures in the region due to floodwaters (Sunshine Coast Daily, 2013). The near-shore northern NSW sites were also impacted by this weather system, but to a slightly lesser extent as the cyclone had been down-classed to a tropical low when it made landfall (ABC Coffs Coast, 2013).

In addition to the storm and weather events affecting the deposition and remobilisation of items, the timing of recreational activities likely contributed to the variability in the collected debris amount between near-shore locations (and to a certain extent between near-shore and offshore). Although removal of debris by beachgoers can be a mechanism that decreases debris on beaches (Bravo, et al., 2009), more often increased beach usage will lead to concurrent increases in debris levels, with popular tourist beaches often needing to be cleaned by local governments or resort owners in the summer months (Golik and Gertner, 1992; Wetzel, et al., 2004; de Araujo and da Costa, 2007; Oigman-Pszczol and Creed, 2007; Santos et al., 2009). At the near-shore temperate/sub-tropical beaches usage increased from December onwards through the Austral summer months, when the weather is relatively warmer. The significantly high levels of debris recovered from near-shore beaches in April likely in part reflect the higher usage that occurred during that six month period (Table 2.11).

Although clean-up activities are known to occur at some of the surveyed beaches by beachgoers and/or concerned locals, these clean-ups are generally piecemeal and unorganised only focusing on a small section of the beach and targeting larger debris items (e.g. beverage bottles) with smaller items (e.g. bottle cap) often overlooked (Rees and Pond, 1995). Due to the variable nature of debris load deposition and remobilisation, and as a result of both environmental and human actions, these activities have recognised biases on debris levels and types recovered.

The significant difference in debris levels between Diggers beach and Alexandria Bay ($p = 0.023$), could be related to the difference in overall beach length. A significant correlation was found between beach length and higher debris loads at near-shore beaches (R^2 = 0.6157), and Alexandria Bay was the longest beach at 1,200 m and Diggers beach was the shortest at 800 m (Table 2.4).

The similar debris loads recovered offshore at the two survey periods could in part reflect the more consistent usage of the marine environment by both commercial shipping and commercial fishing activities. Although the Austral winter months have more ideal weather for boating and recreational activities in temperate regions, tourism does occur year-round in the sub-tropical/tropical offshore sites of Heron and to a lesser extent Northwest Island (Table 2.10). The level of beach tourism at these sites is considerably less than at near-shore beaches, despite Heron Island having the capacity to host hundreds of people due to the presence of a holiday resort, research station and staff living quarters (Hill, et al., 1995). The significant differences in debris amounts between Northwest and Tryon Islands (p = 0.033) could be related to the differences in beach length. A significant correlation was found between length of beach and debris amounts (R^2 = 0.4733). Although size and number of transects were the same on all beaches, Northwest Island was the largest beach surveyed and Tryon the smallest (Table 2.4).

Plastics were the most predominant material type at both offshore and near-shore locations (Figure 2.6). This is a common finding at beaches around the world and is not unexpected due to the high level of plastic production and its persistence within the environment (Andrady, 2000; Derraik, 2002). Both offshore and near-shore sites had high numbers of hard plastic items such as bottle caps, fragments of user plastic items, and bottles (chemical cleaner, beverage containers). These items are commonly found elsewhere at surveyed beaches in Australia (Haynes, 1997; Whiting, 1998; Slavin, et al., 2012; Smith and Markic, 2013) and around the world (Santos, et al., 2009). Few industrial 'virgin' pellets were recovered on near-shore sites with none found on offshore beaches.

The type of material collected differed significantly between near-shore and offshore sites ($X^2_{[12]} = 68.187$, $p < 0.001$; Figure 2.7). This difference appears to be related, at least in part, to the source of the material and the nature of the material. Sheet plastic items for instance, include such items as food wrappers and shopping bags were found at higher levels on near-shore beaches (~11 %) as were fibrous plastic items, which are mainly cigarette butts, as well as paper-cardboard items, such as newspapers (Figure 2.7). These items had most likely entered the waterways via direct pollution by beachgoers, through stormwater runoff, or via wind-blown debris from peri-urban areas. As sheet plastic items are very light-weight they can be readily carried by the wind and are commonly found on urban beaches (Hayward, 1984; Gregory, 1991; Ocean Conservancy, 2010). Debris items such as cigarette butts and newspaper are items commonly found on more populous beaches and are related to passive or intentional littering (Oigman-Pszczol and Creed, 2007; Santos, et al., 2009).

There was a higher percentage of fibrous plastic (primarily cigarette butts) on near-shore beaches compared to offshore sites (14 % and 3 % respectively); with the exception of Heron Island that had cigarette butts from the island visitor and residents. The high number of cigarette butts found near-shore in particular, is in keeping with studies around Australia that estimate upwards of 32 billion cigarette butts are littered every year (Clean Up Australia, 2010). Littered cigarette butts are harmful to wildlife due to the large number of chemicals that are used to grow and process the tobacco and that are used in the manufacturing process (Slaughter, et al., 2000). Both unsmoked and smoked cigarette butts/filters are known to leach some of these harmful chemicals into aquatic ecosystems resulting in toxic effects to both freshwater and marine organisms (Register, 2000; Micevska, et al., 2006); Slaughter, et al., 2011).

Cellulose acetate fibres make up cigarette filters, and each of the 15,000 fibres is treated with titanium dioxide and are held together using triacetin to create a single filter. The layers of paper or rayon wrapping around the filter contains glues and alkali metal salts of organic acid that help maintain burning while the cigarette is being smoked and which also help make these filters quite toxic (Slaughter, et al., 2011). Cigarette butts littered onto beaches or over the side of boats in the southern GBR in particular could have negative repercussions on this already stressed coral system (De'ath, et al., 2012). Thus, debris items can be quite toxic to organisms through their presence, even without ingestion.

The difference in material collected from offshore sites (Figure 2.7) contributed to the greater weight and size of debris items recovered (Table 2.10). Thus, understanding debris material type, amounts and identifying items on a beach is important, as it can have implications to the potential impact to the environment and wildlife therein. The impacts of marine debris upon wildlife, through ingestion and entanglement is the reason that marine debris is classified as a key threatening process by the Australian Government (DEWHA, 2009).

The small plastic fragments that are so common on near-shore and offshore beaches, and the plastic bags and sheeting common to near-shore beaches can pose a threat to marine wildlife through ingestion (Laist, 1997; Bugoni, et al., 2001). This can have implications to marine biota within the area and is explored further in Chapters 3 with ingestion in wedge-tailed shearwaters that are nesting nearby to surveyed beaches. Alexandria Bay, QLD, and Diggers Beach, NSW, had balloons, and/or balloon paraphernalia present in transects. Balloons are notoriously harmful to marine life due to their resemblance to prey items when mobilised in water (Lutz, 1990). A migrating short-tailed shearwater (*Ardenna tenuirostris*) found dead in Coffs Harbour (location of both Diggers Beach and Ocean View Beach) contained in its gut contents a balloon with ribbon attached; with the proventriculus so impacted it was likely the main contributing factor to its demise (Verlis, unpublished data).

Colours were relatively similar on near-shore and offshore sites ($X^2_{[8]} = 7.993$, $p = 0.434$) and off-white/clear items were the most common colour debris item at all surveyed sites (Figure 2.8). Blue-purple items were the second most common colour of items, with the level being higher offshore (24 %). The higher levels of blue-purple and black items offshore were mostly items such as fragments, mainly hard plastic, and bottle caps. No temporal and spatial patterns of debris item colours between locations or within near-shore or offshore locations were evident.

The colour of debris objects may have implications for marine wildlife, as off/white-clear items are the most common colour of item ingested by both seabirds (Furness, 1985b; Ogi, 1990; Eriksson and Burton, 2003; Titmus and Hyrenbach, 2011; Rodriguez, et al., 2012; Verlis, et al., 2013), and sea turtles (Bugoni, et al., 2001; Lazar and Gracan, 2011). There has been limited published research on the occurrence of marine debris colour found in debris surveys and any potential colour selection by affected organisms (Verlis, et al., 2013). Shoreline and at-sea trawl surveys for marine debris should record and report on colour to aid in understanding the potential of colour to influence wildlife-debris interactions.

HYPOTHESIS H_{III}: No variation will exist within and between beach zones at near-shore and offshore beaches.

Differences of debris within beach zones were observed both offshore and near-shore and therefore reject H_{III}. The significantly higher levels of debris in the western zone of Heron Island ($F_{[2,15]} = 27.472$, $p < 0.001$; Table 2.13) was attributed to the proximity to the jetty and high level of human traffic through this beach zone. While the southern zone of Diggers beach was shown to have higher amounts of debris, particularly in May, and this was attributed to proximity to a small creek which appeared to have transported items from a nearby park. Certain zones on a beach, like those near to entry points, stairs, creeks and/or rubbish bins (receptacles) can increase debris levels in and around those areas (Morgan, et al., 1993; Edyvane, et al., 2004). Although this study attempted to reduce influences of entry points by sampling 10 m away from these types of zones, the spread of debris from these areas could have been more extensive.

The significant differences seen within near-shore and offshore zones is also likely influenced by coastal morphology and the presence and extent of nearby reefs. Near-shore sites are predominantly influenced by southerly swells and this is reflected in the shape of beaches (Short, 2006), with many having prominent headlands. These headlands generally lead to refraction of waves around them causing a loss of wave energy and reducing the energy of these waves reaching the southern section of the beach (Herfort, 1997; Short, 2006; 2007). This reduction in energy could lead to a release of any debris carried within that water. Thus, it was unexpected that the near-shore sites had southern zones with significantly more debris than their northern zones ($p = 0.006$).

Marine debris is carried along by currents and tides and if its density is altered can move through the water column (Maximenko, et al., 2012). Beach orientation, bathymetry of an area, and the debris material and its buoyancy can also contribute to deposition and remobilisation of marine debris on beaches (National Research Council, 1995; Kiessling, 2003). Transport of debris on and off of beaches occurs mainly through near-shore currents, and tidal inundation with the strength and direction of wind influencing the amounts and distribution of debris on a beach (Vauk and Schrey, 1987; Williams and Tudor, 2001a,b; Smith and Markic, 2013). Different zones of a beach can experience greater levels of deposition due to factors such as in areas of greater beach width and/or presence of native vegetation (de Araujo and da Costa, 2007). Sites in this study were chosen to have similar physical characteristics to minimise these potential confounding factors.

All the near-shore beaches could be considered to be intermediate beaches characterised by a prominent surf zone with rips and sand bars, and having fine to medium sand (Short, 2006; 2007). The shape of these beaches will influence the local currents, the extent of exposure to wind and wave action and will subsequently impact upon the amount, distribution and type of debris that is deposited (Herfort, 1997). All selected near-shore beaches had human activity associated with them, and the southern zones of all three beaches were the most human-occupied sections (pers. obsv.). The significant differences between zones are likely influenced by the human traffic that may exist in the area, in addition to wind and current patterns.

HYPOTHESIS H_{IV}: The source of marine debris will not differ significantly between near-shore and offshore sites.

Near-shore and offshore surveyed beaches differed significantly in their source of marine debris, thus refuting H_v. Offshore sites had significantly more debris attributed to oceanic sources (60 %; $F_{[1,13]} = 0.975$, $p = 0.001$; Figure 2.9). Alternatively, near-shore beaches had significantly more debris classified as being land-based sourced (55 %, $F_{[1,13]} = 11.808$, $p = 0.004$; Figure 2.9). As already discussed, near-shore sites in this study (Table 2.4; Chapter 1, Sections 1.14.2-1.14.3) were located closer to population centres and this close proximity is reflected in the greater contribution of land-based sourced debris. The reasoning behind this is that urban areas, with larger populations provide more readily available debris that can be washed or blown in from streets and from stormwater discharge. This pattern is common for other Australian beaches, where land-based sources are often identified as significant sources of marine debris (Pruter, 1987; Gregory, 1991; Cunningham and Wilson, 2003; Ocean Conservancy, 2010; Slavin et al., 2012).

Beach tourism debris was the greatest individual source of marine debris overall for both offshore and near-shore sites (although not significantly so), with these sources identified as being significant contributors to beach debris (Corbin and Singh, 1993; Santos, et al., 2005; Oigmann-Pszczol and Creed, 2007). At offshore sites, this was likely due to the swamping influence of the significant tourist activities that occur at Heron Island and to a lesser extent at Northwest Island, which is clearly seen in Figure 2.10a. In general, there was a trend of decreasing beach-tourism sourced debris with distance from tourist facilities. For example, Tryon Island has no formal tourist activities present and the contribution of land-based debris was very low (< 5 %; Figure 2.10a). Tryon Island theoretically had no tourist activity at the time of the surveys, however, due to the inability to assign a zero to any one source; it still registered as having land-beach tourism source inputs. Also giving evidence to the influence of beach tourism is in the zone differences along individual beaches. At Heron Island for instance, significantly more debris was recovered in the western zone near to the jetty where a great deal of ferry/boat and snorkelling/swimming activity occurs ($F_{[2,15]}$ = 27.472, p <0.001; Table 2.13). Of importance, is that the presence of humans (directly or indirectly) strongly influences the occurrence of marine debris. This has environmental management implications at these important seabird and turtle nesting sites. A study done in the 1990s at Heron Island found that the development of infrastructure and influx of people did not appear to have a negative impact on wedge-tailed shearwater breeding population numbers at that time (Hill, et al., 1995). However, this study did not examine the impacts of waste generated on the island to resident wildlife. Further research on the impacts of tourisms in the GBR from a littering perspective would be beneficial as this study has indicated the influence of beach tourism as a source (Figure 2.10a) at Heron Island (see Chapter 3).

The higher levels of debris occurring from oceanic-based sources at offshore islands was similar to what was observed on islands in the northern GBR and in the Swain Reefs with items sourced to nearby commercial shipping and fishing activities

(Haynes, 1997; Appendix D, Verlis, et al., 2014; Chapter 4). The influence of commercial fishing activities to offshore sites in this study were lower than that seen in Northern Australia where the majority of debris is attributed to this source (Kiessling, 2003); although generally less beach tourism occurs in Northern Australia than that in the southern GBR and hence, this pattern is not totally unexpected. The source of debris does appear to be strongly reflected in the level and type of nearby activities either onshore or at sea (Canadian Council of Ministers for the Environment, 1999). A number of fishing fleets operate within the GBR and a great deal of recreational fishing occurs with access to the reefs being possible from Gladstone, QLD. The shipping route to access ports along the GBR has resulted in more than 9,600 commercial ship voyages in the reef and 3,947 individual ships attended reef ports in 2012 (Smith, 2015). The Capricorn-Bunker Group of Islands is surrounded on all sides by shipping routes (Haynes, et al., 2000 Figure 2.11), thus the potential for exposure to shipping generated wastes is quite high at these islands sites. Increased port activities in the region shipping traffic is likely to lead to increases in ship-sourced marine debris, and marine debris is identified an area of concern in the GBRMPA 30-year outlook report (Commonwealth of Australia, 2015).

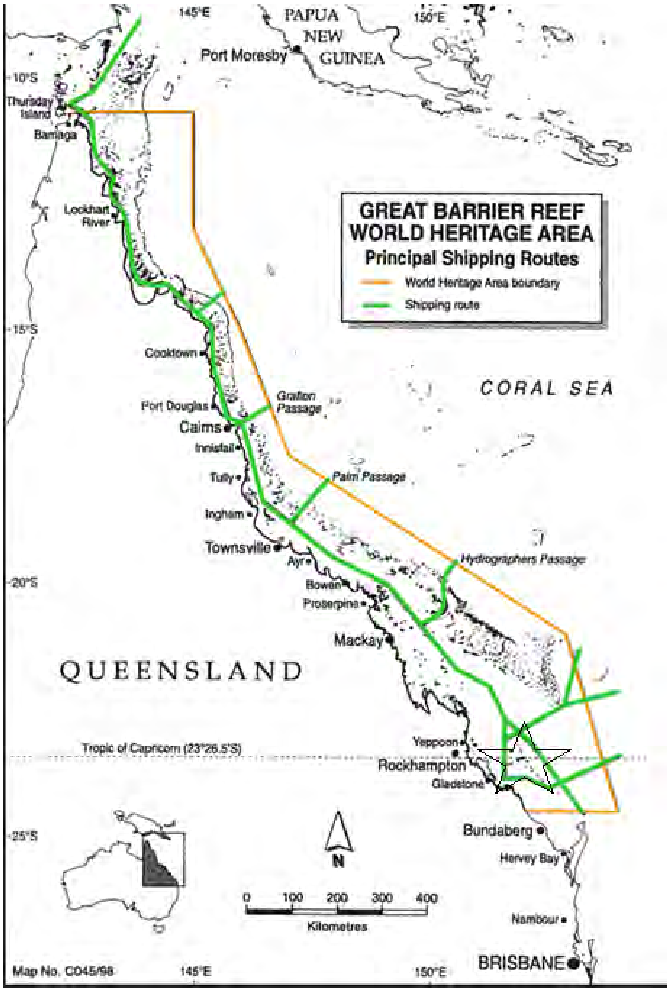


Figure 2.11: Shipping routes in the Great Barrier Reef World Heritage Area (GBRWHA) - Capricorn-Bunker group of islands is within the black star outline (map from Haynes, et al., 2001, p49)

2.6 Conclusions and Recommendations

Nearly all proposed hypotheses were refuted (H_{II}, H_{III}, H_{IV}) with the crux of this chapter clearly demonstrating that there are significant differences between debris amounts and types between near-shore beaches and at offshore islands in the study area. Overall near-shore locations had higher debris loads (items m^{-2}) and greater amounts of material by weight; although further surveys over at least three year period are needed to confirm these findings within a seasonal context. This would ideally be managed via quarterly surveys. Further long-term (10-20 year) studies and monitoring would then provide insights into long-term driving forces such as ENSO (El Niño Southern Oscillation) events and changing climatic regimes. Monitoring of debris trends that result from this increased activity could help in developing appropriate management approaches.

The source of marine debris appeared to contribute to the amounts and types recovered. Land-based sources, such as stormwater, had a significantly higher influence (i.e., higher levels) at near-shore sites. Conversely, offshore sites were closer to, and more influenced by, oceanic sources of debris such as shipping, fishing and recreational boating activities. The sources of and differences in types of debris recovered at near-shore and offshore locations has implications for management of this issue. A one-sized fits all management style cannot be adequately applied both near-shore and offshore locations as their sources and type of debris differ. Hence, management actions need to be tailored to consider this. Increased education and monitoring of marine debris pollution is needed to inform about and report on the changing amounts and sources of debris.To help mitigate the problem of oceanic sourced marine debris a clearer understanding of the dynamics of marine debris source and transport, and its accumulation within all zones of the marine environment (beach, water column, benthic) is important. Tourism in the GBR is responsible for adding billions of dollars to the Australian economy each year, and near-shore sites are popular holiday areas for Australians (Kookana and Pham, 2013). Tourism and recreational activities at beaches and at sea are important contributors to the marine debris that is deposited upon surveyed beaches (Figure 2.9). This indicates that litter and marine debris educational initiatives are perhaps warranted to aid the public to fully grasp their contribution to this issue.

The enforcement of current maritime legislation that prohibits the disposal of rubbish at sea should be supported and strengthened. The greatest source of debris at offshore sites was from oceanic sources (60 %), reinforcing this need. The monitoring and management of marine debris clearly falls within the goals of the Commonwealth's threat abatement plans as marine debris is a key threatening process. In addition, the offshore sites fall within Capricornia Cays National Park and Capricornia Cays National Park (Scientific) management plan (Queensland Parks and Wildlife Service, 2000). Marine debris initiatives, such as reducing plastic bag usage, and increasing recycling could be incorporated into the management of recreation, tourism and visitor activities as well as in educational initiatives undertaken by the State under the guidance of the Commonwealth Government that oversees the Great Barrier Reef Marine Park Authority (GBRMPA). Any initiatives that are introduced can then be monitored through marine debris surveys that provide a performance measure for management to determine their effectiveness (Moore, 2008). The Marine Debris Pollution Index (Table 2.14) developed in this thesis could help facilitate the monitoring activities and may be used to report upon the ecological risk of marine debris to the region (see Chapter 5).

CHAPTER 3

Ingestion of Plastic Marine Debris by the Wedge-Tailed Shearwater (*Ardenna pacifica*) at Nesting Sites on the East Coast of Australia

3.1 Introduction

One of the main interactions marine debris has with animals is through ingestion that can lead to morbidity and mortality (Fry, et al., 1987; Ryan, 1987b; Auman, et al., 1997; OSPAR Commission, 2008). Ingestion can also expose birds (and other organisms) to chemical contaminants that may have been preferentially adsorbed to the plastic from within the water, or from chemicals that are intrinsically part of the plastic from the manufacturing process (Derraik, 2002; Colabuono, et al., 2010; van Franeker, et al., 2011). Ingesting these toxin coated plastics may also affect bird health, reproduction, and general well-being (Guruge, et al., 2001; Colabuono, et al., 2010; Yamashita, et al., 2011), with the potential for these contaminants to be concentrated up the food chain (Endo et al., 2005; Teuten, et al., 2007; Chen and Hale, 2010).

More than 56 % of studied seabirds have interacted with marine debris (Gall and Thompson, 2015), with subsequent negative health effects observed in a number of species. The evidence for these negative affects is not strong (Ryan and Jackson, 1987; Moser and Lee, 1992); but can include suppressed appetite and reduced growth (Ryan, 1988a), decreased fat deposition (Connors and Smith, 1982), and lowered fledgling mass (Sievert and Sileo, 1993; Lavers, et al., 2014). Plastic ingestion has also been linked to satiation and dehydration in chicks of poor condition (Auman, et al, 1997), damage to the digestive system (Pettit, et al., 1981; Sileo and Fefer, 1987) and in extreme cases has caused blockages and starvation (Zonfrillo, 1985; Dickerman and Goelet, 1987; Pierce, et al., 2004). The specific cues for intentional marine debris ingestion by seabirds are not clear.

It is theorised by some researchers that the feeding behaviour of individual species and the resemblance of debris items to natural food may make some species more susceptible to debris ingestion (see Table 1.13 in Chapter 1; Bourne and Imber, 1982; Day, et al., 1985; Ryan, 1987a; Moser and Lee, 1992; Robards, et al., 1995). The Procellariiform order is especially at risk of ingestion, due to their behaviours (including method and location of feeding), their stomach physiology, and the limited ability of this order to regurgitate unless feeding its chick (Day, et al., 1985; Fry, et al., 1987; Sileo, et al., 1990; van Franeker and Meijboom, 2002; Hutton, et al., 2008; Colabuono, et al., 2009; see also Chapter 1 Section 1.10.2 and 1.13.1).

The wedge-tailed shearwater is a Procellariiform and a pelagic seabird that feeds mostly on small fish, cephalopods and crustaceans (Harrison, 1983; Marchant and Higgins, 1990; Pelagicos, 2005; Crowley, et al., 2008). In some areas, this species can be found hunting with schools of predatory fish and cetaceans that drive prey to the surface (Shealer, 2002; Pelagicos, 2005). Their feeding behaviour can include contact dipping, dipping, surface seizing and pursuit-plunging (Harrison, 1983; Marchant and Higgins, 1990), and they may also scavenge behind trawlers and fishing boats (Marchant and Higgins, 1990; Burger, 2001; Pelagicos, 2005). Wedge-tailed shearwaters will typically fly less than 10 m above the ocean surface while hunting and often targets ocean convergence zones and areas that favour higher productivity that may also act to concentrate debris (Burger, 2001). This could potentially expose this species to an increased risk of plastic marine debris ingestion. This species at Capricorn-Bunker Island sites in the southern GBR are known to undertake bimodal foraging (Peck and Congdon, 2005) and will forage quite close (30 km up to 100 km) to the nesting colony while feeding their young (Cecere, et al., 2013; McDuie., pers comm.).

Responding to local resource availability a number of seabirds from the Order Procellariiform are known to balance the cost of maintaining body weight and the cost of parental care by regulating foraging trip duration during the chick rearing period

(Baduini and Hyrenbach, 2003; Welcker, et al., 2009). The short trips are used to gather food for chicks while long trips are used to replenish energy lost during chick provisioning (Shealer, 2002). Several species exhibit a bimodal foraging strategy that alternates between short (1 – 5 day, inshore) and long (6 – 29 day, pelagic) foraging trips (Shealer, 2002; Baduini and Hyrenbach, 2003; Peck and Congdon, 2005). This bimodal foraging strategy is more often seen in tropical-subtropical species and those in temperate areas. Long trip foraging grounds targeted by bimodal species often areas with higher productivity indicated by having greater chlorophyll a concentrations (Baduini and Hyrenbach, 2003).The bimodal foraging strategy is not universal in Procellariiformes and can differ from year to year within a given population, with some undertaking bimodal and unimodal foraging based on individual body condition (Baduini and Hyrenbach, 2003). The wedge-tailed shearwaters at Heron Island are recorded as undertaking bimodal foraging with short trip durations of 1-3 days and long trips of up to 8-days at long-shelf habitats (Smithers, unpubl. data, as cited in Baduini and Hyrenbach, 2003; McDuie, et al., 2014). This differed to wedge-tailed shearwaters in Hawaii and the French Frigate Shoals that undertook unimodal short trip foraging trips lasting between 1-2 days at narrow shelf oceanic habitats (Baduini, 2002). Oceanic productivity patterns can have an important role in foraging strategies and distribution of seabirds during the breeding season (Baduini and Hyrenbach, 2003).

At locations around the Pacific Ocean, including Australia, the wedge-tailed shearwater is known to ingest plastics (Fry, et al., 1987; Sileo, et al., 1990; Ainley, et al., 1990a; Spear et al., 1995; Hutton, et al., 2008). The first study to show ingested plastic by the wedge-tailed shearwater was Fry, et al. (1987) in the Hawaiian Islands of Midway Atoll and Oahu. Since then, a number of studies have shown the incidence of ingestion in the wedge-tailed shearwater, and have indicated a risk for transference of plastic from the adult parent bird to its chick(Sileo, et al., 1990; Hutton, et al., 2008).

Transference is related to the birds' limited tendency to regurgitate unless feeding its young (Azzarelllo and Van Vleet, 1987; Fry, et al., 1987; Hutton, et al., 2008). Ingestion was investigated successfully in some of these studies by a live regurgitation stomach lavage method.

No studies have looked at plastic ingestion in seabirds in the GBR or at nesting shearwater populations along the mainland East Coast Australia. This is despite the world's largest nesting population of wedge-tailed shearwaters located in the Capricorn-Bunker Group of islands (Hill, et al., 1995). Additionally, it is the only Procellariiform nesting in this area, making it an ideal species to study plastic ingestion in the southern GBR.

3.1.1 Methods to Sample Stomach Contents of Seabirds

A number of techniques are available to sample birds to detect ingested material. Many seabird species will regurgitate when handled (Ashmole and Ashmole, 1967; Harrison, et al., 1983; Ryan and Jackson, 1986) allowing for ready access to stomach contents for analysis. Stomach flushing and the use of emetics are also non-lethal methods of determining the stomach contents of birds that do not spontaneously regurgitate. These methods may also provide a way to systematically collect diet information and can provide non-biased samples, which can be more difficult to obtain with spontaneous regurgitate (where the bird regurgitates on its own, usually due to fright/stress) as not all stomach contents may be voided (Votier, et al., 2003).

The use of emetics is controversial due to certain compounds, like antimony potassium tartrate, having harmful and sometimes deadly effects on dosed birds (Randall and Davidson, 1981; Ford, et al., 1982; Diamond, et al., 2007). More recent studies have shown that ipecacuanha (ipecac), which is a natural extract from the root of the rubiaceous plants (*Cephaelis ipecacuanha* or *C. acuminate*) may be a safe emetic to use (Diamond, et al., 2007; Bond and Lavers, 2013). However, its use does not always result in the bird regurgitating (e.g., Horne, 1985). Stomach flushing (or gastric lavage) techniques have been developed as a non-lethal alternative for sampling stomach contents, with this technique having been validated in many studies for its effectiveness and low impact on birds both young and old (Ford, et al., 1982; Wilson, 1984; Ryan, 1987b; Votier, et al., 2003; Neves, et al., 2006).

The first standardised stomach lavage method was developed by Randall and Davidson (1981). This method was not ideal however, as it did not yield all stomach contents (larger prey items were not always recovered due to restrictions from tube sizing) and it was thought that the stress from this method could result in the abandonment of eggs or young by the sampled birds (Randall and Davidson, 1981; Ford, et al., 1982; Wilson, 1984). Consequently Wilson (1984) developed a simpler and less stressful stomach pump procedure that improved upon the Randall and Davidson (1981) method.

Subsequent testing of Wilson's (1984) technique has shown that it may also not recover all contents (Horne, 1985; Lishman, 1985; Gales, 1987) and that it may be less effective on birds that have full stomachs where items are tightly packed (Lishman, 1985; Gales, 1987). The proportion of food recovered by a single pumping was found to be negatively correlated with total stomach contents and a single pumping only removed total contents when stomachs were less than 20 % full (Ryan and Jackson, 1986). This technique's effectiveness is related to the degree of digestion that has occurred, with less digested items being recovered more readily (90-100 % recovered), than more fully digested food items (80 % recovered) as demonstrated in little penguins (Gales, 1987). However, the issues related to recovery can be overcome by flushing the bird a second time, to ensure a more complete recovery of stomach contents (Ryan and Jackson, 1986; Gales, 1987; Neves, et al., 2006). Other potential negatives to a stomach flushing technique are that it may stress birds and can be labour intensive to undertake (Votier, et al., 2003).

The Wilson (1984) lavage technique has however, been used successfully and has been repeatedly undertaken with no apparent negative effects in thousands of birds, representing at least 24 different species; including at least eight species of penguin, white-chinned petrels, arctic terns, and Cory shearwaters (Wilson, 1984; Horne, 1985; Votier, et al., 2003; Neves, et al., 2006). Only one known fatality exists and it was attributed to worker incompetence (Ryan and Jackson, 1986). This technique is most effective for species with simple stomach morphologies (Wilson, 1984; Ryan and Jackson, 1986; Ryan, 1987b).

Procellariiform gizzard contents (with the exception of albatrosses and giant petrels) cannot be removed/sampled accurately by this technique, as a result of the narrow, U-shaped isthmus that exists between the proventriculus and ventriculus (Figure 1.6; Furness, 1985a; Ryan and Jackson, 1986). Accurate sampling is thought to only be accomplished through killing the bird (Furness, 1985a; Ryan and Jackson, 1986; Ryan, 1987b); although a study done by Sileo, et al. (1990) did use a lavage technique on petrel and shearwater species, including the wedge-tailed shearwater with some success. The gizzard in petrels is thought to only contain more resistant prey remains, and not fresh food items (Furness, 1984; Ryan and Jackson, 1986; Ryan, 1987b). Hence, sampling the gizzard contents is important in a plastic ingestion study as this is where plastics would likely accumulate over the long term.

The proventriculus can still reveal recent plastic ingestion however, and plastics accumulated in the short-term will be present here. Overall the stomach flushing protocol is a valid and typically non-lethal method to determine the stomach contents of most avian species (Ford, et al., 1982; Votier, et al., 2003). As such the gastric lavage method is the technique that was subsequently chosen to investigate the ingestion of marine debris by nesting wedge-tailed shearwaters within this study area.

3.1.2 Potential Interactions of Marine Debris and Seabirds of the Great Barrier Reef

The GBR is home to more than 20 different seabird nesting species (Commonwealth of Australia, 2009). Wedge-tailed shearwaters are abundant within the GBR's Capricorn-Bunker group of islands in particular, and are found burrowing in the ground of *Pisonia* forests on the more vegetated cays and islands (Hutchings, et al., 2008). This species is found nesting at locations offshore in the southern GBR and near-shore in southern Queensland (QLD) and in northern New South Wales (NSW) (Chapter 1 Section 1.14 and Chapter 2).

The broad aim of this chapter was to assess the occurrence of marine debris ingestion in wedge-tailed shearwater adults and late-stage chicks, and to compare rates of marine debris ingestion between offshore islands in the southern GBR to near-shore locations in south east QLD and northern NSW. It is thought that birds nesting closer to more polluted (near-shore) areas (Chapter 2) will have higher incidences of plastic ingestion.

The specific null hypotheses addressed within this chapter are:

- **HYPOTHESIS H_V**: There will be no ingestion of marine debris by the wedge-tailed shearwater in study areas;
- **HYPOTHESIS H_{VI}** : There will be no difference in the ingestion (amounts, types, occurrence) of marine debris by wedge-tailed shearwaters at near-shore and offshore sites (spatially);

- **HYPOTHESIS H_{VII}**: There will be no difference in the ingestion (amounts, types, occurrence) of marine debris by wedge-tailed shearwaters at offshore sites temporally;
- **HYPOTHESIS H_{VIII}**: No difference will exist in the plastic ingestion occurrence between adult wedge-tailed shearwaters and the late-stage chicks;
- **HYPOTHESIS H_{IX}**: There is no correlation between plastic ingestion and seabird body condition as indicated by bird morphometric measurements; and
- **HYPOTHESIS H_X**: No difference exists between marine debris material type and colour found in beach transects near to nesting sites and that found ingested by the wedge-tailed shearwater.

3.2 Methods

3.2.1 Site Selection

Surveys were conducted on both offshore and near-shore locations on the east coast of Australia, specifically a subset of the locations surveyed in Chapter 2. Offshore islands where birds were sampled were Heron Island and Northwest Island in the Capricorn-Bunker Group of Islands within the southern GBR, and near-shore sites in southern Queensland and northern NSW at Mudjimba and Mutton Bird Islands, respectively (refer to Figure 1.10).

3.2.2 Sample Size

A modified Standard Error equation using a 95 % Confidence Interval (Bradley, 2007) was used to determine the number of birds that needed to be sampled to be sure that the sample proportion was within 0.05 of the correct value (Equation 3.1). Thus, solving for *n* provided the number of birds that needed to be sampled to show a result that falls within a 95% confidence interval (CI) (k = 1.96, k is a standard number for a 95 % CI), with an alpha of 0.05, and a 21 % incidence rate (p) (based on trial data of the percentage of wedge-tailed shearwaters that had ingested plastic marine debris at Heron Island in May 2012).

This was determined to be 255 birds per location.

Equation 3.1

$$n = p(1-p)1.96^2/0.05^2$$

$$n = (0.21)\ (1-0.21)(3.8416)/(0.0025)$$

$$n = 255$$

In addition, at least 40 birds per sampling time per site was what van Franeker (2011) determined to be an adequate number to provide a regionally relevant representation of ingestion in the northern fulmar (*Fulmaris glacialis*). Therefore, the overall goal for this project was to sample at least 255 wedge-tailed shearwaters in total from all sites, with at least 40 birds from each site in the Capricorn Bunker of islands and at both Mudjimba and Muttonbird Islands during each sampling season.

Due to poor weather conditions, or restrictions in time, it was not always possible to reach sampling targets. For example, in the case of the Mudjimba Island, access was only achieved once and was limited to a 3-hour period due to tidal access restrictions. As such, only nine live birds were able to be found and processed at this site at that time, with one dead bird collected for necropsy.

When possible, dead wedge-tailed shearwaters were collected and necropsied using the method developed by van Franeker (2004), to supplement the live regurgitation data. However, most birds were alive when sampled, with only nine birds found dead and collected from sites for necropsy. In live sampled birds, the sex could not be determined so any differences in ingestion between male and females could not be ascertained.

The lavage approach was more suited to late-stage chicks and adults due to possible concerns over the well-being of earlier stage birds to this technique (Animal

Ethics CQUniversity Approval A11/09-276). All late-stage chicks were sampled at roughly the same time in development, with late-stage chicks at Mudjimba Island and Muttonbird Island sampled a month before those at Heron Island and Northwest Island, as these birds to the south are generally older due to an earlier nesting time (Roberts, et al., 1973). The sampled late-stage chicks were no longer completely covered in down, which would be present until 75-85 days post-hatching. Down was observed on the abdomens, necks or heads of sampled late-stage chicks, which can persist after 90 days post-hatching (Petit, et al., 1984). The wedge-tailed shearwater is thought to lose between 10-15 % of its weight prior to fledgling (Petit, et al., 1984), however, this had not yet occurred in the sampled late-stage chicks and they were no longer in their vertical growth phase (10 – 40 days post-hatching).

3.2.3 Sampling Times and Location

Sampling was undertaken for periods of between three to seven consecutive days/nights in February 2012, and May 2012, and in April 2013 and May 2013, at the above mentioned locations (Figure 3.1; Table 3.1). Different areas of each site were chosen for sampling every day/night (marked by flagging tape) to try to eliminate the likelihood of resampling the same birds and to reduce stress in other birds and wildlife present within the area. An opportunistic sampling design was used based on accessibility, and the presence of overhead clearings in the vegetation (when present), so as to see adult birds landing. Sample areas were chosen purposefully off-track as sampling (especially during the day) was required to be undertaken out of view of island visitors. Care was taken to prevent damage to burrows when catching and sampling birds. An approximate sampling area of 20 by 20 m was used, with between four and six different areas sampled in each experimental period. All wedge-tailed shearwaters were captured by hand at burrows within the chosen area were checked for chicks during the day, and any adults landing in or entering into burrows within this area were sampled in the evening.

The sampling area was within the central area of the colony, with areas that fell within the periphery of the area not being sampled. This was due to possible conflicts with turtle activity, safety issues relating to sheer cliff drop-offs at some locations, and to eliminate any influencing factors that could be impacting on birds that choose peripheral nesting sites. Birds landing were captured by hand and placed into a cotton pillowcase, or calico bag until processing could take place. A major limitation to this survey was the requirement of sampling adult birds immediately on their return, with this restricting the number of adult birds that could be sampled in one evening. Late-stage chicks could be sampled at any time, as they were restricted to their burrows.

With the exception of Heron and Mudjimba Islands, all sites were sampled on at least two occasions (Table 3.1). Heron Island was sampled more extensively, as it was the site where methods were initially trialled (Appendix C: Verlis, et al., 2013). Mudjimba Island was sampled only once due to difficulties associated with access.

Table 3.1: Location and time of sampling of wedge-tailed shearwaters at offshore and near-shore locations

<table>
<tr><th></th><th>Site Sampled</th><th>Time of Sampling</th><th>Life-Stage Sampled</th></tr>
<tr><td rowspan="2">Offshore Locations</td><td>Heron Island
(23°27'S, 151°57'E)</td><td>*February 2012
*May 2012
April 2013
May 2013</td><td>Adults
Adults and Late-stage chicks
Late-stage chicks
Late-stage chicks</td></tr>
<tr><td>Northwest Island
(23°18'S, 151°42'E)</td><td>May 2013</td><td>Late-stage chicks</td></tr>
<tr><td rowspan="2">Near-shore Locations</td><td>Mudjimba Island
(26°63'S, 153°13'E)</td><td>April 2013</td><td>Late-stage chicks</td></tr>
<tr><td>Muttonbird Island
(43°31'S, 145°97'E)</td><td>April 2013</td><td>Late-stage chicks</td></tr>
</table>

*Method trialling trips

3.2.4 Sampling Protocol

The morphometric characteristics of the live birds sampled were based upon the methods of van Franeker (2002) and Camphuysen (2007). An adaptation of these methods was used to record morphometrics of dead birds (in good condition). Dead birds were collected from sampling sites whenever possible, using heavy-duty plastic bags, labelled with date and location details, and then kept frozen at -24°C. They were later necropsied according to the method outlined by van Franeker (2004). This method determined the body condition and weight of the dead bird with the proventriculus and gizzard extracted and their contents examined.

For sampling of live birds, the method used was as follows:

After capture, birds were weighed (g) in a calico bag (less bag weight = 50 g dry) or pillowcase (less pillowcase weight = 100 g dry) using a Pesola spring scale (accurate to ± 0.1 g). Morphometric measurements were then taken of the bird, wing length (cm) was measured using a flat ruler, and a vernier calliper was used for all other measurements (mm; accurate to ± 0.1 mm) (Figure 3.1):

1) Culmen length (CL) (feathers to tip of beak and end of tube to tip of beak);
2) Bill depth (BD) (top of bill to bottom of point);
3) Tube length (TL) (feathers to end of tube);
4) Head length (HL) (back of head to bill tip);
5) Tarsus length.

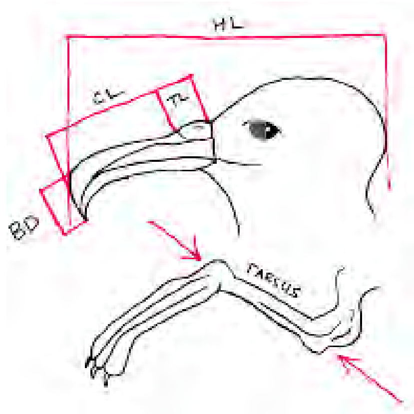


Figure 3.1: Wedge-tailed shearwater morphometric measurements (modified from van Franeker, 2004)

A modified version of the stomach flushing method as described in Wilson (1984) was used on the captured wedge-tailed shearwaters to determine ingestion of plastic marine debris. To obtain stomach samples a water-based lubricant was applied to the end of a polyvinyl tube for ease of insertion and to reduce the chance of oesophageal injury. The tube (with an inner diameter of 3.6 mm and outer diameter of 5.6 mm) was passed into the beak and slid down into the proventriculus. Ambient temperature seawater was poured into the tube via a funnel until water came out the beak. The tube was then removed and the bird inverted over a large-lipped tray to collect the sample that was flushed out of the bird. The process was repeated to ensure as complete a removal of proventricular contents as possible. The trial sampling at Heron Island in February 2012 indicated that the majority of proventricular contents were cleared in the first flush. After lavage, the neck of the bird was massaged to help remove any remaining items from the oesophagus.

The contents of the tray were emptied into a pre-labelled plastic sealable bag. Bags were pre-labelled with the following details (unique bird identification (ID) number, date of collection, location). Stomach contents collected from the flushing were kept cool in a bucket with frozen ice-packs until returned to the laboratory, where they were frozen and stored at -24°C until laboratory analysis.

Post stomach flushing, supplemental feeding of captured birds was attempted using slurry of pureed tinned sardines, canola oil and seawater via a large 60-cc syringe. Based on a study by Baduini (2002), it was expected that the wedge-tailed shearwater chicks should receive between 40-60 grams of food each day from their parent. However, most chicks refused this meal and attempting to forcefully administer the supplemental feed caused undo stress and in such instances was forgone. The same issues were encountered with adults. If the sampled bird began to exhibit signs of stress from the supplemental feeding it was abandoned. This was not expected to cause undue harm to the birds, as chicks are regularly fed by both parents (Congdon, et al., 2007).

3.2.5 Sample Analysis – Stomach Contents

In the laboratory, a modified protocol by van Franeker (2004) was used to analyse samples. Defrosted stomach content samples were rinsed through a 1-mm stainless steel sieve as per van Franeker (2011). The numbers of fish vertebrae present were counted, as well as other readily identifiable items, such as squid beaks and pumice stones. Any possible plastic was removed by forceps and placed onto a watch glass for further examination under the microscope. If there was any ambiguity as to whether an item was coral/shell or plastic, a dilute nitric acid (10 % HNO_3) test was used. In the presence of nitric acid, calcium carbonate items react to produce bubbles (carbon dioxide) and this easily differentiated the plastic items that do not react. Following the extraction of any plastic, the remaining stomach sample was then transferred to a pre-weighed labelled glass jar and dried in an oven for approximately two to three days at 100 – 105°C. Jars were then weighed and recorded, and dried stomach content weight determined by subtracting the pre-weighed (empty) jar weight from the dried jar weight.

3.2.6 Sample Analysis - Plastics

Each plastic particle was dried at room temperature (> 24°C) and weighed to the nearest 0.1 g using an analytical scale (accurate to 0.00001 g) and dimensions measured using vernier callipers (accurate to 0.1 mm). The mean (± standard error) for length and weight of all ingested marine debris plastic items was determined. Individual plastic items were counted, recorded and categorised as either user (i.e., fragments of large items, like bottles or ropes) or industrial (i.e., nurdles/virgin pellets) plastic, with any other characteristics also recorded (i.e. scratches). Plastic fragments were assigned to one of eight broad colour categories (off/white-clear; grey-silver; black; blue-purple; green; orange-brown; red-pink, and yellow) by comparing individual pieces to an expanded colour wheel that included 72-colours (TigerColour, 2013). The percentage of different ingested marine debris material types, and colours were also determined.

Ingested plastic fragments greater than 4 mm, were placed into a solution of honey, maple syrup, gylcerin, water, rubbing alcohol and canola oil (‘density tower’). This was done to determine density and thus provide an indication of plastic type, as well as give an indication of how readily the plastic particle would float in sea-water (Miami University Middleton, 2001).

3.2.7 Determination of bird body condition

Determining the condition of the wedge-tailed shearwater was accomplished by considering the mass relative to a number of body morphometric measurements, with this providing an approximation of fat reserves (Gosler, 2004). Previous studies have measured tarsus length to determine growth in the wedge-tailed shearwater (Peck and Congdon, 2006), or examined the ratio of bird body mass to bill length, or tarsus length, to ascertain body mass (Gosler, 2004). To overcome any age-related differences in morphometric measures in the late-stage chicks and adults a reasonable estimate was obtained by considering the mass relative to bird size by regressing mass on a size measure and using the residual score as a measure of condition to give an approximation of fat reserves (Gosler, et al., 1998; Gosler, 2004). As there are a number of morphometric measures that were taken of the bird (e.g. tarsus length) a Principal Component Analysis was run to compare different morphometric measures (tarsus length, wing length, head length and culmen length). Culmen length had an eigenvalue of 99.8 % variation (1.000). The PC1 values and mass were used to run a regression and the standardised residual scores were used as the condition values for the sampled birds.

3.2.8 Data Analysis

All statistical tests were undertaken in the program SPSS Statistics (Version 20.0.0.1) and significance was represented in all statistical tests by a $p < 0.05$. To determine representation of different debris colour and type, the debris was categorised as outlined in Chapter 2, Section 2.3.2.3 and analysed using a Chi-square test for independence (Acampora, et al., 2014), with the expected values for the colour and material type of debris items based on shoreline transect data at the same/nearby locations.

The mean ± standard error of ingested pieces was determined. The difference in the number of pieces ingested between years, between near-shore and offshore birds were determined by a Mann-Whitney U-test when data failed conditions of normality to perform a parametric test. The occurrence of ingestion between near-shore and offshore birds was ascertained using a Mann-Whitney U-test.

A linear regression analysis was used to determine the relationship in ingestion incidence and in the number of pieces of plastic ingested, to ascertain if relationships occurred between the body condition of late-stage chicks that had ingested plastic and those that had not. A linear regression was also used to determine if there was a relationship in size of regurgitated pumice and plastic, and any relationship between regurgitated pumice and squid beaks. Additionally, a Spearman's Rank Correlation was run to see if a relationship existed between ingestion of pumice and plastic.

The data was first checked for normality and heterogeneity. If these conditions were not met the data was log-transformed. If data still failed normality or heterogeneity, a Mann-Whitney U-test or a Kruskal Wallis H-test was run instead of a one-way ANOVA. These analyses were run to determine if there were differences in the size and weight of ingested of plastic pieces and if the percent of ingested plastic differed between near-shore and offshore birds. Analysis was also undertaken to determine if there was any difference in ingestion between sampled years, and to determine if there were a difference in pumice ingestion in birds at off-shore and near-shore sites.

3.3 Results

A total of 199 birds were sampled over two breeding seasons at four different locations (Table 3.2). In 2012, 56 birds were sampled (32 adults and 24 chicks), and in 2013, a total of 135 late-stage chicks were sampled. There were 35 plastic fragments ingested over the 2012-13 sampling periods. It was decided after 2012 that sampling would focus solely on late-stage chicks due to the significantly higher incidence of ingestion (~21 %; $U = 0.000$, $p = 0.046$), with no adult wedge-tailed shearwaters found to have ingested plastic in 2012. In 2013, ~12 % of late-stage chicks ($n = 143$) had ingested plastic marine debris (Table 3.2). Over both sampling seasons, ~13 % ($n = 211$) of late-stage chicks had ingested plastic marine debris at both offshore and near-shore sites. The average number of ingested plastics from both sampling periods and all sampling locations was 1.5±0.2 pieces per bird.

Table 3.2: Summary of detected ingestion of plastic marine debris at sampling sites during both sampling periods in both adult and late-stage chicks

Time	Location	Near (N)-/ Offshore (O)	No. sampled birds		No. ingested		% ingested		No. Plastic pieces
			Adults	Chicks	Adults	Chicks	Adults	Chicks	
Feb-12	Heron Is	O	19	n/a	0	n/a	0	n/a	0
May-12	Heron Is	O	13	24	0	5	0	20.8	16
	Total 2012		**32**	**24**	**0**	**5**	**0**	**21**	**16**
Apr-13	Heron Is	O	n/a	20	n/a	2	n/a	10	3
Apr-13	Muttonbird Is	N	n/a	40	n/a	6	n/a	15	6
Apr-13	Mudjimba Is	N	n/a	10	n/a	4	n/a	40	4
May-13	Northwest Is	O	n/a	35	n/a	3	n/a	8.6	4
May-13	Heron Is	O	n/a	30	n/a	2	n/a	6.7	2
	Total 2013		**n/a**	**135**	**n/a**	**17**	**n/a**	**13**	**19**
	Overall Total		**32**	**159**	**0**	**22**	**0**	**14**	**35**

NB: n/a indicates that no birds in this age category had been sampled at this time.
NBB: Muttonbird Is Apr 2013 includes eight-fledglings collected by WIRES volunteers from around Coffs Harbour in June 2013; and at Mudjimba Is in Apr 2013, includes one freshly dead chick collected at sampling site.

At offshore locations approximately 11 % of sampled wedge-tailed shearwater chicks had ingested plastic (Table 3.2), with an average number of 1.92±0.29 plastic items per bird (Table 3.3), while around 20 % of near-shore late-stage chicks had ingested plastic with an average of 1.00±0.00 plastic items. The percentage occurrence was not significantly different between near-shore and offshore late-stage chicks ($H_{[3]} = 3.667$, $p = 0.300$), but there was a significant difference in the number of pieces ingested between near-shore and offshore birds ($U = 40.000$, $p = 0.032$) with significantly more plastic is fed to offshore chicks along with their meals. The mean length and weight of ingested plastic pieces was significantly lower in near-shore birds ($U = 62.000$, $p = 0.028$ and $U = 54.500$, $p = 0.013$, respectively; Table 3.3)

Examining ingestion levels by site, the near-shore Mudjimba Island off the Sunshine Coast, QLD, had the greatest proportion of wedge-tailed shearwaters that had ingested plastic in the 2013 sampling period (Table 3.2), although each bird had only one piece of plastic in their proventriculus. When calculated for the two separate survey times, the number of plastic pieces recovered in late-stage chicks was significantly lower during the 2013 compared to 2012 sampling season (Table 3.3) ($U = 10.000$, $p < 0.001$). Although fewer birds were sampled and only at Heron Island in the 2012 sampling period, no significant difference was seen in the condition of birds between the two sampling times ($F_{[1,18]} = 0.640$, $p = 0.435$).

Table 3.3: Summary of the mean ± S.E. for weight (g), greatest length (mm), area (mm^2) and number of pieces of ingested plastic regurgitated/extracted from offshore and near-shore wedge-tailed shearwaters and combined total overall

Location	Weight (g) ± S.E	Length (mm) ± S.E.	Area (mm^2) ± S.E.	Number ± S.E
Offshore Islands	0.027±0.012	9.02±0.85	67.1±14.5	1.92±0.29
Near-shore Islands	0.025±0.013	5.86±0.50	22.5±9.61	1.00±0.00
Combined Overall	0.040±0.0078	8.12±0.80	54.3±11.2	1.52±0.20

No significant differences were found in the condition of late-stage chicks that had, or had not ingested plastic ($U = 1091.000$, $p = 0.204$). There was also no correlation between the condition of late-stage chicks that had ingested plastic and the number of particles ingested ($R^2 = 0.023$, $p = 0.532$).

Hard plastic fragments were the most predominate debris item found on all beaches (see Chapter 2, Figure 2.4) and were the most common debris type fed along with meals to wedge-tailed shearwater late-stage chicks at all locations (Figure 3.2). Overall, only four material types were represented; all were plastic. Hard plastic user plastics was the most common type (97 %), and only one industrial/virgin plastic pellet was found in regurgitate (Figure 3.2).

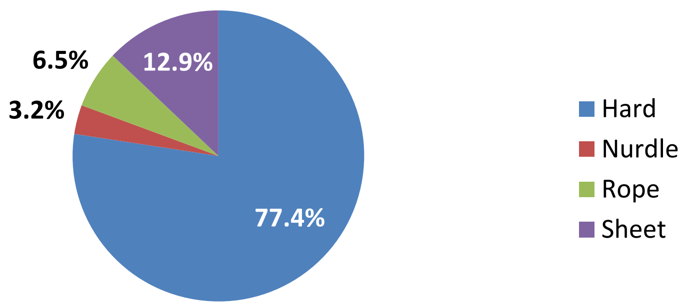


Figure 3.2: Type of plastic ingested by wedge-tailed shearwaters at both offshore and near-shore sites

The majority of ingested plastics were of Low Density Polyethylene (LDPE) (61 %), with 36 % being Polypropylene (PP) and only 4 % being ridged Polyvinyl Chloride (PVC) as determined using a density tower (Miami University Middleton, 2001). When ingestion at offshore and near-shore sites were examined separately, in regurgitate from wedge-tailed shearwaters offshore only two plastic types, hard plastic (92 %) and sheet plastic (8 %) were recovered (Figure 3.3). There was a significant difference in plastic types and colours collected offshore from beach surveys and those plastics ingested by offshore wedge-tailed shearwaters ($X^2_{[3]} = 6.400$, $p = 0.041$ and $X^2_{[8]} = 21918.060$, $p < 0.001$, respectively).

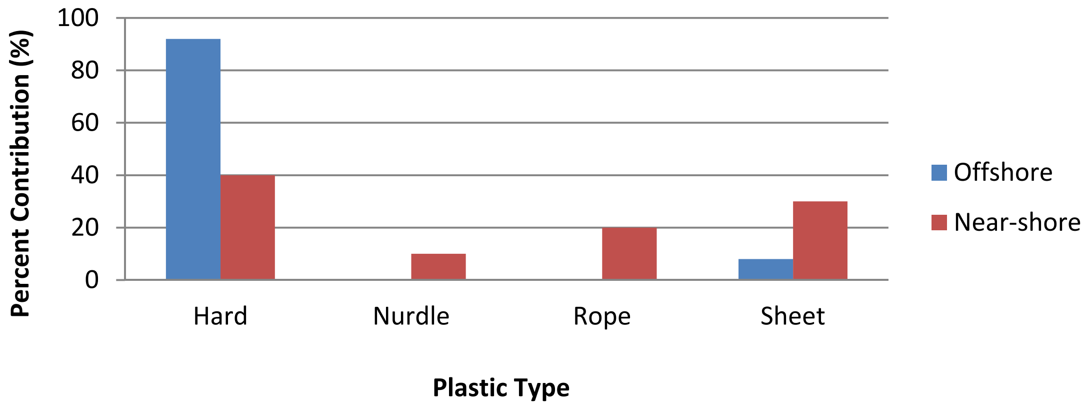


Figure 3.3: A comparison of the type of ingested plastic between wedge-tailed shearwaters at offshore (n = 25 pieces) and near-shore locations (n = 10 pieces)

In addition, there was an absence of any blue coloured plastic ingested, with off/white-clear (42 %) and considerably more green (33 %) coloured plastic in the regurgitate of offshore birds compared to that recovered on offshore shorelines (Figure 3.4a). Four plastic types were represented in regurgitated plastics in near-shore wedge-tailed shearwaters with the majority being fragments of hard plastic (Figure 3.3).

A large proportion of all plastic was off/white-clear (~35 %), and blue-purple and grey-silver tied as the second most common colour (Figure 3.4b), with no green or black plastic recovered in regurgitate of near-shore birds. The blue items ingested were fibres of rope plastic, possibly from degraded fishing line and were very small in size (range 1.06 - 1.55 cm). Overall there was no significant difference between the materials or colours of regurgitated plastic and recovered debris on shorelines in the near-shore environment ($X^2_{[3]}$ = 2.412, p = 0.299, and $X^2_{[8]}$ = 8.623, p = 0.375, respectively).

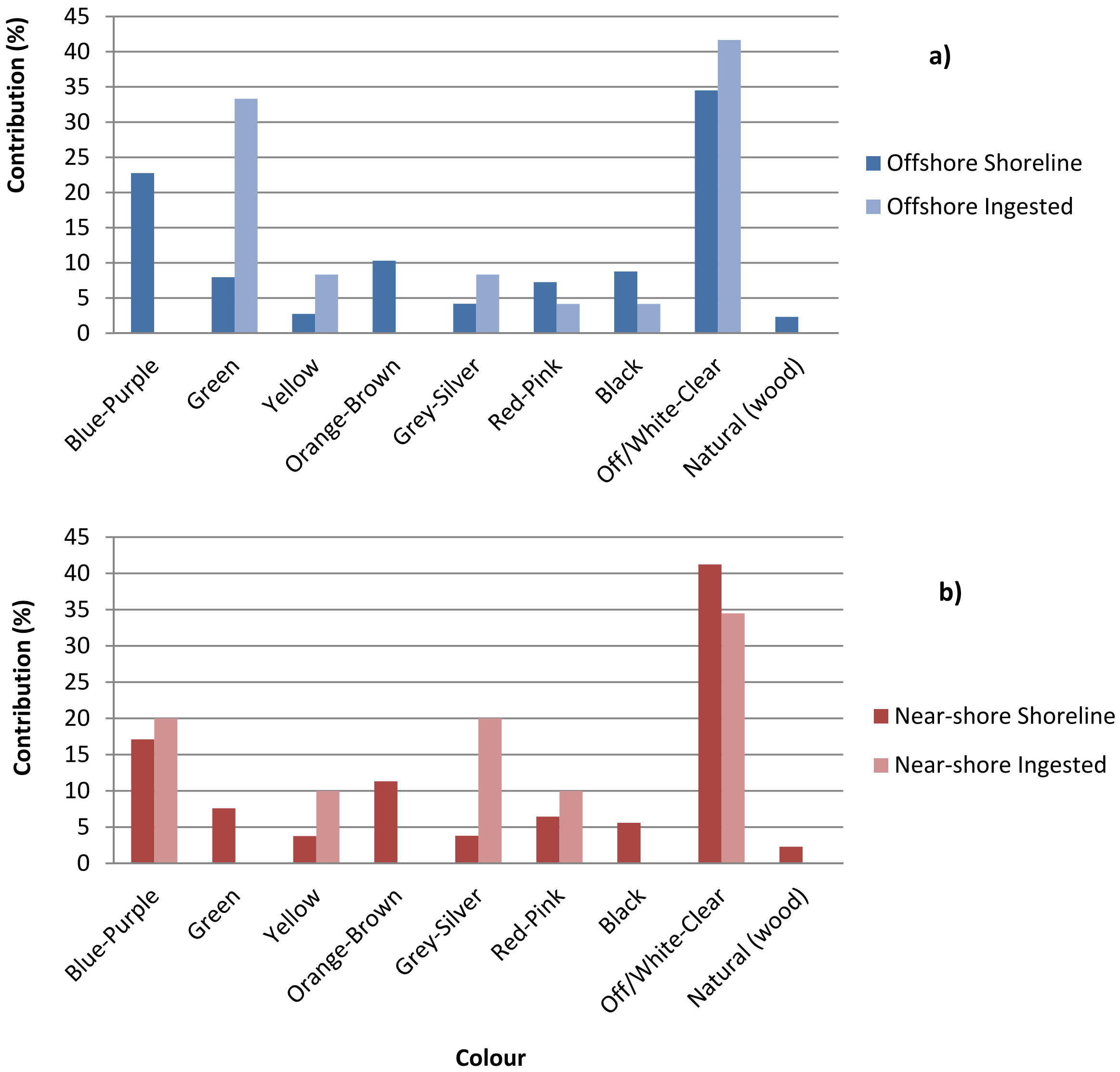


Figure 3.4: A comparison of debris colours from beach surveys and nesting wedge-tailed shearwaters regurgitate at **a)** offshore; and **b)** near-shore sites.

The birds with the greatest mass were from offshore Northwest Island in May 2013, and those with the lowest were in April 2013 at near-shore Mudjimba Island (Table 3.4). The mass, culmen, head and tarsus measurements were all relatively similar between offshore and near-shore wedge-tailed shearwaters ($p > 0.05$ ($p = 0.064$, $p = 1.000$, $p = 0.348$) for all three measures).

Table 3.4: Mean morphometric measures for sampled late-stage chicks at offshore and near-shore sites (birds are thought to be roughly at the same stage of development, see Section 3.2.2)

	Location	Date	No. birds sampled	Mass ± S.E. (g)	Culmen ± S.E. (cm)	Head ± S.E. (cm)	Tarsus ± S.E. (cm)
Offshore	Heron	May 2012	24	433.33±9.65	5.53±1.49	8.51±0.060	5.21±0.037
	Heron	April 2013	20	451.00±16.19	3.81±0.03	8.15±0.07	5.21±0.032
	Northwest	May 2013	35	461.14±9.67	3.77±0.27	8.14±0.041	5.26±0.032
	Heron	May 2013	30	411.67±11.73	3.76±0.03	8.00±0.06	5.30±0.035
Near-shore	Muttonbird	April 2013	40	410.00±8.66	3.60±0.03	8.02±0.08	5.25±0.032
	Mudjimba	April 2013	10	396.00±32.05	3.72±0.05	8.22±0.07	5.40±0.080

Overall, ~36 % of surveyed late-stage chicks had pumice stones in their proventriculus (Table 3.5). None of the surveyed birds at Mudjimba Island had pumice stones, but the sample size was small with only 10 birds sampled at this site (Table 3.5). Over half (~58 %) of the late-stage chicks at Muttonbird Island had pumice present in their regurgitate, but there was no significant difference between birds with pumice and surveyed location ($H_{[2]} = 1.331$, $p = 0.514$), or between near-shore and offshore locations ($U = 68.500$, $p = 0.101$). The size and weight of recovered pumice were similar between birds at the different locations (Table 3.5). Only one sampled adult at Northwest Island in December 2012 contained a pumice stone and so adults were not included in this analysis.

Table 3.5: Pumice stone data in the regurgitate of late-stage wedge-tailed shearwater chicks

Location	No. Pumice stones	% Late-stage chicks with Pumice (n)	Mean Length ± S.E. (mm)	Mean Weight ± S.E. (g)
Muttonbird Is.	79	57.5 (23)	9.1±0.38	0.56±0.15
Mudjimba Is.	0	0 (0)	0	0
Heron Is.	64	25.0 (15)	10.9±0.60	0.60±0.09
Northwest Is.	64	30.6 (15)	9.9±0.74	0.74±0.07

Additionally, there was no significant correlation between pumice stone number and ingested plastic number, with only one bird that had both plastic and pumice in its regurgitate (Spearman rho = 1.000, $p = 0.102$, $n = 53$). Pumice stones were heavier than recovered regurgitated plastic pieces, but even with the greater size (cm) of pumice stones compared to regurgitated plastic, there was a positive correlation between the two based on size (R^2 = 0.243, p = 0.003). Additionally, a significant correlation was shown between the percent of recovered pumice and squid beaks (R^2 = 0.8396, p = 0.084) from regurgitate.

Squid beaks were recovered from more than 75 % of Muttonbird late-stage chicks. One bird at this site had 72 squid beaks in its regurgitate (size range 0.20 - 1.54 cm). In May 2013, at Heron Island there were squid beaks in 63 % of chick regurgitate, while in May 2014 at both Heron and Northwest Islands only 28 % of chicks contained squid beaks, and at only low levels per bird compared to Muttonbird Island. Mudjimba Island had the lowest levels of recovered squid beaks in chick regurgitate (30 %).

3.4 Discussion

This chapter sought to determine the incidence of ingestion of plastic in the nesting wedge-tailed shearwater and (any) differences of ingestion between populations at offshore southern GBR nesting sites and those nesting near-shore along the east-coast of Australia (Queensland and New South Wales). Data from shoreline surveys conducted at and/or near to these nesting sites were undertaken (Chapter 2) to give an indication of the potential level of pollution in the foraging area of the surveyed wedge-tailed shearwaters.

HYPOTHESIS H_V: There will be no ingestion of marine debris by the wedge-tailed shearwater in study areas.

Procellariiformes are known to be at particular risk of marine debris ingestion with approximately 80 % of species in this order ingesting plastic (Table 1.11; Robards, et al., 1995; Ryan, 2008; Colabuono, et al., 2009; Acampora et al., 2014). Ingestion of plastic marine debris by wedge-tailed shearwaters has been documented in a number of studies (Table 3.6). This research adds to these findings, and the results of this study are in keeping with lower plastic levels recovered from wedge-tailed shearwaters at other locations (Table 3.6). Therefore Hypothesis H_V is not supported.

Table 3.6: Ingestion of marine debris by wedge-tailed shearwaters at locations around the world

Region	Location	Number Collected	% Ingestion	Authors
North Pacific	Kauai, Midway Atoll, Tern Island, Johnston Atoll, Nihoa Island, Laysan Island	n = 192 n = 61 n = 133 n = 5 n = 60 n = 35	3-29 % adult and chick 13-29 % adult and chick 15-23 % adult and chick 5 % adult 3 % adult 14 % adult	Sileo, et al. (1990)
North Pacific	Midway and Oahu Islands, Hawaii	n = 20	60 % adult	Fry, et al. (1987)
South Pacific	Year round in tropical Pacific Breed in South Pacific and winter in tropical Pacific	n = 23 n = 62	9 % light-phase 24% dark-phase	Spear, et al. (1995)
Pacific Region	Equatorial region	n = 35	3 % age not specified	Ainley, et al. (1990a)
Australian Territory	Lord Howe Island	n = 30 n = 22	43% chicks; 14% carcasses	Hutton, et al. (2008)
Australia	Heron Island, Great Barrier Reef, QLD	n = 32 n = 74	0 % (n = 0) adult 12.2 % (n = 9) chick	This study
Australia	Northwest Island, Great Barrier Reef, QLD	n = 14 n = 35	0 % (n = 0) adult 8.6 % (n = 3) chick	This study
Australia	Mudjimba Island, Sunshine Coast, QLD	n = 10	40 % (n = 4) chick	This study
Australia	Muttonbird Island, Coffs Harbour, NSW	n = 8 n = 48	0 % (n = 0) adult 12.5 % (n = 6) chick	This study

The higher level of ingestion that occurs in Procellariiformes, compared to other seabird orders, has been attributed in part to feeding method, as those species that feed by scavenging, or at/near the ocean surface by seizing or dipping are thought to be at more risk due to the increased chance of contact with floating marine debris (Table 1.13; Day, 1980; Furness, 1984; Ryan, et al., 1987a; Nel and Nel, 1999; Auman, et al., 2004). Other seabird studies have found that floating plastic has made up between 12-100 % of ingested plastic (Furness, 1983). The regurgitated plastics were identified as being polyethylene (61 %) and polypropylene (36 %), which has low densities that allow them to float (Blumberg, 1993). Only one ingested piece was found to be of rigid PVC. Polypropylene and polyethylene are some of the most common types of plastic also found ingested by other seabird species (van Franeker, 1983; Day, et al., 1985; Engler, 2012). Common polypropylene products include beverage caps and reusable food containers, and polyethylene is generally used to make bottles and shopping bags (Engler, 2012). Hard plastic items such as water bottles, bottle caps, crates and containers were also common items recovered from surveyed beaches in Chapter 2.

The lower incidence of plastic marine debris ingestion by this species in the sub-tropical locations in the Capricorn-Bunker Group of Islands could also in-part be a reflection of the lower pollution levels present in the marine environment (Chapter 2) compared to populations at other locations in Australia or around the world. For instance, at Lord Howe Island (LHI) foraging locations are potentially more polluted as indicated by a higher incidence of plastic ingestion in wedge-tailed shearwaters and flesh-footed shearwaters at this site (Hutton, et al., 2008; Lavers, et al., 2014). LHI wedge-tailed shearwaters are known to feed in a slightly different manner than those at Heron Island: LHI birds forage using a unimodal (instead of a bimodal) foraging strategy (Peck and Congdon, 2005).

Birds at Heron Island show a bimodal foraging strategy that is thought to be associated with the poorer resources near the Heron Island colony. Studies on wedge-tailed shearwater chicks between colonies at LHI and Heron Island was theorised that differences in growth are due to variations in the amount of food fed to chicks, and the quality of that food, with chicks at Heron being fed more prey with a higher-lipid content (Peck and Congdon, 2005). This indicates a difference in prey selection, and as the birds are foraging in different areas, these could be factors in the lower level of ingestion of plastic at Heron and Northwest Islands than that seen at LHI (Hutton, et al., 2008).

Sex-specific foraging differences may also potentially influence type of prey items fed to chicks. Although the amount of food fed to chicks between the sexes was not different, the male wedge-tailed shearwaters were significantly more likely to feed chicks than females (Peck and Congdon, 2006). Males also dived deeper to access prey than females, even though the wedge-tailed shearwater is a monomorphic species (Peck and Congdon, 2006) indicating that the sexes may be foraging for slightly different prey species. This raises the question of whether one sex is more likely to encounter and regurgitate food with plastic debris to their chicks based on the differences in the foraging area they use and the prey species they may encounter.

The differences in ingestion level by the wedge-tailed shearwater compared to other shearwater species, such as the flesh-footed shearwater and the short-tailed shearwater, could also be due to factors such as prey preference and foraging strategies (Ainley, et al., 1990a,b). The short-tailed shearwater for instance, is known to feed exclusively on krill (*Nyctiphanes australis*). No studies have examined this particular krill species to determine the rate of uptake of plastic; however zooplankton are known to indiscriminately ingest microplastics (Frias, et al., 2014; Desforges, et al., 2015). In a study by Ainley, et al. (1990a) in the eastern Equatorial Pacific, the lower levels of ingestion in the wedge-tailed shearwater was attributed to this species chasing more active prey, such as flying fish and squid. Other Procellariiformes that are less specialised feeders will eat both live and dead prey, and more frequently forage in areas such as convergence zones (Ainley, et al., 1990a) and could potentially be exposed to more marine debris.

The stomach flushing technique used can only clear proventricular contents, so perhaps more debris is within the gizzard. However, the study by Hutton et al (2008) indicated that in flesh-footed shearwaters, at least, 94 % of proventricular contents were cleared with flushing. Regardless, the inability to clear gizzard contents could potentially contribute to lower levels of recovered marine debris in regurgitate of live wedge-tailed shearwaters in this study, compared to those studies that have necropsied only dead birds.

HYPOTHESIS H_{VI}: There will be no difference in the ingestion (amounts, types, occurrence) of marine debris by wedge-tailed shearwaters at near-shore and offshore sites (spatially)

More chicks had plastics in their regurgitate at near-shore locations (17 %) than at offshore islands (11 %), although this was not statistically significant ($F_{[1,4]} = 2.217$, $p = 0.211$). This finding does not support Hypothesis H_{VI}. Ingestion levels are similar to those wedge-tailed shearwaters surveyed by Sileo, et al. (1990) within the North Pacific. Interestingly, the opposite trend was seen in the number of plastic items in regurgitate with significantly more plastic pieces per bird in offshore late-stage chicks ($U = 40.00$, $p = 0.032$). The amount of offshore ingestion fell into the range reported by Fry, et al., (1987) in Hawaii, with between two to six fragments being ingested per bird.

The near-shore birds contained plastic fragments in the same range as that reported in equatorial regions by Ainley, et al., (1990a), with one fragment on average. The slightly higher incidence of plastics in the wedge-tailed shearwater nesting near-shore could be influenced by a closer proximity to higher levels of marine debris from land-based sources. This is consistent with the results from Chapter 2 where the levels of marine debris at near-shore sites were significantly higher than offshore sites ($H_{[5]} = 26.938$, $p < 0.001$). The significantly higher levels of marine debris (Chapter 2) within the area and an increased incidence of plastic debris ingestion within near-shore nesting wedge-tailed shearwater sites warrants further sampling to confirm this trend. Very few studies have examined environmental levels of marine debris and compared these levels to those amounts found in wildlife. This is the first study to compare environmental levels of marine debris (Chapter 2) to that found ingested by wedge-tailed shearwater (or any animal) in the southern GBR and in those nesting near-shore at East Australian coastal locations.

The greater range of plastic types ingested by near-shore birds (Figure 3.3) could in part be a reflection of the higher pollution levels and the greater range of plastic types and more diverse debris within the environment closer to near-shore nesting locations (Shannon Weiner Diversity Index 1.9 compared to 1.3 at offshore sites, Table 2.5). For instance, more sheet plastic (Figure 2.4) was recovered at near-shore beaches, and the only incidence of virgin pellet ingestion occurred in a late-stage chick at Muttonbird Island (a near-shore site). Virgin pellets were collected at the Coffs Harbour marina beach during the sampling period and were recovered within transect, indicating that these pellets were in the area. Types of ingested debris and that in the environment were not significantly different between near-shore beaches and in birds ($\chi^2_{[5]} = 2.412$, $p = 0.299$). However, there was a significant difference in the types of plastic ingested and those recovered on beaches offshore ($\chi^2_{[5]} = 6.400$, $p = 0.041$). This indicates that the debris taken up by near-shore wedge-tailed shearwater may just be a reflection of what is in the environment. While offshore perhaps wedge-tailed shearwaters (and/or their prey) are influenced by other factors like different feeding cues or preferred and/or available prey species. This was indicated by much fewer squid beaks retrieved from the regurgitate of birds at Northwest and Heron Islands in the 2013 sampling period; compared to near-shore birds at Muttonbird Island.

The mean area ($U = 62.000$, $p = 0.028$) and weight ($U = 54.500$, $p = 0.013$) of regurgitated plastic pieces were significantly different between offshore and near-shore wedge-tailed shearwaters (Table 3.3). The overall size of ingested plastic items (8.12 mm) was larger than that recorded by Fry, et al. (1987), but is in the range reported by Spears, et al. (1995). I have earlier surmised that those ingested plastic pieces < 8 mm, could be the result of secondary ingestion from prey species, such as fish (Verlis, et al., 2013). Procellariiformes are able to feed energy-rich prey to chicks via processed stomach oil following prolonged foraging trips (Baduini and Hyrenbach, 2003). This puree could contain secondary plastics if the now-pureed prey species had ingested any plastic items. The wedge-tailed shearwaters in Hawaii consumed prey species between 2-8 cm, and a pilchard sp. ~20 cm in length was recovered in the regurgitate of an adult wedge-tailed shearwater at Heron Island in May 2013. The sizes of ingested plastics were all substantially smaller than these prey species (Table 3.3). The possible secondary ingestion of these fragments from prey items could indicate either a colour preference by the prey species, or an indiscriminate uptake based on prevalence within the environment. A great number of pelagic fish species have been shown to have ingested plastics (Possatto, et al. 2011; Lusher, et al., 2013), although further work needs to be done on ingestion levels in specific prey species for wedge-tailed shearwaters to ascertain the role of secondary ingestion in this species.

Birds could also be mistaking these plastics for natural items. Pumice stones, for instance, are commonly found in the regurgitate of late-stage chicks at other locations in Australia (Hutton, et al., 2008) and in this study, nearly 50 % of surveyed late-stage chicks at Muttonbird Island regurgitated pumice (Table 3.5). The pumice has likely resulted from the eruption of underwater volcanoes. The uptake of grey coloured plastics or those items lighter in tone could be related to their resemblance to natural items, which are also floating on the ocean surface. The reason for pumice uptake is not clear, as the wedge-tailed shearwater already has a muscular gizzard to breakdown hard objects (Barrett, et al., 2007). These stones could further aid in the breakdown of hard prey remains, as indicated by the high amount of squid beaks especially in Muttonbird Island birds (75 % of birds with squid beaks). Although Fry, et al., (1987) found a negative correlation between presence of squid beaks and plastic in wedge-tailed shearwaters, however this was in the gizzard contents. Seabirds in the Antarctic that had taken up pumice were thought to have done so in order to aid in gizzard grinding (although in this study, all recovered pumice was retrieved from the proventriculus), or possibly taken up due to the presence of marine life, such as barnacles growing on its surface (Simpson, 1964). A number of researchers have noted the adherence of prey items biofouling debris items, including flying fish eggs that are laid en masse to floating flotsam, and can have an attractant quality for uptake (Connor and Smith, 1982; Fry, et al., 1987; Ryan 1987a). The possible uptake of pumice for the reason of feeding on biofouling could increase the occurrence ingestion of plastics for the attached biofouling organisms, such as goose-barnacles that are known to adhere.

The use of visual cues is known in a number of seabird species. Ainley, et al., (1990a) refers to a particular prey search-image that seabird species may be responding to and suggests that there are differing visual cues for different species. Shearwaters fly less than 10 m above the ocean surface and have the potential to dive up to 3 m (Burger, 2001). This close proximity to the water, choice of active prey and that the wedge-tailed shearwater forages most actively during the day indicates the role of visual predation by this species (Ainley, et al., 1990a; Shealer, 2002). In general, bird vision is superior (to humans, for instance) due to things like the avascularised avian retina that prevents shadows and light scattering (Gunturkun, 2000).

In addition, birds are tetrachromats, having four retinal cones that contain at least five different oil droplets that allows for the birds to utilise a greater spectral range that includes UV vision (Bowmaker, 1980; Cuthill et al., 2000). This UV information is an important component for a number of avian behaviours, such as foraging and signalling (Cuthill, et al., 2000). The increased visual range could be a factor in plastic ingestion as different plastic can absorb UV light. The diet of wedge-tailed shearwaters of small fish (e.g. flying fish) and cephalopods may influence the uptake with off-white/colour and lighter tones (such as green and yellow) resembling the natural tones of prey species.

Additionally, Procellariiformes are known to use olfaction for oceanic navigation (Reynolds, et al., 2015). A recent study by Savoca and Nevitt (2014) has shown that dimethyl sulphide (DMS) is a compound that many species of Procellariiforms use to locate Crustaceans. Olfaction is used by Procellariiformes for foraging and in other behaviours, such as mate identification and nest location (Hutchinson and Wenzel, 1980; Verheyden and Jouventin, 1994; Osemegnie and Steinberg, 2009). A great number of terrestrial birds use olfactory cues to locate and discriminate between foods, and olfaction can have a role in influencing hormonal responses in birds (Mason and Clark, 2000). The wedge-tailed shearwater is one such bird that has been suggested could potentially use olfaction to locate prey items (Grubb, Jr., 1972; Hutchinson and Wenzel, 1980). The olfactory cues often employed by Procellariiformes could have a role in the uptake of marine debris if the items have absorbed fish or other prey-like odour compounds from the oceanic environment, or contain odours from fouling organisms (e.g. goose barnacle). A number of influencing physiological factors could potentially be contributing to the ingestion of marine debris plastic by this species and warrants further investigation.

HYPOTHESIS H_{VII}: There will be no difference in the ingestion (amounts, types, and occurrence) of marine debris by wedge-tailed shearwaters at offshore sites temporally

More plastics were found in regurgitate of late-stage chicks in 2012 (~21 %) than in the 2013 (~12 %), with the average number of regurgitated plastic marine debris pieces recovered per bird also being lower in 2013 (U = 40.000, p = 0.0032; Table 3.3). Thus Hypothesis H_{VII} is not supported by these findings. These differences could be related to the natural variability that occurs in the environment, and subsequently influence marine debris presence and amounts due to seasonal wind and wave movements. Although offshore shoreline beach debris levels were quite similar between survey times in May 2012 and 2013, while near-shore there were significantly more debris recovered during the second survey time in April 2013 ($F_{[1,52]}$ = 10.563, p = 0.002; Table 2.7, 2.8). However, there was only one sample period for near-shore birds and this was in 2013 and levels were higher at this location.

This variability demonstrates the need for this type of sampling to occur over multiple years to give a true indication of the ingestion risk in order to overcome variability in seasonality, sample-size and site accessibility. Plastics were found in regurgitate of 13 % of all surveyed wedge-tailed shearwater late-stage chicks for the region (n = 211). This level of plastic ingestion was lower than that recorded for wedge-tailed shearwaters at Midway Atoll (29 %) (n = 253) (Sileo, et al., 1990), on Lord Howe Island (43 %) (n = 30) (Hutton, et al., 2008) and on the Hawaiian Island of Manana (60 %) (n = 20) (Fry, et al., 1987) (Table 3.6). The EcoQO index created for the northern fulmars to provide an ecological indicator of marine debris levels within the North Sea was set at < 10% of birds with less than < 0.1 g of plastic in stomach from a sample of 100 to 500 birds over a five-year period (OSPAR Commission, 2010). The overall levels recorded for the wedge-tailed shearwater at surveyed locations in this study and mean weight, occur just above this amount over a two-year period, although debris amounts by weight in most instances were less than 0.1 g (see Chapter 5 for discussion of risk). So this species in these survey locations does not meet these double requirements, however this is only based on one or two-years of data. Based on the number of wedge-tailed shearwaters influenced by marine debris ingestion there is a need for continued monitoring of this pollution threat. A creation of pollution EcoQO using the wedge-tailed shearwater could be developed for these sampled areas. This would be especially helpful in the southern GBR, where the wedge-tailed shearwater is the only nesting Procellariiform and occurs in abundant numbers (Hill, et al., 1995). More seasonal data for a minimum of four years is needed to test these approaches and develop a more appropriate weight of ingested plastic for this species.

HYPOTHESIS H_{VIII}: No difference will exist in the plastic ingestion occurrence between adult wedge-tailed shearwaters and the late-stage chicks

Perhaps one of the most significant findings over the course of this research was that none of the sampled adults, but ~13 % of late-stage chicks, had ingested plastic in their regurgitate (Table 3.2). Thus Hypothesis H_{VIII} was not supported by this finding). This may however, be related to the low opportunity of actually sampling an adult bird that had just fed upon plastic during its last foraging trip, and/or capturing a bird that foraged to feed its young, versus foraged to build up its own body reserves (Congdon, et al., 2003; McDuie, et al., 2014). However, since plastics were found within sampled chicks (Table 3.2), this indicates that adults are taking up plastics and feeding it to their young (as these late-stage chicks are still totally dependent upon their parents for food).

Other studies have also shown juvenile Procellariiformes with higher marine debris ingestion levels than adults (Day, et al., 1985; Fry, et al., 1987; Ryan, 1987a; Sileo, et al., 1990; Hutton, et al., 2008; Acampora, et al., 2014), with plastics fed to chicks along with their meals (Ryan, 1988b; 1990; van Franeker and Meijboom, 2002). Procellariiform adults are thought to incidentally offload their plastics to their chicks that they themselves have accumulated over the winter month's away (Ainley et al., 1990a,b). A study by Ryan (1987a) found that the incidence and amount of plastic recovered from a bird was affected by the age, time of year and place and year of specimen collection (Ryan, 1987a). Alternatively, in wedge-tailed shearwaters such as those in this study, adults forage to improve their own reserves at a distance from the nesting location in pelagic waters (Congdon, et al., 2003). During this time they could encounter more polluted areas, and hence they potentially have accumulated plastics that may then be passed in the meal subsequently fed to chicks. Additionally, what food is carried in the bill to nestlings can be different to what is taken up by foraging adults. Foraging adults would tend to swallow smaller items they find and taking larger prey items back to the nest (Sutherland, 2004). This could partially explain why the plastics were found in the chicks but not the adults.

The gastric lavage technique used in this study (Wilson, 1984) only flushes the proventriculus therefore the sampling may fail to yield 'true' amounts (as the flush will only provide the most recently caught/fed items) as the gizzard is restricted due to the presence of the narrow, u-shaped isthmus junction (Ryan and Jackson, 1986; Ryan, 1988b; Spear, et al., 1995). As chicks can potentially be fed more than once a day and their digestive system may not be as fully developed as an adult, meals may have been more likely to be found in the proventriculus when sampling occurred. As already acknowledged, the lavaging technique only clears the proventricular contents, so the adult bird would have to have fed on plastic in this feeding event Thus, I postulate that there is a higher likelihood of finding ingested items within the proventriculus of chicks then adults.

HYPOTHESIS H_{IX}: There is no correlation between plastic ingestion and seabird morphometric measurements as indicated by bird body condition.

Previous studies have shown a positive correlation between the number of plastic particles and body weight of seabirds (Spear, et al., 1995), with heavier birds ingesting more pieces of plastic. This was attributed to them being more efficient foragers and feeding at areas like convergence zones where both plastic and prey accumulate (Spear, et al, 1995; Nevins, et al., 2005). This was not seen in this study. There was no significant difference in the body condition of the wedge-tailed shearwater chicks found to have ingested plastic and those that had not in this study (U

= 1091.00, p = 0.204). Thus Hypothesis H_{IX} is not rejected. Nor was there a correlation between the number of ingested plastic pieces and body condition (R^2 = 0.023, p = 0.532) suggesting the ingestion of plastic did not influence or impact on growth in this species. A number of factors can influence body condition of birds, even if a significant relationship had been found with plastic ingestion. This could be a result of seasonal or climatic factors that may affect prey numbers and/or the health of adult birds, and/or it could be due to the presence of potentially harmful chemical contaminants that could be present on the ingested plastics (Yamashita, et al., 2011).

HYPOTHESIS H_X: No difference exists between marine debris material type and colour found in beach transects near to nesting sites and that found ingested by the wedge-tailed shearwater.

The greater mean number of ingested plastic and the higher amount of hard plastic fragments ingested by wedge-tailed shearwaters at offshore sites could in part be related to the location where these birds forage. The wedge-tailed shearwater is known to feed at or near to convergence zones and other areas where prey accumulate due to oceanographic or bathymetric conditions that encourage aggregations (Marchant and Higgins, 1990; McDuie, et al., 2014). As hard plastic fragments are the most common item type on both near-shore beaches and offshore islands in the southern GBR (Chapter 2 and 4) and in surveys both in Australia (Frost and Cullen, 1997; Whiting, 1998; Cunningham and Wilson, 2003; Slavin, et al., 2012; Smith and Markic, 2013) and around the world (Barnes, et al., 2009; Costa, et al., 2010), that hard plastic fragments were the most common type ingested may be related in part to the prolific presence within the environment.

Plastic fragments in the environment degrade into progressively smaller pieces due to mechanical or chemical means (Andrady, 2000; Barnes, et al., 2009). This degradation then makes these fragments more available to a wider suite of marine life and allows for the potential of secondary ingestion of marine debris plastics up the food-chain. A trawl survey for marine debris on the east coast of Australia has shown significant amounts of microplastics in local waters (Reisser, et al., 2013), thus the potential for prey species to ingest plastic is quite high.

At LHI, the prey species most often targeted by wedge-tailed shearwaters were squid (Hutton, et al., 2008), and it was thought that northern fulmars in the UK were ingesting condoms and sheet polythene from grocery bags because the birds were mistaking them for nereid worms (polychaetes) and squid (cephalapods) (Zonfrillo, 1985). The ingestion of sheet plastic items by wedge-tailed shearwaters in this study could also be linked to the similarity of these items in appearance to natural prey items, such as squid, although the size of these items draws this into question as ingested plastic items were smaller, as discussed above. Not a great deal of information is currently known about the diet of wedge-tailed shearwaters at these survey areas and if these prey species have themselves ingested marine debris plastics. Further research into the diet of the wedge-tailed shearwater at these nesting locations and locating where birds forage locally when provisioning their chicks would be beneficial in further informing on marine debris interactions with this species. Additionally, an understanding of the other stressors to the bird in regards to diet would be beneficial. This includes the age and experience of the parents, presence of any disease, injuries, or parasites and poor weather may affect body condition and could influence feeding behaviour.

White was the most common colour of ingested plastic in both near-shore and offshore birds (50 and 42 %, respectively) and is often reported as a colour of plastic ingested by other seabird species (Ogi, 1990; Eriksson and Burton, 2003; Titmus and Hyrenbach, 2011; Carey, 2011; Acampora, et al., 2014). In offshore birds, green items were the second most common colour in regurgitate (~33 %), similar to that seen in the wedge-tailed shearwater in the North Pacific (Sileo, et al., 1990). However, no near-shore birds had green plastic in their regurgitate. Blue-purple coloured items were tied as the second most common colour in near-shore birds, however, no offshore birds were found to have ingested items of this colour (Figure 3.4). Blue coloured marine plastic has been recorded in Antarctic prions (*Pachyptila desolata*) on Heard Island (Auman, et al., 2004). Blue-purple was one of the most common colours of debris items in near-shore beach debris surveys, along with off/white-clear coloured marine debris items (Figure 3.4). Thus, at near-shore sites, again, the colour selection of the wedge-tailed shearwater may to a certain extent reflect plastic type in the environment, where the colour of debris on beaches and that ingested were similar ($\chi^2_{[8]} = 8.623$. $p = 0.375$). At offshore sites however, there was a significant difference in colours of items recovered on beach and that fed to wedge-tailed shearwater late-stage chicks ($\chi^2_{[8]} = 21918.060$, $p < 0.001$). These different trends in colour selection may be a result of the prevalence of colours in the environment (near-shore birds), or again that an actual colour preference by the bird or their prey exists for offshore birds. Limited data exists on the diet of the wedge-tailed shearwaters at the surveyed locations so testing this hypothesis H_X is limited.

3.5 Conclusions and Recommendations

Ingestion of marine debris plastic is occurring in wedge-tailed shearwaters nesting in the southern Great Barrier Reef and at near-shore sites along the east coast of Australia. Although ingestion was not occurring in the wedge-tailed shearwater at levels seen in more highly impacted species, such as the northern fulmar (van Franeker and Meijboom, 2002), or the short-tailed shearwater (Carey, 2011). Further sampling is needed to determine more accurately the preference and size of ingested plastics and ascertain if secondary transfer of these items is occurring by quantifying plastic ingestion in prey species. Additional analysis of the plastics for chemicals (both natural odours and contaminants) could also provide evidence for potential cues for uptake and suggest possible influences on the health and wellbeing of these seabirds. The present study found no change in body condition in birds that had plastic present suggesting little threat to this species in the sampled areas at present. A plastic risk matrix for wedge-tailed shearwaters is developed in Chapter 5 (Table 5.8) that considers the level of ingestion and the Marine Debris Pollution Index from Chapter 2. Due to the limited data set of this research, it is presented as a case-study that further data would strengthen. In Chapter 4, a further interaction with marine debris is examined with the nest material of brown boobies in the Swain Reefs of the Southern GBR.

CHAPTER 4

Assessment of Marine Debris in Nest Material of the Brown Booby (*Sula leucogaster*) within the Southern Great Barrier Reef

4.1 Introduction

The incidence of animal entanglement in marine debris is, in some instances, more readily recognised than ingestion (Laist, 1997; Cecarelli, 2009). However, there is some dispute as to whether ingestion or entanglement poses the greater threat to animals (Laist, 1987; SCBD and STAP-GEF, 2012). This point is irrelevant in the Australia legislative context (DEWHA, 2009) as in both instances the incidence is likely underestimated due to the limited ability to detect affected animals (Laist, 1987; Chapter 1 Section 1.2).

The accumulation of marine debris in the environment is also damaging to organisms through alteration of habitat structure, modification of light and oxygen levels, and through the physical degradation of habitat by smothering, fragmentation and abrasion (Gregory, 1999; U.S. EPA, 2011). Coral reefs, for instance, can be physically injured or modified by entangling debris. This may then lead to reduced habitat heterogeneity and could potentially impact the survival of those species reliant on this important habitat (Donohue, et al., 2001; Asoh, et al., 2004; U.S. EPA, 2011).

Many factors can influence the likelihood of an interaction between marine debris and an animal. In seabirds, these include the amount and type of material, its distribution and the birds' behaviour (Laist, 1987). The presence of marine debris within the foraging areas of seabirds can increase the likelihood of interaction (Rodriguez, et al., 2013), with evidence that marine debris is found to accumulate in oceanic frontal systems, convergence zones and in commercial fishing grounds where seabirds are known to feed (Dixon and Dixon, 1981; Slip, Green and Woehler, 1990; Barnes, et al., 2009; Maximenko, et al., 2012). Discarded fishing line and ropes can lead to entanglements that may cause amputation, decrease an animal's ability to forage, and/or lead to death (Laist, 1997; Cercelli, 2007; Votier, et al., 2011). The use of marine debris as nest material is a further way for entanglement to occur (Bond, et al., 2012).

Many breeding seabirds have been shown to use marine debris in their nests, with items such as plastic strapping and netting being incorporated into nest material (Nel and Nel, 1999; Phillips, et al., 2010; Votier, et al., 2011; Bond, et al., 2012). The presence of fishing and shipping activities within the area has influenced the presence and types of items found within nests (Nel and Nel, 1999; Norman, et al., 1995). The use of discarded ropes and strapping from fishing activities by gannet species has been theorised to relate to the similarity in appearance to marine algae that is also used as nest material (Montevecchi, 1991; Norman, et al., 1995; Votier, et al., 2011). Consequently some seabird species may choose anthropogenic material which resembles the organic material that would normally be taken up and utilised as nest material. The brown booby (*Sula leucogaster*) has not had its nest material extensively studied (Ostrowski, et al., 2005; Lavers, et al., 2013), but recent findings show that plastic items are used by this species (Lavers, et al., 2013; Appendix D: Verlis, et al., 2014). Bird guides also generally reference the use of marine debris and other items such as plant remains as nesting material by this species (Marchant and Higgins, 1990; Simpson and Day, 2010). Thus, the use of marine debris is readily acknowledged in this species even if research is limited. Additionally, where this species is sourcing debris items for use within the nest is not known, but items are speculated to be sourced locally (Lavers, et al., 2013).

The brown booby is in the Order Suliformes (formerly Pelecaniformes) that includes Sulidaes (boobies and gannets), an Order known to be at risk for entanglement in marine debris (Conant, 1984; Laist, 1987; 1997; Coles and Pierce, 2003). Unlike the wedge-tailed shearwaters that use burrows for nesting (and hence no debris) the brown booby is a surface nest builder. The act of nest building in the Sulidaes may be undertaken to form a functional structure, or it can be symbolic during courtship and nesting (Nelson and Baird, 2002). In both instances, close interactions occur between mates that serves to strengthen the pair bond. Males present the female material in a ritualized manner with the female doing the majority of the nest building (Marchant and Higgins, 1990; Nelson and Baird, 2002).

The study of seabird interactions with marine debris has been suggested as a more cost-effective and efficient way to monitor marine pollution levels in the environment (Ryan, et al., 2009; EU, 2013). In Canada and the European Union, monitoring of nest material for marine debris has been suggested for inclusion of larger marine debris monitoring activities (EU, 2013; Provencher, et al., 2015) and is proposed as a non-destructive sampling technique that can identify the types and amounts of marine debris available within the foraging range (Podolsky and Kress, 1989; Provencher, et al., 2015). In addition, this method can indicate the amount of interaction that occurs between the potential debris source and the seabird species (Nel and Nel, 1999).

The three main aims of this chapter were to:

- Identify the amount and type of natural and anthropogenic material used in brown booby nests;
- Determine if there is a relationship between debris material found in nests and that found on the shoreline; and
- Develop a novel technique to monitor marine debris in nest material of brown boobies.

From these aims, the potential interaction of marine debris on nesting brown boobies is considered. Shoreline marine debris surveys were conducted at the nesting sites (or near to, in the case of the Capricorn Bunker group of Islands), to compare the type and amounts of debris, and to determine if there was a relationship between debris in nest and those in shoreline transects. The cays and islands of the GBR are zoned according to allowed uses and access (see Section 1.14.1) and this thesis also aimed to determine if amounts of marine debris differed between the zones. The use of nesting material as a surrogate to monitor for marine debris pollution in the area was determined by comparison to these shoreline marine debris surveys. The outcomes of this study provide a preliminary understanding of the utilisation of both natural material and marine debris by this species. This was the first study to quantify debris levels on beach shorelines and examine interactions with this species in the ecologically important GBR World Heritage Area. Additionally, new techniques to monitor marine debris in nests are presented.

The five hypotheses addressed in this chapter were:

- **HYPOTHESIS H_{XI}**: No marine debris was used in the nest material of brown boobies in the southern Great Barrier Reef;
- **HYPOTHESIS H_{XII}**: No correlation existed between the presence of marine debris on beaches of surveyed sites and the use of marine debris in brown booby nests in the same location;
- **HYPOTHESIS H_{XIII}**: There was no difference in types, colours, and size of marine debris used as nesting material by brown boobies between sites (spatial);
- **HYPOTHESIS H_{XIV}**: There was no difference in the types, colours and size of materials used in brown booby nesting material over time (temporal); and
- **HYPOTHESIS H_{XV}**: There was no difference in amounts of debris on cays in different Great Barrier Reef Marine Park zones.

4.2 Methods

4.2.1 Study Sites

Eleven brown booby nesting sites were examined within the southern Great Barrier Reef region, nine in the Swain Reefs and two in the Capricorn Bunker group of islands. Of these sites, all are managed by the Great Barrier Reef Marine Park Authority (GBRMPA) to ensure sustainable and viable access and use of this world heritage area (see Chapter 1 Section 1.14.1). Sites were accessed on three separate occasions in the Swain Reefs, and on two occasions in the Capricorn-Bunker Group of Islands.

4.2.1.1 Swain Reefs

The Swain Reefs are located in the most south-eastern part of the GBR north east of Gladstone, Queensland, Australia, and are the farthest reefs (150-200 km) from the Australian mainland (Flood and Heatwole, 1986; Smith, et al., 1990; Queensland Government, 2013). The Swain Reefs are composed of small cays and reefs and are discussed in more detail in Chapter 1 Section 1.14.1.2.

There were nine coral cays in the Swain Reefs accessed for nest and debris surveys. Each cay is surrounded by an individual reef with size and position varying. These sites are summarised in Table 4.1 and shown on Figure 1.11.

Table 4.1: Site descriptions for Swain Reef study sites

Site Name	Beach Slope	Area	Position of Cay relative to its reef	Substratum type and uniformity	Prevailing wind at time of sampling
Bacchi Cay	7°/12%	0.5 ha	West	50 % sand 30 % coral rubble 10 % reef rock	North-East
Frigate Cay	8°/14 %	2 ha	West	80 % sand 20 % coral rubble	South-East
Price Cay	7°/12 %	1.6 ha	West	70 % sand 10 % coral rubble 20 % vegetation	South-East
Bylund Cay	13°/21 %	0.6 ha	East	95 % sand 5 % coral rubble	South-East
Riptide Cay	6°/10 %	0.25 ha	East	10 % sand 90 % coral rubble	North-East
Thomas Cay	6°/11 %	1 ha	East	80 % sand 20 % coral rubble	South-East
Distant Cay	> 10 %	0.25 ha	Central	100 % coral rubble	North-East
Gannett Cay	7°/12 %	1.7 ha	Central	85 % sand 15 % coral rubble	North-East
Bell Cay	< 5 %	1.5 ha	Central	70 % sand 10 % coral rubble 20 % vegetation	North-East

Only Price and Bell Cays were moderately vegetated (native grasses and herbs), all the other sites were composed of coarse carbonate sand and bioclastic sediment and/or coral rubble (Flood and Heatwole, 1986; Queensland Government, 2013). These cays host the major breeding populations of brown boobies and masked boobies (*S. dactylatra*), and are the only southern GBR nesting site of the lesser frigatebird (*Fregata ariel*) (Queensland Government, 2013). Extreme weather events, such as cyclones can have profound impacts on the stability and structure of these cays (QPWS, 2000).

Access to, and direct human contact with, Bacchi, Bell, Bylund, Frigate, Gannett, Price and Thomas cays, and the surrounding marine park is limited by the Commonwealth Marine Park zoning (preservation-pink-zone) and all-year national park restricted access (Appendix B). Access to Distant and Riptide cays are seasonally restricted (1 October to 1 April) under the Queensland *Nature Conservation Act 1992* (https://www.legislation.qld.gov.au/LEGISLTN/CURRENT/N/NatureConA92.pdf). Due to the conservation value of these cays no tourism operators are permitted within the Swain Reefs National Park, but multi-day charter trips for fishing, as well as general public fishing, snorkelling and diving do occur within the area. As a result of the remoteness and the complexity of navigating this coral system, day-trips are not feasible and inexperienced recreational boaters are uncommon (Queensland Government, 2013).

4.2.1.2 Capricorn-Bunker Group of Islands

The islands in the Capricorn Bunker Group of Islands support critical nesting sites for loggerhead (*Caretta caretta*) and green turtles (*Chelonia mydas*), and many seabird species (Stokes, et al., 1997). This includes the second largest breeding population of brown boobies in the GBR (QPWS, 2000). The islands occur on planar reefs of varying sizes, with West Fairfax being a vegetated sand cay, and east Fairfax a coral rubble cay with vegetation. Nesting sites for brown boobies have been recorded on East and West Hoskyn and East and West Fairfax Islands (QPWS, 2000), with all these islands being preservation pink zones (Appendix A). However, when accessed in March 2013, only East and West Fairfax Island had active nests, or evidence of recent nesting by these birds. As such, only East Fairfax nests were surveyed in this study (Table 4.2).

Table 4.2: Site description for Capricorn Bunker Group of Islands

Site Name	Slope	Area	Positon of cay relative to its reef	Substratum type and uniformity	Prevailing wind at time of sampling
East Fairfax Island	> 10 %	42 ha	East	5 % sand 45 % coral rubble 50 % vegetation	South-East
West Hoskyn Island	3° / 5 %	7 ha	West	25 % sand 5 % coral rubble/rock 70 % vegetation	South-East

NB: Nest surveys were conducted on East Fairfax, while beach marine debris surveys were conducted on nearby West Hoskyn Island.

4.2.2 Sample Size

To determine the number of nests that needed to be sampled, a modified Standard Error equation using a 90 % Confidence Interval Standard Error (k = 1.645, k is a standard number for a 90 % CI) with a 0.05 precision was used (Bradley, 2007). No baseline literature was available for brown booby marine debris usage in nests at the start of this project. A preliminary trip was undertaken to Swain Reefs in June 2012, and detected plastic in ~53 % of nests. This sample proportion (*p*) was subsequently used to determine confidence intervals as illustrated in Equation 4.1.

Equation 4.1

$$n = p(1-p)(1.645)^2/(0.05)^2$$

$$n = (0.5263)(1-0.5263)^2(2.706025)/0.0025$$

$$n = 270 \text{ nests to be sampled}$$

The ideal number of nests to be sampled was determined to be 270 (Equation 4.1). Unfortunately, due to the limited number of nests present on the Swain Reef Cays, the limitation on time when visiting these sites, and the cancellation of a trip due to adverse weather, far fewer nests were sampled than had been initially planned for (96 nests were surveyed, representing a > 80 % CI). This project did rely upon opportunistic sampling opportunities: site access was contingent[1] on participating on the scheduled Queensland Parks and Wildlife Service (QPWS) seabird surveys. Hence, the sampling times for this research were dependent on working with and around the QPWS sampling schedules. Thus, the nest sampling in this project was not the primary consideration for time on site. This created logistical constraints as the quantitative sampling design could not be accommodated, but these constraints were considered worthwhile as the research at these southern cays represent a first record of marine

[1] This research project defrayed costs by sampling when QPWS had room available for external researchers on their live-aboard vessel. Without the use of the QPWS vessel, this research could not have occurred.

debris data. Consequently, care was taken to opportunistically sample as many nests as possible when access to the cays was provided.

Overall this still allowed for the sampling of two seasons (summer and winter). It was hoped that two summer and two winter samples would occur; however, due to unforeseen weather conditions (i.e., a number of high impact cyclones in one season) lead to one summer trip cancellation, leaving an unbalanced design (one summer trip and two winter trips to Swain Reef sites). This does represent a limitation to this study and was taken into consideration when choosing the appropriate statistical tests. At Fairfax Island, 277 nests were surveyed over two sample time periods that occurred just over 12 months apart. So at this location an adequate sample size was met.

4.2.4 Nest Sampling

To sample nests for debris, transects (range between 10 to 50 m, depending on cay length) were run transversely across the cay with every second or third nests opportunistically surveyed, depending on nest density. Occupied nests were not sampled unless the occupying bird flew away prior to sampling. On average, only 30 minutes was available for undertaking the nest surveys on visited Swain Reef cays.

The nest area was sampled using a 0.5 x 0.5 m quadrat centred over the nest. Nests can vary in size but the majority fitted within this quadrat. At least one picture was taken of the sampled nests from a standardised height of ~ 1 m ensuring the entire quadrat frame was in shot. Any marine debris present was collected for further analysis and natural material was characterised and counted using the photographs (see Section 4.2.6). The nest of this species degrades once the chick is hatched, and due to the time interval between sampling trips, the surveyed nests were not marked.

Collected marine debris nest items were categorised by material and type of object, with weight, greatest size measure and characteristics such as colour recorded.

Determining the source of the marine debris was accomplished using a percentage allocation scoring technique (Whiting, 1998; Tudor and Williams, 2004). Refer to Chapter 2 Section 2.3.2.3 and 2.3.2.4, for full explanation of characterisation and sourcing of collected debris items.

4.2.5 Beach Shoreline Debris Surveys

Marine debris surveys were undertaken on the same cays and at the same times in the Swains where the nest surveys occurred, and on an adjacent island in the Capricorn-Bunker Group (West Hoskyn; which is 5.2 nm from East Fairfax). Debris surveys were also carried out on Bell and Bylund Cays, despite no nesting brown boobies at these locations. This broad sampling provided a more thorough examination of marine debris loads in the marine environment. West Hoskyn was surveyed in the Capricorn-Bunker Group due to the topography of East Fairfax Island, being unsuitable for debris deposition due to the beach steepness and the substrate was composed of large coral pieces. The inclusion of West Hoskyn as a substitute for East Fairfax is justified because there is no information on where the birds gather nest-making materials. The debris surveys reflect what is in the nearby marine environment, which I infer based on visual observation, would be the same for both islands because of their close proximity, the position of both islands is the same and they are both exposed to the same prevailing winds and currents. The area of beach survey at each site is summarized in Table 4.3.

Table 4.3: Area of beach surveyed and cay/island total area with GBRMPA zoning designation

Location	Transect Area (Feb, Mar, Aug 2013, April 2014)	Transect Area (June 2012)	Area of Cay/Island	GBRMPA zoning (Appendix A and B)
Swain Reefs				
Bell Cay	1,500 m^2	-	15,000 m^2	Pink - Preservation
Riptide Cay	300 m^2	-	2,500 m^2	Green – Marine Park
Price Cay	1,500 m^2	750 m^2	16,000 m^2	Pink - Preservation
Bylund Cay	450 m^2	225 m^2	6,000 m^2	Pink - Preservation
Thomas Cay	1,500 m^2	750 m^2	10,000 m^2	Pink - Preservation
Bacchi Cay	1,500 m^2	750 m^2	5,000 m^2	Pink - Preservation
Frigate Cay	1,500 m^2	750 m^2	20,000 m^2	Pink - Preservation
Gannett Cay	1,500 m^2	-	17,000 m^2	Pink - Preservation
Distant Cay	300 m^2	-	2,500 m^2	Green – Marine Park
Capricorn-Bunker Island Group				
West Hoskyn Island	1,500 m^2		125,000 m^2	Pink - Preservation

Three 10 m wide belt transects were run just above the high tide (or strand) line on the windward shore of each cay. The belt transect length was determined by cay size and ranged from 10 to 50 m (total area of 300 m^2 to 1,500 m^2) with total transect area recorded (Table 4.3). Transects were spaced in order to sample the two ends and middle of the beach, representing three zones of the beach. As described in previous chapters, all surface marine debris items present (> 1 cm) were collected from within the belt transects. In June 2012, transect widths of only 5 m (total area of 750 m^2 and [225 m^2 Bylund]) were utilised due to time constraints. Therefore, to overcome the differences in sampling effort (sample area surveyed) the data were standardised to amount per m^2. All marine debris items were classified according to the material type (e.g. hard plastic, glass, metal), the object type (e.g. bottle, fragment), colour and the weight (using an AND GF-10K balance accurate to 0.01 g) and greatest-length size measurements (using a metal ruler accurate to 0.1 cm).

4.2.6 Nest Photograph Analysis

The software Coral Point Count with Excel extensions version 4.1 (CPCe4.1; Koehler and Gill, 2006) was used to analyse the nest photographs taken of surveyed sites to determine presence of both natural and anthropogenic material types and amounts. A legend of the material present in a nest was created (Table 4.4) using these photographic images. To ensure consistency of interpretation for debris type identification in a nest, a protocol was created to dictate how the pictures would be characterised.

To determine how many random points were needed to accurately reflect the quantity of material (both organic and synthetic) used in the nest in each photograph, a pilot study was run. The pilot study analysed eight random nest photographs from two of the time periods that had at least some synthetic marine debris material in order to determine the number of points needed to accurately reflect the synthetic/anthropogenic nest contents. For each photograph a series of random points (10, 20, 40, 60, 80, 100, 120, 200) were generated on the photos with the material found beneath each identified point classified according to the protocol outlined above and using the material legend (Table 4.4). Totals for synthetic marine debris from each point were summed and means were determined. The means for each random point group were then graphed against each time set to determine the lowest number of points required to accurately reflect nest contents (Figure 4.1).

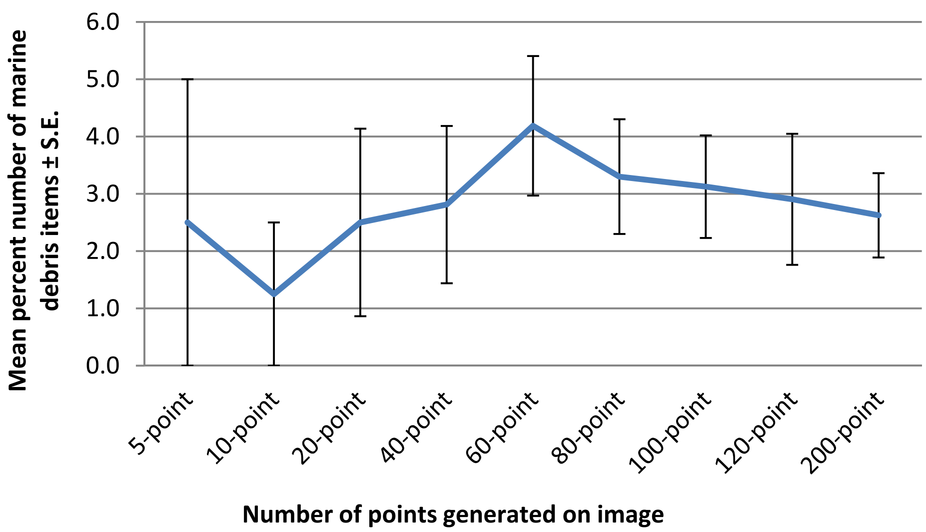


Figure 4.1: Determination of the number of randomly allocated points required to accurately assess the amount of marine debris in an individual brown booby nest

The results showed that the mean debris was greatest in the 60-point sample. At the higher points (80, 100, 120, 200), multiple sampling of the same item occurred. Therefore, 60-points provided the greatest chance of detecting plastics and other anthropogenic debris in the photo but decreased the occurrence of sampling the same item multiple times. Lower than 60-points, the asymptote in the curve has not yet been reached. To further confirm that 60-point's was the best endpoint, 10, 60, and 100 points were chosen from the pilot range. A further eight photographs were then analysed with the 10, 60 and 100-points generated on the image. The results confirm that 60-points was indeed the lowest number of points needed to accurately reflect nest contents as indicated by the levelling off of the curve (Figure 4.2).

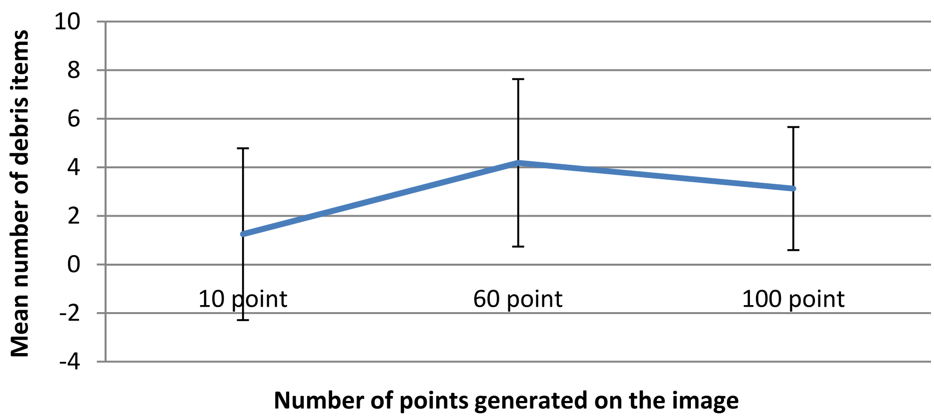


Figure 4.2: The refined number of randomly allocated points required to accurately assess the amount of marine debris in an individual brown booby nest.

The protocol for nest picture analysis in CPCe4.1 is as follows:

1. The yellow positioner tool was fitted around the perimeter of the nest to provide for best-fit, using the quadrat frame as a guide (Figure 4.3);
2. Sixty (60) random points were then generated on the image within this designated area. Any item under a random point was identified using the legend. Each point was zoomed in on to confirm what was beneath the point (Table 4.4; Figure 4.3);

3. Background surface material was defined as vegetation, coral rubble, sand, or coral platform;
4. If the randomly generated point fell on the quadrat frame, the item beneath the frame was classified; and
5. Classification of marine debris followed the methods described in Chapter 2, Section 2.3.2.3.

Table 4.4: Legend of material classification for use in CPCe4.1 (Koehler and Gill, 2006) nest analysis

Organic Debris	Synthetic Debris	Background	Other
Coral	Glass	Sand	*Other
Shell	Metal	Coral rubble	Unknown
Seaweed and Algae	Rubber	Coral platform	
Animal matter – non-bird	Cloth	Vegetative matter	
Feather	Plastic – Hard		
Bird bone	Plastic – Rope		
Twig/branch	Plastic – Sheet		
Seed	Plastic - Fibrous		
Leaf and needle	Processed Wood		
Pumice	Plastic - medical		
Cuttlebone			
Woods			

*Other included broken booby egg(s)

Figure 4.3: Sample image of nest photo in the Coral Point Counter Program. Yellow arrow demonstrate the yellow positioner tool (thin square outlines around the laid quadrat. Green arrow indicates overlaid points (e.g., "R")(CPCe4.1; Koehler and Gill, 2006)

NB: Colour box and overlayed letter points are created by the computer program and could not be altered to make larger.

4.2.7 Classification of the nest structure

A nest grading system was created to further aid in the assessment of marine debris interactions with this species, at these survey locations. The structure of the nest was graded (e.g. 1, 2, 3 or 4) to give an indication of nest age and condition. This was accomplished by examining the features of the nest (see Table 4.5 for details). Not all conditions must be met to have a particular grade applied, and there is some subjectivity when reviewing the photographs (Figures 4.4a,b,c,d).

Table 4.5: Grading factors to determine nest condition

Grade One *(Figure 4a)*	**Grade Two** *(Figure 4b)*	**Grade Three** *(Figure 4c)*	**Grade Four** *(Figure 4d)*
- Viable egg and/or bird present in nest; - Clearing present in central part of nest (depending on substrate type*); - Nest roughly round in shape; - Fresh/ many new feathers as nest material	- No egg /or bird; - Clearing present in central part of nest (depending on substrate type*); - Some nest structure still visible i.e. one side of nest; - Older/fewer feathers as nest material	- Items more congregated than in surroundings area; - No egg; - No defined clearing; - No or very few or old feathers; - items much more dispersed	- Nothing recognisable as having been a nest; - Randomly dispersed items

*Not always present when coral rubble main substrate

As feathers were one of the main items found in low grade number nests the condition of feathers was also used to further assist the grading of nest condition. Feathers were graded using an 0.1 (excellent) to 0.4 (poor) scale and are described in Table 4.6. As an example, a nest could have an egg with feathers with minor wear and therefore be graded "1.2" (with the first numeral referring to the nest condition and the second referring to the feather condition), or a nest could have no egg and only partial nest structure visible containing feathers with major wear and be graded as a "2.3". Refer to Figure 4.4 to see examples of feathers in different grades of nest.

Table 4.6: Feather condition index for use within grading nest condition

.1	Excellent, clean, fresh vanes and straight rachis
.2	Good, minor wear to peripheral vanes
.3	Fair, major wear over whole feather, possibly faeces on feather
.4	Poor, feather is losing definition, partial degradation, rachis curled, vanes and barbules missing

4.2.7.1 The Use of Nest Photographs to Assess Marine Debris Presence and Structure

The percent cover of marine debris found in nest photographs was strongly correlated to the number of individual marine debris items retrieved from nests (R^2 = 0.975, $p = 0.001$). This gives strength to the use of this photographic technique to quantify the presence and cover of marine debris items in nest material when items cannot be physically collected.

Additionally, the grading of the nests based on condition was a potentially viable nest classification method. There was a weak positive correlation ($\rho = 0.245$, $n = 64$, $p = 0.05$) between amount of debris and nest condition. Additionally, weak negative correlations were found between debris amount and feather condition ($\rho = -0.353$, $n = 64$, $p = 0.004$) and debris amount and feather number ($\rho = -0.533$, $n = 64$, $p < 0.001$). This lends support to the variables being used to grade the nest material, although further validation is required.

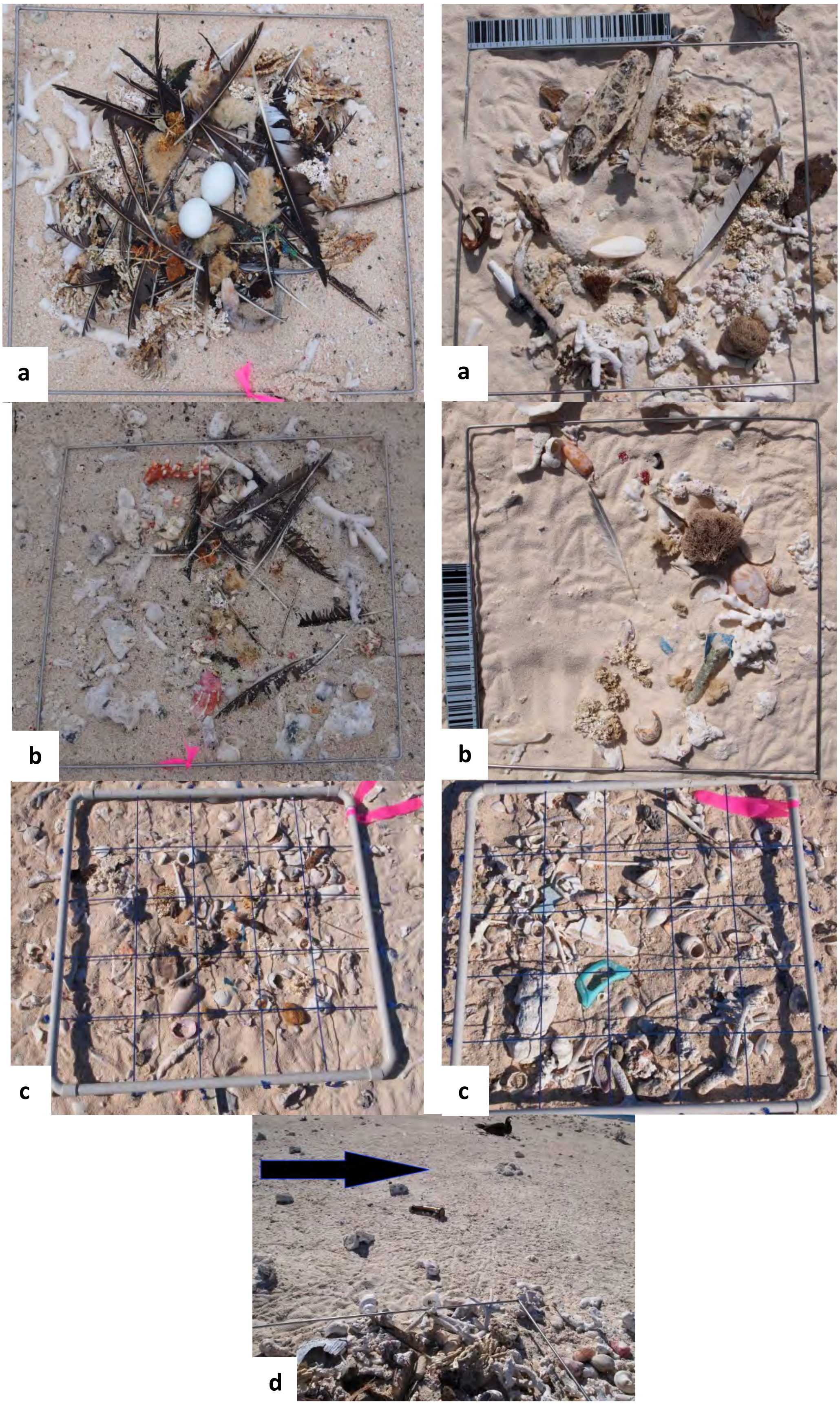


Figure 4.4: Nest grading examples for four grades described in Table 4.5. **a)** Grade one nest examples, **b)** grade two nest examples, **c)** grade three nest examples, and **d)** grade four (black arrow indicates an example area with no obvious nest material)

4.2.8 Sourcing Marine Debris

The method to allocate the source of marine debris items recovered from nest material and from debris recovered from beach survey transects was based on a percentage allocation method used by Whiting (1998) and described in detail in Tudor and Williams (2004). This particular method is flexible and allows for debris items to be classified as originating from more than one source, as no one item could be definitively attributed to one source (Tudor and Williams, 2004). The sources considered in this research were land (beach tourism), commercial shipping, commercial fishing, recreational boating/fishing, and stormwater discharge. The technique is described in detail in Chapter 2 Section 2.3.2.4.

4.2.9 Data Analysis

The mean (± 1 standard error) for size and weight of all marine debris items found in transect and within nests was determined. The percentage of different marine debris material types, items, and colours of debris items in transect and that used as nest material were determined for each sampling period.

The program SPSS Statistics (Version 20.0.0.1) was used to run statistical tests. For all statistical tests significance was represented by $p < 0.05$. Data was tested for normality using Kolmogorov-Smirnov test and heterogeneity with the Levene statistic, if the data failed either of these assumptions, it was log-transformed, if that data still failed, a non-parametric equivalent test was run instead (e.g. Mann-Whitney U-Test).

The Swain Reef nesting sites were considered separately to the Capricorn Island sites when undertaking statistical analysis (unless otherwise stated) due to the different geographical locations. This helped to avoid some of the confounding factors (such as tides, wind, storms and human activities) that may differentially influence marine debris deposition at these different southern GBR locations.

4.2.9.1 Nest Data

A temporal analysis of the mean number of debris items in a nest was performed using a one-way ANOVA, and a Kruskal-Wallis H-test to examine the mean number of items in relation to position of the Cay to the reef. The spatial patterns of the mean number of nest items between cays was analysed using a Kruskal-Wallis H-test. A one-way ANOVA was used to examine the mean number of items in nests based on GBRMP zoning.

The mean length of debris items in nests was examined using a Kruskal-Wallis H test for temporal and spatial cay relationships. A Kruskal-Wallis or a one-Way ANOVA was used to analyse the mean length and weight of debris items in relation to position of the cay relative to the cays associated reef (i.e., west, central, east). Temporal and spatial patterns for mean weight of debris items in nests were examined using a one-way ANOVA. Differences in debris colour and material type between that collected from nest and from shoreline beach surveys were both tested using a chi-square (χ^2) analysis.

4.2.9.2 Beach Shoreline Data

A temporal analysis of the mean number of items per transect was examined using a one-way ANOVA. A spatial analysis of the mean number of items between cays was undertaken using a Kruskal-Wallis H Test. Failing the condition of homogeneity of variance, a Mann-Whitney U-test was run to compare the number of debris items in transect (per m^2) depending on the location of the cay in relation to its reef (i.e., west and east). Shoreline debris data for central and east positioned cays were pooled as a Mann-Whitney U test demonstrated no statistically significant differences between the two cays ($U = 7.000$, $p = 0.879$). To detect potential differences from the influence of GBRMPA zones, the mean number of shoreline debris items was compared between the green and pink management zones.

Temporal patterns in the mean size of shoreline debris items were examined using a one-way ANOVA. Similarly, the position of the cay and spatial patterns between cays was examined using a Kruskal-Wallis H-test. Kruskal-Wallis H tests were also used to examine temporal and spatial patterns in the mean weight of shoreline debris items between cays and by the position of the cay relative to reef .

A linear regression analysis was used to determine the nature of the relationship that existed between marine debris types found on the beach and within nests using the number of items of a particular debris type and by amount within transect and within nest. A chi square (χ^2) analysis was undertaken to determine if differences existed between the colours and material types of nest marine debris items and those found in transects, using transect colours and material types as the expected values.

A Shannon-Weiner diversity index was used to determine how the varied types of debris differed found in nest and in beach transects. Correlations were run between debris amounts and nest condition using a Spearman Correlation to examine relationships between debris amount and feather condition in nest and debris amount and number of feathers in nest. Temporal and spatial patterns in nest condition were examined using a Kruskal-Wallis H-test. A test of the relationship between the coral count program and marine debris in nest material using preliminary data demonstrated a good fit. A Spearmans rank correlation was used to examine relationships between material type collected from a nest and that generated from the coral count programme photo analysis (described above in Section 4.2.6) for which there was a significant relationship ($r = 0.881$, $n = 10$ $p = 0.001$).

4.3 Results

4.3.1 Nest Surveys

4.3.1.1 Presence and Amount of Marine Debris

A total of 373 nests were surveyed collectively across seven sites in the Swain Reefs (n = 96), and one site in the Capricorn Bunker Group of islands (n = 277) within the southern Great Barrier Reef. Of these surveyed nests, ~23 % contained marine debris (referred to as contaminated nests). The number of contaminated nests is much higher (58 %) when the Swain Reef sites are considered in isolation (range 40 to 75 %; Appendix D; Verlis, et al., 2014), with only ~11 % of nests in the Capricorn Bunker Island site of East Fairfax being contaminated. Of the ~23 % contaminated nests, the average number of items per nest was quite low 3.1±S.E.0.3 (range = 1 to 23 items), and just over half of all contaminated nests (~57 %) contained only one piece of marine debris. Due to the differences in site locations and amounts, whenever possible the Swain Reef sites will be reported separately to East Fairfax and West Hoskyn Island sites in the Capricorn Bunker Group of Islands.

4.3.1.2 Swain Reefs

The 58 % of contaminated nests in the Swain Reefs, had an average number of 4.1±0.6 items per nest (range = 1 to 23 items). A total of 227 marine debris items were recovered from all nests across all time periods and locations in the Swain Reefs. The total number of items in these individual nests between the time periods was significantly different ($\chi^2_{[2]}$=7.471, p=0.024), with June 2012 (dry season) having the greatest number of marine debris items per nest (9.1±1.9 items) and 90 % of those nests with debris had more than one debris item (n = 56 nests with debris; Table 4.7).

There appeared to be more nests with debris in August (dry season) 2013 (~75 %) and fewer nests with debris in February 2013 (~31 %)(Table 4.7). The mean number of debris items in nests between time periods was found to be significantly different ($H_{[2]}$= 7.917, p= 0.019) and the mean number of items in nests was temporally significant ($F_{[2,10]}$ = 13.015, p = 0.002). The greatest recorded number of debris items present in nests was at Price, Bacchi and Frigate Cays (Table 4.8). However, the mean number of marine debris items between the cays was not significant ($H_{[2]}$= 1.429, p = 0.490).

Table 4.7: Summary of nest marine debris data for all surveyed Swain Reef sites

	June 2012	**February 2013**	**August 2013**	**Overall Mean**
Nests with marine debris	52.6 % (n = 19)	30.8 % (n = 26)	74.5 % (n = 51)	58.3 % (n = 96)
Percent Coverage marine debris	7.06	1.05	3.47	3.26
Size (cm) mean ± S.E.	8.1±0.7	11.3±4.6	8.7±0.5	8.6±1.0
Weight (g) mean ± S.E.	6.1±1.3	10.2±6.5	5.8±0.7	6.1±1.5
Mean no. of marine debris items in nest ± S.E.	9.1±1.9	1.6±0.2	3.4±0.4	4.1±0.6

The cays with the greatest amount of debris items retrieved collectively from nests across all surveyed times was Frigate (n = 116) and Price (n = 60) Cays. However, the mean number of items was not found to be significantly different between cays ($H_{[6]}$= 8.860, p = 0.182) (Table 4.8). Significant differences were seen between the number of items in nests on cays that are to the west of their respective reef ($F_{[1,13]}$= 5.068, p = 0.044), such as Frigate and Price Cay, as opposed to those cays to the East or Central to their reef (Table 4.1).

Table 4.8: Total number of marine debris items recovered from individual nests in the Swain Reefs, southern GBR

Time	Location (no. nest surveyed)	Total no. items recovered in all surveyed nests (no. nests with debris)	Mean no. items in nest with debris ± S.E.	Mean Length debris ± S.E. (cm)	Mean Weight debris ± S.E. (g)
Jun-12	Price (n = 9)	44 (n = 3)	14.7±6.4	8.4±1.0	4.5±1.5
Aug-13	Price (n = 9)	16 (n = 6)	2.7±0.8		
Jun-12	Bacchi (n = 3)	14 (n = 3)	4.7±0.7	17.0±7.4	5.1±2.1
Feb-13	Bacchi (n = 8)	3 (n = 2)	1.0±0.0		
Aug-13	Bacchi (n = 2)	1 (n = 1)	1.0±0.0		
Jun-12	Thomas (n = 4)	10 (n = 1)	10±0.0	15.3±4.9	6.9±2.2
Aug-13	Thomas (n = 8)	4 (n = 4)	1.0±0.0		
Jun-12	Frigate (n = 3)	24 (n = 3)	8.0±5.1	9.4±1.1	8.4±3.5
Aug-13	Frigate (n = 16)	92 (n = 18)	5.1±0.7		
Feb-13	Distant (n = 8)	8 (n = 4)	2.0±0.4	5.5±0.9	7.7±4.7
Aug-13	Distant (n = 8)	5 (n = 5)	1.0±0.0		
Feb-13	Riptide (n = 10)	1 (n = 1)	1.0±0.0	9.0±0.9	15.7±8.0
Aug-13	Riptide (n = 3)	2 (n = 2)	1.0±0.0		
Aug-13	Gannett (n = 5)	3 (n = 2)	1.5±0.5	3.1±0.6	0.67±0.1

NB: Only nests that contained marine debris are presented here

The overall mean length and weight of debris items was 8.6±1.0 cm and 6.1±1.5 g, respectively (Table 4.7). The weight of debris in nests did not differ significantly between sampling periods ($F_{[2,53]}$= 0.584, p= 0.561). There were however, significant temporal differences in the size of debris items ($H_{[2]}$ = 22.728, p < 0.001). Similarly, there was no spatial pattern based on debris weight ($H_{[6]}$= 9.837, p= 0.132), but a spatial pattern based on debris item length and the position of the cay relative to its reef was evident ($H_{[6]}$= 14.208, p= 0.027).

4.3.1.3 Fairfax Island

There were more nests that contained marine debris in the April 2014 sampling period, however, nearly double the number of nests were surveyed in this second time period. When standardised for this uneven sampling effort, the mean number of contaminants was quite similar between time periods, but the weight of items (74.9±34.8 g) in the nests increased dramatically during the second sampling period. A total of 36 items were collected from nests over the two survey periods (pooled sample data), with an average of only one item per surveyed nest (Tables 4.9 and 4.10).

Table 4.9: Summary of marine debris items detected in brown booby nests at East Fairfax Island, Capricorn Bunker Group of Islands

	March 2013	**April 2014**	**Overall Mean**
Nests with marine debris	7.8 % (n = 90)	11.8 % (n = 187)	10.5 % (n = 277)
Percent Coverage marine debris	0.91	1.22	1.10
Length (cm) mean ± S.E.	24.9±8.3	26.7±4.7	34.2±9.6
Weight (g) mean ± S.E.	7.4±2.6	83.0±34.5	59.4±30.4
Mean no. of marine debris items in nest ± S.E.	1.0±0.0	1.1±0.07	1.1±0.1

Table 4.10: Total number (pooled sampling periods) of marine debris items recovered from individual nests on East Fairfax Island, Capricorn Bunker Group of Islands

Time	**Location (no. nest surveyed)**	**Total items recovered in nest**	**Mean no. items in nest± S.E.**	**Mean Length± S.E. (cm)**	**Mean Weight± S.E. (g)**
Mar-13	E. Fairfax (n = 90)	7	1.0±0.0	24.9±8.3	7.6±2.6
Apr-14	E. Fairfax (n = 187)	30	1.1±0.1	26.7±5.4	43.5±26.02

NB: Only nests that contained marine debris are presented here

Debris items were larger in both length and weight in East Fairfax Island nests (34.2±9.6 cm and 59.4±30.4 g, respectively), than those at the Swain Reefs. The number of items in a nest did not significantly differ between survey times ($t_{[1]}$ = 7.286, p = 0.087). The size of items between time periods was quite similar, but not statistically so (Table 4.6a; U = 74.500, p= 0.899). Debris items appeared heavier in April 2014 but again, this pattern was not statistically significant (Table 4.8a; U = 72.000, p= 0.799). Hence, no temporal or spatial patterns were evident.

4.3.1.4 Natural Materials used in nests

The prevalence of marine debris within nests was quite low, contributing only 3.4 **%** to total nest material in the Swains and only 1.1 % at Fairfax Island with the remainder of nest material composed of natural items. Swain Reefs nests, in June 2012, had the highest amount of natural material present (93 %), and in March 2013 at

Fairfax Island the greatest amount of natural material was present in surveyed nests (99.0 %)(Tables 4.11 and 4.12).

Table 4.11: Percentage coverage of natural and marine debris in nests of brown boobies at sample locations in the Swains Reef (number of items is presented in parentheses) at three different survey times

		June 2012 (%)	February 2013 (%)	August 2013 (%)	Overall Contribution (%)
Natural Material	Coral	43.6 (142)	40.2 (267)	40.9 (473)	22.6 (882)
	Feather	7.7 (25)	37.4 (249)	13.5 (156)	12.7 (430)
	Seaweed Algae	13.5 (44)	11.3 (44)	13.7 (159)	7.2 (278)
	Wood	2.2 (7)	0.30 (2)	2.7 (31)	1.2 (40)
	Cuttlebone	2.2 (7)	0.15 (1)	0.61 (7)	0.38 (15)
	Seed	5.5 (18)	0.30 (2)	1.6 (18)	0.97 (38)
	Leaves Needles	0	0	0.09 (1)	3.2 (1)
	Shell	16.0 (52)	6.9 (46)	9.8 (113)	5.4 (211)
	Twig Branch	1.2 (4)	0.15 (1)	0.26 (3)	39.7 (8)
	Animal Matter Non Bird	0.31 (1)	0	1.0 (12)	0.33 (13)
	Bird Bone	0	0	0.52 (6)	0.20 (8)
	Pumice	0.61 (2)	0.30 (2)	10.4(120)	3.2 (123)
	Other	0.31 (1)	2.0 (13)	1.3 (15)	0.72 (28)
Marine Debris	Plastic Hard	4.3 (14)	0	2.6 (30)	1.3 (44)
	Plastic Sheet	0	0	0.17 (2)	0.09 (2)
	Plastic Rope	0.31 (1)	0.45 (3)	0.26 (3)	0.36 (7)
	Metal	0.31 (1)	0	0	0.05 (1)
	Processed wood	0.92 (3)	0	0.35 (4)	0.33 (7)
	Glass	0	0	0.09 (1)	0.05 (1)
	Rubber	1.2 (4)	0.60 (4)	0.26 (3)	0.51 (11)

In the Swain Reefs, coral was the most common material in nests (41 %), followed by feathers (20 %), and a few twigs-branches. The natural materials utilised in nests between sampling times did not differ significantly in the Swains ($F_{[2,11]}$ = 0.196, p = 0.826). This differed to Fairfax Island where nests were primarily composed of twig-branch material (57 %), followed by leaves and needles (24 %) (Table 4.12).

Table 4.12: Percentage coverage of natural and marine debris in nests of brown boobies at sample locations at Fairfax Island, Capricorn Bunker Group of Islands, southern GBR (number of items is presented in parentheses) at two survey times

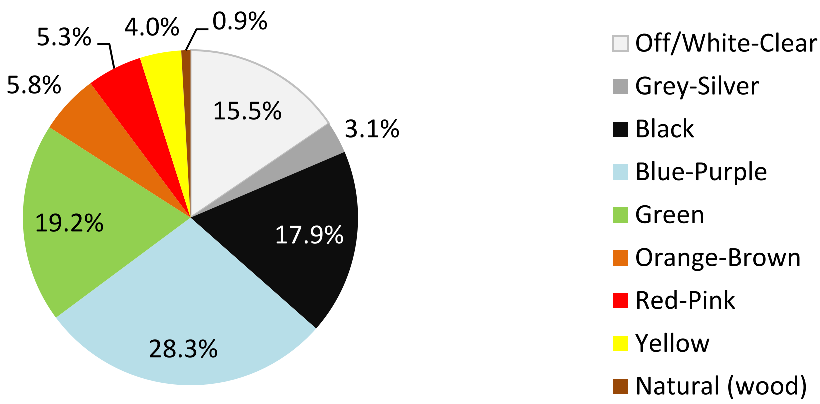
		March 2013 (%)	April 2014 (%)	Overall Contribution (%)
Natural Material	Coral	0	18.8 (540)	11.7 (540)
	Feather	3.7 (64)	6.4 (183)	5.3 (247)
	Seaweed Algae	0.11 (2)	0	0.04 (2)
	Wood	0.34 (6)	0.70 (20)	0.56 (26)
	Cuttlebone	0	0	0
	Seed	0	0	0
	Leaves Needles	7.0 (123)	34.3 (984)	24.0 (1107)
	Shell	0	0	0
	Twig Branch	87.9 (1543)	37.4 (1073)	56.6 (2616)
	Animal Matter Non Bird	0	0.03 (1)	0.02 (1)
	Bird Bone	0	0.03 (1)	0.02 (1)
	Pumice	0.57 (1)	1.1 (30)	0.67 (31)
	Other	0	0	0
Marine Debris	Plastic Hard	0.34 (6)	0.31 (9)	0.32 (15)
	Plastic Sheet	0	0	0
	Plastic Rope	0.23 (4)	0.45 (13)	0.37 (17)
	Plastic Foamed	0	0.03 (1)	0.02 (1)
	Metal	0.11 (2)	0	0.04 (2)
	Processed wood	0.23 (4)	0.21 (6)	0.22 (10)
	Glass	0	0.14 (4)	0.09 (4)
	Rubber	0	0.07 (2)	0.04 (2)

There was a moderate correlation between coral rubble background substrate and amount of marine debris items recovered from nests at these sites ($R^2 = 0.445$, $p = 0.001$). Little correlation existed between amount of debris items recovered from nests and those with background substrates of sand or vegetative matter ($R^2 = 0.006$, $p = 0.246$, and $R^2 = -0.80$, $p = 0.850$, respectively).

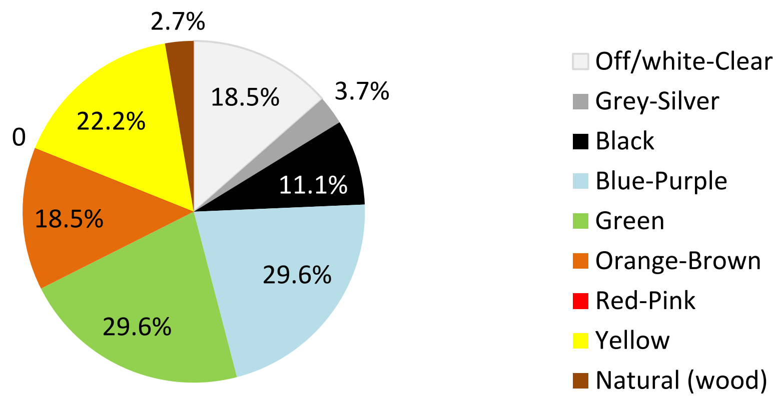
4.3.1.4 Colour of debris items in nest

The nests debris items recovered from Swain Reef sites included all colours, with blue being the most common debris colour in this location (Figure 4.5a). Green, black and off/white-clear items were also quite common, with few wood, grey-silver or yellow items found in nests. This differed to East Fairfax Island nests that had more yellow and orange-brown items recovered (Figure 4.5b). Although similar to the Swains, blue and green coloured debris were the most common colours at East Fairfax

(~30 %; Figure 4.5b). Fewer marine debris items were collected from Fairfax Island nests (n = 27), which limits the analysis and conclusions that can be drawn from this data.



a

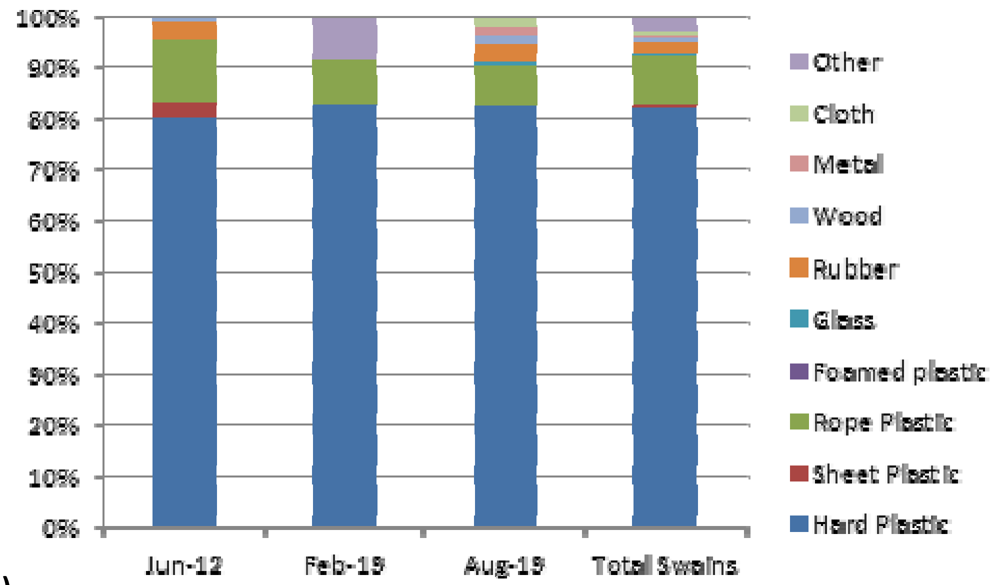


b

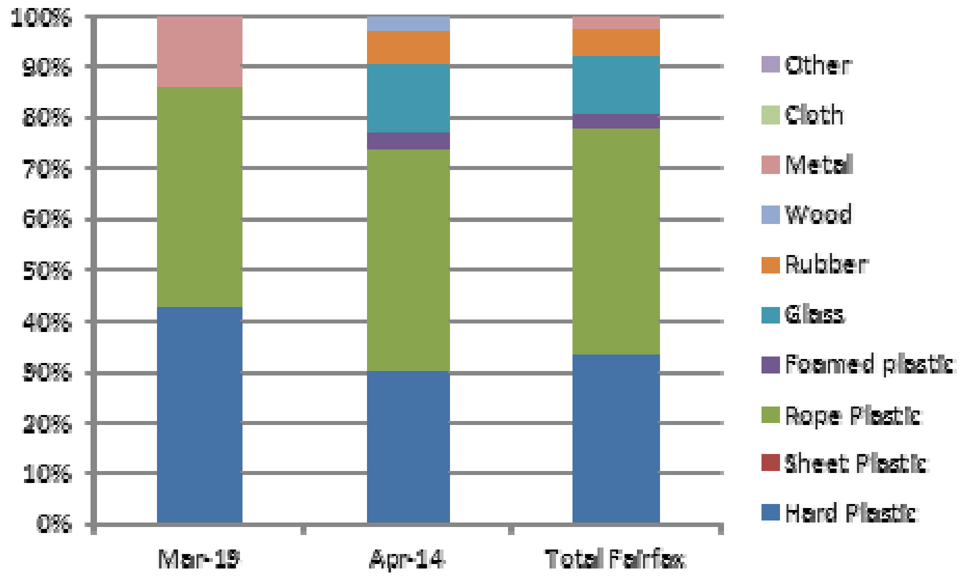
Figure 4.5: Proportion (%) of marine debris item colours used in nest material of brown boobies all survey times in the **a)** Swain Reefs, and at **b)** East Fairfax Island

4.3.1.5 Debris Types and Items in nests

The most common marine debris type recovered from surveyed nests in the Swain Reefs was hard plastic (82 %) (Figure 4.6a). This differed to Fairfax Island where rope plastic was more prevalent (44 %) in nests then followed by hard plastic (33.3%; Figure 4.6b). The greatest diversity of marine debris item types used in nests was in August 2013 (and is supported by the findings of the Shannon Weiner Diversity Index, Table 4.10). Although lower in debris type number, the patterns in debris type were similar between August and February. In February 2013, only three material types were used as nest material in the Swains (Figure 4.6a), with the majority being hard plastic. The Fairfax Island site had a high amount of rope plastic and hard plastic fragments with these items making up the majority of anthropogenic item material (Figure 4.6b).



a)



b)

Figure 4.6: Proportion of marine debris item types found in brown booby nests at **a)** Swain Reef sites, and **b)** East Fairfax Island

The Shannon-Weiner diversity index also showed that February had the lowest range of debris items recovered from both nest and beach transects, and that August had the greatest range in both nest and transect at the Swain Reef sites (Table 4.13). Overall the diversity of debris types was lower in nests (0.75) compared to beach transects (1.13) at the Swain Reef sites. In contrast, at the Fairfax Island nest site debris diversity was higher (1.42) than transects at the nearby Hoskyn Island (1.04).

Table 4.13: Shannon-Weiner Diversity Index for marine debris items recovered from nest and beach surveys at different time periods

Location	Month	Nest	Transect
Swains	Jun-12	0.70	0.62
Swains	Feb-13	0.57	0.30
Swains	Aug-13	0.72	1.65
Fairfax	Mar-13	1.00	0.94
Fairfax	Apr-14	1.40	1.09

The most commonly identified marine debris items found in individual nests in the Swain Reefs were hard plastic fragments, bottle caps and lids (Table 4.14). There were also items like a plastic razor, comb, and stationery items (pen, marker) (~4 %) present. Within beach transects items such as thongs (flip-flops/jandals), balloons, a bar fridge and a fishing rod were recovered. The materials found in nests differed significantly from the types of materials recovered from beach transects ($\chi^2_{[6]} = 14.092$, $p = 0.029$).

Table 4.14: Most common marine debris items (%) found in brown booby nests and on surveyed beaches in the Swain Reefs overall and Capricorn Bunker Group of Islands

Item	% Nest (no.)	Item	% Beach Transect (no.)
Swain Reefs			
Hard plastic fragment	25.1 (58)	Hard plastic fragment	39.6 (67)
Bottle cap and lid	17.6 (38)	Bottle (glass and plastic)	16.0 (27)
Rope, Net, Strapping, Cords	9.3 (22)	Plastic bottle cap and lid	7.7 (13)
Plastic Crate (fragment)	5.3 (14)	Rope, Net, Strapping, Cording	4.1 (8)
Plastic Handle	3.5 (8)	Processed wood	3.6 (6)
Toothbrush	3.5 (8)	Light bulb and fluorescent tube	2.4 (4)
Cylume stick	2.2(5)	Cylume stick	2.4 (4)
Item	**% Nest (no.)**	**Item**	**% Beach Transect (no.)**
East Fairfax			
Ropes, Net and Line	41.0 (16)	Hard plastic fragment	32.7 (464)
Hard plastic fragment	33.3 (13)	Bottle (glass and plastic)	19.9 (283)
Bottles (glass and plastic)	10.3 (4)	Plastic Bottle cap and lid	17.4 (247)
Rubber thong fragments	5.1(2)	Rope, Net, Strapping, Cording	4.2 (59)
Aluminium can	2.6(1)	Processed wood	2.6 (37)
Plastic bait bag	2.6(1)	Cylume stick	1.7 (24)
Processed wood wainscoting	2.6(1)	Light bulb and fluorescent tube	0.7 (10)
Foam fragment surfboard	2.6(1)		

There was no statistically significant correlation between the number of debris items in nests and that found on beaches ($R^2_{[3]}$= -0.86, p = 0.830). Correlations existed between certain items in transect and in nest, such as the amount of rope ($R^2_{[9]}$ = 0.606, p = 0.002) and to a lesser extent with rubber ($R^2_{[9]}$= 0.407, p = 0.019, Figure 4.7). Although rope was dependent upon a single outlier, and the significance of this relationship is lost by its removal.

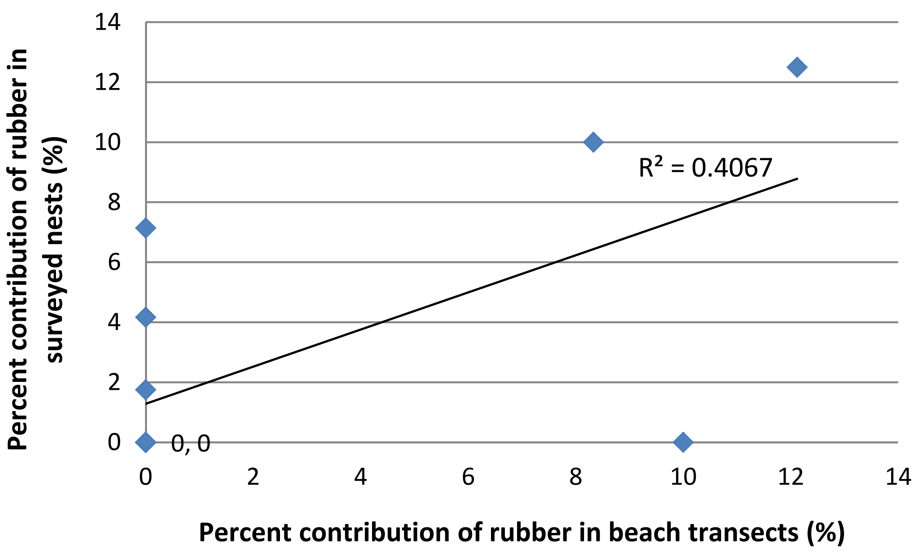


Figure 4.7: The proportion of rubber in beach transect compared to rubber in nests at surveyed sites

4.3.2 Beach Transect Surveys

4.3.2.1 Presence and Amounts

Across all locations and sampling times 0.04 items m^{-2} were found on sampled beaches. Overall, the greatest number of items per m^2 were found on West Hoskyn Island, Price Cay and Frigate Cay, and the lowest amounts on Riptide Cay and Gannett Cay (Table 4.15). This shows a westward gradient pattern, with significantly more debris retrieved from cays positioned west (Tables 4.1 and 4.2) of their respective reef ($U = 4.591$, $p=0.032$).

Table 4.15: Number of items of marine debris collected per m^{-2} from all surveyed beaches

Beach	Count (items/m^2)	Position relative to reef
W. Hoskyn Island	0.17	West
Price Cay	0.03	West
Frigate Cay	0.02	West
Bylund Cay	0.01	East
Distant Cay	0.007	Central
Bell Cay	0.005	Central
Bacchi Cay	0.004	West
Gannett Cay	0.003	Central
Riptide Cay	0.003	East
Thomas Cay	0.003	East

A total of 178 items were recovered from beach transects at all Swain Reef locations. The mean length of debris items were 15.4±2.6 cm, with a mean weight of 87.1±21.4 g (Table 4.16). The most common debris type recovered was hard plastic (~77 %) followed by metal (~6 %) and glass/ceramic (~5 %) (Figure 4.8).

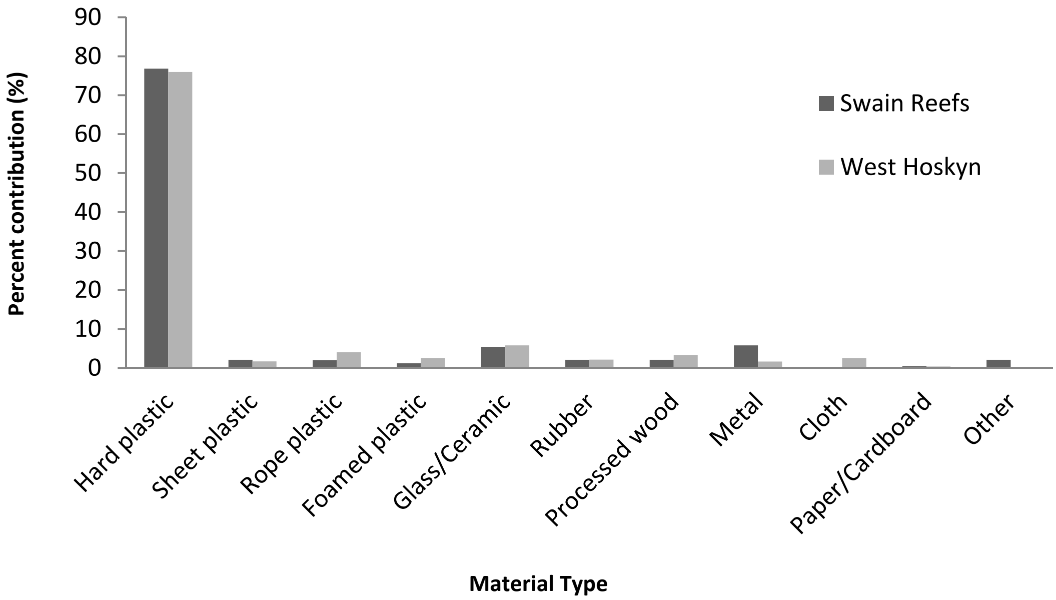


Figure 4.8: Total overall percent contribution of different marine debris material types recovered from beach shoreline debris surveys in the Swain Reefs and from West Hoskyn Island at all survey times

Similar amounts of debris were recovered at West Hoskyn at both survey periods (Table 4.17) but a great deal more was collected overall (1419 items) compared to Swain Reef beaches. In August 2013, the heaviest (130.3±35.3 g) and the widest variety of debris items (n = 74 items) were collected. In June 2012, the smallest mean size of debris items were recovered (10.2±4.0 cm), and in February 2013 the fewest number of items and item types were recovered (Table 4.16).

Table 4.16: Summary of marine debris items recovered from beach surveys at Swain Reef locations across all sampled time periods

	June 2012	February 2013	August 2013	Overall
No. transects run	n = 12	n = 12	n = 24	n = 48
No. items collected	93	11	74	178
Size mean (cm ± S.E.)	10.2±4.0	24.6±13.5	20.6±2.9	15.4±2.6
Weight mean (g ± S.E)	31.0±17.1	33.8±18.3	130.3±35.3	87.1±13.3
Count (items/m^2)	0.03	0.005	0.007	0.01
Weight (g/m^2)	0.7	0.08	0.9	0.7
Non-Plastic (%) Marine Debris				
Cloth	0.0	0.0	0.0	0.0
Glass/Ceramic	3.2	0.0	12.3	5.4
Metal	3.2	9.1	4.6	5.8
Paper/Cardboard	0.0	0.0	1.3	0.43
Rubber	1.1	0.0	6.2	2.1
Wood	1.1	0.0	7.7	2.1
Other (coal)	0.0	0.0	4.6	2.1
Plastic (%) Marine Debris				
Hard Plastic	87.1	90.9	49.2	76.9
Sheet Plastic	1.1	0.0	6.2	2.1
Rope Plastic	2.2	0.0	4.6	0.0
Foamed Plastic	1.1	0.0	3.1	1.2
Fibrous Plastic	0.0	0.0	0.0	0.0

No cloth items or medical and fibrous plastic debris items were found in any of the sampled transects.

Table 4.17: Summary of marine debris items recovered from West Hoskyn beach surveys at both survey times and overall

	March 2013	April 2014	Overall
No. transects run	n = 9	n = 9	n = 18
No. items collected	760	659	1419
Size mean (cm ± S.E.)	13.6±0.91	18.7±3.9	16.0±1.6
Weight mean (g± S.E)	33.8±3.4	85.0±33.0	57.6±11.8
Count (items/m^2)	0.2	0.2	0.2
Weight (g/m^2)	1.8	5.2	3.5
Non-Plastic (%) Marine Debris			
Cloth	0.53	4.9	2.5
Glass/Ceramic	5.3	6.4	5.8
Metal	1.3	2.0	1.6
Paper/Cardboard	0.66	0	0.35
Rubber	3.8	0.15	2.1
Wood	3.6	3.0	3.3
Other (Coal)	0.0	0.0	0.0
Plastic (%) Marine Debris			
Hard Plastic	78.4	73.1	76.0
Sheet Plastic	2.0	1.4	1.7
Rope Plastic	4.0	4.1	4.0
Foamed Plastic	0.53	4.9	2.5
Fibrous Plastic	0	0.15	0.07

Using the Marine Debris Pollution Index generated in Chapter 2, the Swain Reef sites all had a Marine Debris Pollution Index score of ‘Green 8’ at all survey times (all sites were pooled due to the low level of debris recovered in transect), while West Hoskyn (March 2013 and April 2014) was at both survey periods at ‘Green 7’ (Table 4.18).

Table 4.18: Marine Debris Pollution Index for all surveyed sites (generated from Table 2.11)

Location	Survey Time	Debris m^{-2}	Mean debris item Area (cm^2)	Pollution Index Score
Swain Reefs	June 2012	0.03	117.9±87.1	**8**
	February 2013	0.005	66.1±28.9	**8**
	August 2013	0.007	101.5±21.3	**8**
West Hoskyn Island	March 2013	0.2	96.3±39.1	**7**
	April 2014	0.2	116.6±10.1	**7**

In June 2012 and March 2013, the highest levels of blue-purple debris items were recovered from beach transects, while February and August had higher levels of off/white-clear. Interestingly, the highest level of black items was in February 2013 (27 %), but at all other survey times black items were quite low, making up ≤ 10 % of debris items (Figure 4.9a).

The most common debris item colour in all transects at all surveyed locations was blue (30 %) and off/white-clear (28 %). Items of yellow (2 %) and grey-silver (2 %) were the least common colours recovered (Figure 4.9).

The colour of marine debris items used by brown boobies in nests and that found on beaches in the Swains were significantly different ($X^2_{[8]}$ = 16.029, p = 0.042; Figures 4.5a,b and 4.9a,b). At East Fairfax Island nests and on the beach transects at West Hoskyn, the percent contribution of colours were not significantly different ($X^2_{[8]}$ = 10.297, p = 0.245). Additionally, there was a very strong correlation in the colours of debris items in beach transects at West Hoskyn and those recovered in transects at Swain Reef sites (ρ= 0.883, n = 9, p = 0.002).

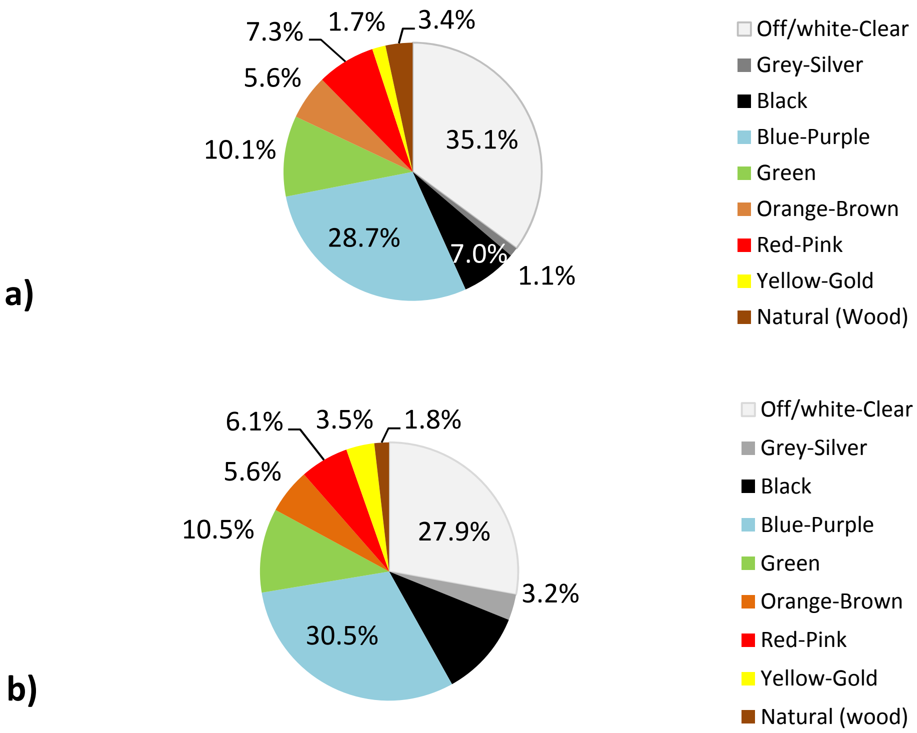


Figure 4.9: Comparison of the proportion of different coloured marine debris items recovered in beach surveys at different time periods in a) the Swain Reefs; and **b)** at West Hoskyn Island

4.3.2.3 Sources of Recovered Debris items

Labelling and bar codes on debris items recovered from both nest and shoreline survey showed that items originated from at least 14 foreign countries (Table 4.19). These items (excluded the Australian identified items that made up ~ 35 % of recovered items) were most commonly sourced from China, Indonesia, and Japan.

Table 4.19: Number of foreign origin marine debris items from nest and transect surveys

Country	Nest	Transect
China / Hong Kong	-	23
Indonesia	1	19
Japan	-	15
Singapore	-	5
Philippines	-	4
Malaysia	-	3
Korea	-	2
Papua New Guinea	-	2
Peru	1	1
Thailand	-	1
Ukraine	-	1
United Arab Emirates	-	1
United States of America	-	1
Vanuatu	-	1

Nests and beach transects had similar amounts of debris from land (beach tourism), storm-water discharge, and recreational fishing/boating sources. The only difference between nest and beach debris amounts was that the greatest contributor to nests was debris originating from commercial fishing, while beach transects had higher loads originating from commercial shipping (Figure 4.10). This pattern occurred at both Swains and Fairfax Island sites. Oceanic based sources accounted for the greatest proportion of recovered debris items both in the Swains and at Fairfax Island.

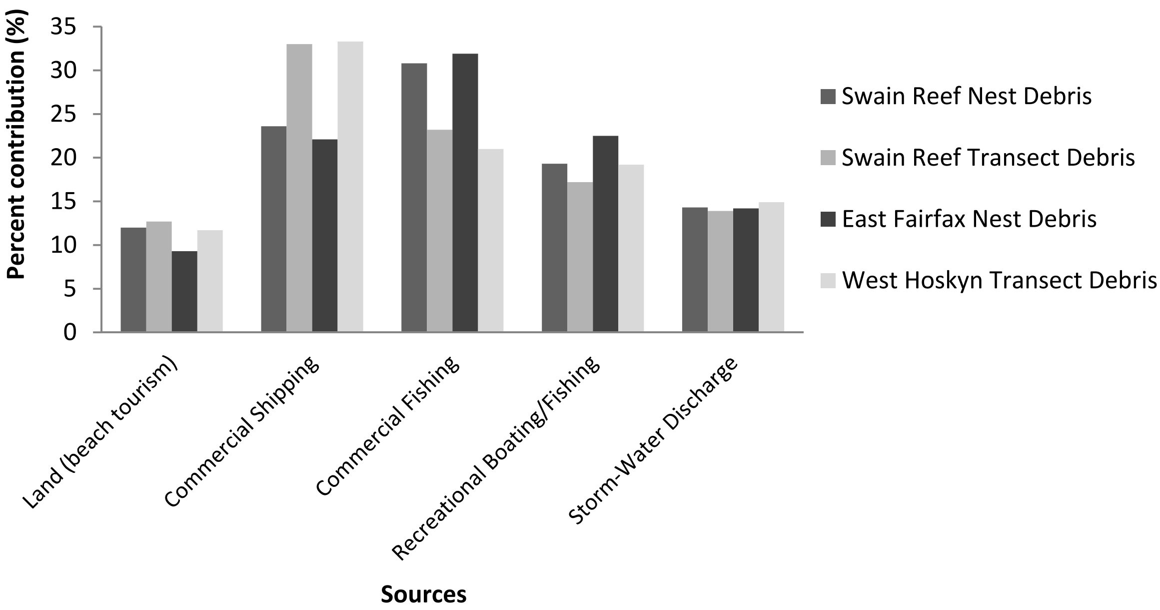


Figure 4.10: Sources of marine debris from survey sites. Swain Reef nest (n = 277 items) and transects (n = 169 items) and at Capricorn-Bunker nests (n = 37 items) and transects (n = 1419 items)

4.3.2.3 GBRMPA Zoning

Analysing marine debris data relative to their surrounding marine park zoning indicated that there was a statistically significant difference in the amount of debris on beach transects in the green versus the pink zones (Mann Whitney U-test = 3.500, p = 0.031). The pink zone had more items than the green zone (Table 4.15). This pattern was not evident however, in the mean number of items in nests between the zones (Mann-Whitney U-test = 5.00, p = 0.110).

4.4 Discussion

The monitoring of marine debris in nest material of seabirds has been suggested as a way to determine offshore marine debris pollution levels, its sources, and the potential impacts of this pollution on seabirds (Nel and Nel, 1999; Ryan, et al., 2009; Provencher, et al., 2015). This research is the first to determine the usage, type and source of marine debris in the nest material of brown boobies at locations in the southern GBR, an important seabird breeding and nesting area. Shoreline debris surveys were run at the nesting sites and this gave a comparison to usage in nest material, and provided an indication of the appropriateness of nest material as a monitoring tool through the use of novel survey techniques. This study also provided further evidence that remote areas are affected by marine debris, specifically plastic pollution.

4.4.1 Nest Marine Debris Photographic Analysis Method and Nest Condition Grading

Remote video technology (McQuillen and Brewer, 2000) and still cameras are commonly used to monitor birds and other wildlife in their natural environments (Browne, and Gehrt, 2009). A new and novel photographic analysis of brown booby nests to assess nest contamination proved to be accurate. This can be used in lieu of direct collection of marine debris from the nest, if time is limiting (R^2= 0.975, p = 0.001). As brown booby nests degrade with time, this method can also categorise nest condition and be used to effectively determine some relationship with debris loads. Even if marine debris items are physically collected, this photographic quadrat technique has the benefit that photographs are non-destructive and less invasive to the birds. Although natural materials can be quantified and qualified by both methods, if time is limited, photographs can provide for this data collection and allows for researchers to 'revisit' the data at a later date.

When examining nest degradation (Figure 4.4), it is recommended that this photographic method be used with nests of grade 1 and 2 only; although more work is needed to verify this approach. This classification does require the nests to be graded at the sites. If unsure of grading, photographs can be taken and the images sorted back in the laboratory. The designation between the grades is visually apparent and the application of the grading system does become easier as familiarity leads to better image recognition that helps in the identification.

HYPOTHESIS *H_{XI}*: No marine debris was used in the nest material of brown boobies in the southern Great Barrier Reef.

Marine debris was present at low levels in the nest material of brown boobies at surveyed locations in the Swain Reefs and at East Fairfax Island in the Capricorn Bunker Group of islands. Thus Hypothesis H_{XI} is not supported. The level of debris in nests at the Swain Reef locations was quite high with nearly 60 % of nests containing marine debris. This higher level is comparable to kittiwake (*Rissa tridactyla*) nests in north-west Denmark (57.2 %) (Hartwig, et al., 2007). At East Fairfax the level of contamination (ranged from ~8 to 26 %) is more comparable to levels seen in brown booby nests at Ashmore Reef (3 -31 %) (Lavers, et al., 2013) but less than that recorded in double-crested cormorant (*Phalacrocorax auritu*) nests in the Gulf of Maine (36 - 39 %) (Podolsky and Kress, 1989). Additionally, in the Swain Reefs contaminated nests had an average of 4.1 items, with more than half (~61 %) of nests containing more than one item, which differed sharply to Fairfax Island (Table 4.7) and Ashmore Reef Sites (Lavers, et al., 2013) with the majority of these nests containing only one item of debris.

The differences in the presence of marine debris in brown booby nests in the Swain Reef sites compared to East Fairfax Island sites may be due to the different geographic position of the nest sites, habitat differences such as varied topography, and substrate, as well as wind and wave action.

Background substrate for instance, could be an influencing factor in these observed differences as a correlation between the presence of debris and a coral rubble background substrate was found. No correlation existed with the substrates of vegetation or sand though. This could be due to the coral rubble trapping and retaining the debris even in strong winds (Williams and Tudor, 2001b). Cays with cobble substrate can indicate a cay is located in an area more prone to storm activity, while sand dominated cays indicate lower storm and cyclonic impacts (Yamano, et al., 2005). A greater influence of storm activity on coral cays could serve to deposit and 'reveal' buried debris items and could potentially be a contributing factor to his correlation of coral substrate to debris presence.

At nesting sites in the Swain Reefs, it was not surprising that vegetation did not have a strong correlation with debris accumulation. As only one Swain Reef site was vegetated, with most Swain Reef cays having a base substrate of sand and/or coral rubble (Table 4.1). East Fairfax also had a coral rubble base, but a lot of vegetation was present in its centre, due to its size and the greater stability of the island (Table 4.2). If natural vegetative debris is scarce it has been suggested that the birds may rely more on marine debris to create nests (Lavers, et al., 2013). This may have relevance to East Fairfax, but was not seen in this study at Swain Reef sites with greater amounts of marine debris detected in the nests on the only vegetated Swain Reef cay, Price Cay, for two of the sampling periods (June 2012, n = 44 total nest items; and August 2013, n = 16 total nest items). In this instance, the vegetation appeared to trap debris items, instead of being used as nest material itself.

At East Fairfax vegetation, twigs and branches made up the bulk of the nesting material in March (~88 %) and overall accounted for just over half (~57 %) of all nest material with only very low levels of marine debris utilised (~11 % of all nests, n = 277 nests). This could indicate that the birds do not utilise marine debris as sufficient natural material was present, or that there is limited marine debris in the environment for the birds to utilise. This last point is unlikely given the shoreline survey at West Hoskyn Island yielded the highest debris amounts of all surveyed sites (Table 4.17). Gannets in Canada (Montevecchi, 1991) and the UK often utilised synthetic rope as nest material due to resemblance to natural long filamentous algae and seaweed

(Votier, et al., 2011). Additionally, in the UK, there was a higher frequency of rope in nests than in beach debris indicating a preference by the gannets (Votier, et al, 2011). If a preference exists for a particular item type, even if debris levels are high in the surrounding environment the birds may not be interacting with it, at least for the purposes of nest building, if it is not of a shape, colour or material they prefer.

Additionally there might be population specific behavioural differences at work. Differences in nest material preferences between the populations could influence upon debris amounts and usage in nests between the locations. Further investigation to understand where debris is sourced for use within brown booby nests would be helpful to understand these site and population differences. This could be achieved by utilising remote video, or still cameras set up on the Cays to monitoring bird movement. Capturing images of the birds returning to the nest site and building the nest would be informative. Cameras are used on northern gannets in the UK along with GPS loggers to observe interactions with commercial fishing vessels (Votier, et al., 2013). Similarly, in areas of high pollution, this technique could inform on interactions of seabirds with marine debris.

HYPOTHESIS H_{XII}: No correlation existed between the presence of marine debris on beaches of surveyed sites and the use of marine debris in brown booby nests in the same location.

The amount and types of marine debris on the beach does not appear to be one of the main influencing factors to debris use in nests, with no correlation of nest material to that on adjacent beaches (R^2 = -0.86, p = 0.830), and no correlation with debris levels directly around the nest ($R^2_{[40]}$ = 0.45, p = 0.179). Hence, Hypothesis H_{XII} is supported by these findings. Only rubber in nests in this study correlated with the respective amounts found on the beach (R^2 = 0.407, p = 0.019). This gives limited support to the assertion that some items are sourced directly from the cay (Lavers, et al., 2013) and may indicate brown boobies have a preference for these items since levels were consistent over the different time periods. This was similar to the finding of gannets in the UK that appeared to have a preference for rope (Votier, et al., 2011). But differed to gannets in Canada (Montevecchi, 1990), and black-legged kittiwakes in Denmark (Hartwig, et al., 2007) that collect nearly all of their nest material from the surrounding waters and beach near the colony. The debris levels in these areas are thought to reflect pollution levels in the adjacent marine environment, and that the levels of debris incorporated into nests corresponded to the amounts of those debris items types (i.e. strings and netting, foil) retrieved from nearby shorelines (Hartwig, et al., 2007).

Within the cays of the Swain Reefs, the position of the cay relative to its surrounding reef had a significant influence on debris loads detected in the beach transects, with greater levels of marine debris accumulating on cays positioned to the west of their reef (Tables 4.15 and 4.16; Mann-Whitney U-test = 7.500, $p = 0.032$). This indicates that the prevailing winds and position of the reef are influencing the debris loads being deposited on shores of Swain Reef Cays. This is supported by what is known about deposition, erosion and the transport of sediments onto and off of cays through wave and wind action, local currents and cyclonic activity (Harmelin-Viven, 1994; Yamano, 2000). Waves in particular help shape the reef through diffraction around platform reefs (Gourlay, 1988). As winds blowing from the south-east are the most common in the area, and if a reef is to the west of the Cay it could allow the debris, along with sediment, to accumulate more readily on these cays.

Nest studies in Canada (Bond, et al., 2012), in the Eastern United States (Podolsky and Kress, 1989) and on Marion Island (Nel and Nel, 1999) have indicated that the nearby anthropogenic activities influence the type of available nest material occurring offshore and in turn may affect the nature and type of material deposited on beaches. The greatest contribution (~74 %) of debris originated from marine based sources in this study (Table 4.10) and was not unexpected due to the isolation of the Swain Reefs (up to 200 km away from mainland Australia and populated areas), with the Capricorn Bunker Group of Islands ~80 km away from the mainland. These findings are similar to patterns in Fog Bay, Northern Australia, where 85 % of all debris items were marine-sourced (Whiting, 1998). Both beach and nest debris items in the Swain Reefs and at the sites in the Capricorn Bunker Islands were most commonly sourced from commercial shipping (33 and 33 %, respectively on beach) and commercial fishing (23 and 21 %, respectively on beach; Table 4.10) and were at levels similar to what was seen in the Capricorn Bunkers offshore sites in Chapter 2. At Marion Island, fishing gear accounted for more than 50 % of items found in association with seabird nests (Nel and Nel, 1999). This debris was attributed to the commercial fishing activity occurring nearby (Nel and Nel, 1999).

Fishing activities are common in the surveyed areas, with more than 60 % of the GBRMP available for fishing activities (commercial, recreational, charter and indigenous) and 750 active licenses in the GBR (Tobin, et al., 2014). Additionally, a number of commercial ports operate along the Queensland coast that border the GBRMP and in some instances occur within the GBR World Heritage Area (i.e. Port of Gladstone). The ships visiting these ports originate from many different countries. For instance, the greatest number of vessels arriving at the Port of Gladstone in 2014 (excluding vessels from Australia n = 96 ships) were from Japan (n = 119), China (n = 87), India (n = 84), Korea (n = 35), Taiwan (n = 20), Brazil (n = 11), Indonesia (n = 10), and Russia (n = 10) (GPC, 2015). Although port side garbage facilities are available to commercial shipping vessels, and strict legislation regarding waste disposal is enacted (Chapter 1 Section 1.8) compliance with correct waste disposal is difficult to enforce, and commercial vessels are known to improperly dispose of their rubbish overboard. For instance, a Chinese shipping company was fined $20,000 for disposing of rubbish overboard ~16 nautical miles north of the Port of Gladstone on June 13, 2013 (Healy, 2014). A number of foreign sourced items were found in both shoreline surveys and in nests suggesting these ships travelling through the GBR are a prime source of marine debris in the area.

Sources could also be foreign commercial fishers, foreign beach tourism, or stormwater discharges that have travelled down the East Australian Current (EAC) as part of the South Pacific gyre, as evidenced from a hard plastic cocktail stick originating from a Balinese resort and a water bottle from Vanuatu. Studies in Northern Australia, found glass bottles from Japan that were attributed to long-line and tuna fisheries (Smith, 1992; Wace, 1995), and certain rubber items have been attributed to Indonesian fishing vessels operating in the area (Kiessling, 2003). The EAC flows southward directly by the cays and islands of the southern GBR (Smith, et al., 1990; Smith, 1992) and can potentially transport items from the South Pacific equatorial current down from the northeast and through the Torres Strait into the GBR.

There was slightly more debris attributed to local recreational boating/fishing sources in the Capricorn-Bunker Islands than in the Swain Reefs (Table 4.10; Chapter 2, Figure 2.7). The Capricorn-Bunker Group of Islands is well within range from the mainland, or recreational boaters (Stokes, et al., 1996); and hence, the greater influence of this source was not unexpected in this area. The remoteness and complexity of the Swain reefs can act to limit the number of recreational visitors to this region. However, commercial fishing and fishing charters are present in the area and these activities have a demonstrated influence upon the cays, with high levels of fishing debris in nest material at both Swain Reef and Capricorn Bunker Island sites (Figure 4.10).

The larger mean size of debris items recovered from beach surveys compared to that found in nests reflect the item types and possibly the ease of carrying smaller items to the nest. Plastic bottles, for instance, were the second most common item in shoreline surveys (16 % Swains and 20 % West Hoskyn; Tables 4.11 and 4.12) but were less prevalent in nests (0 and 10 %, respectively). Beach debris surveys in the northern GBR had similar findings to those found in this study on Swain Reef and West Hoskyn beaches, with such as items of plastic water and laundry bottles and glass alcoholic beverage bottles being common (Haynes, 1997). In August 2013, the heaviest marine debris total weight was recorded on beach transects and this was due to the presence of large pieces of processed wood. The considerably smaller size of objects found in the June 2012 beach surveys (Table 4.8), relates to the large number of fragments collected during this period, with June having the greatest number of fragments recovered in transect across all survey periods. Hard plastic fragments are a common debris type on surveyed beaches in other studies (Frost and Cullen, 1997; Whiting, 1998; Cunningham and Wilson, 2003; Slavin, et al., 2012; Smith and Markic, 2013). Most nests in this study contained small sized objects, such as hard plastic pieces (25 % Swains and 36 % East Fairfax) and bits of rope (Tables 4.11 and 4.12), which is similar to items used as nest material found in other studies (e.g. Hartwig, et al., 2007; Lavers, et al., 2013).

Hard plastic pieces were also the most common item in beach transects. These items types might be readily used by these birds in nests due to their high prevalence in the environment and their ease of movement due to their size. In some instances larger items such as glass bottles and planks of wood were incorporated into nests. However, given the logistics of a bird moving these items, it is more likely that these items were already present in these locations and the bird chose to nest at that spot in order to utilise the item. The birds appear to purposefully interact with large marine debris present in the environment and this behaviour may also extend to smaller items, like the fragments, even if no statistical relationship exists between these amounts in transects and in nests in this study. More data on the nesting behaviours of this species is needed.

Surveyed beaches had on average 0.01 items m^{-2} (n = 48 transects) in the Swains and much higher debris loads (0.3 items m^{-2}) at West Hoskyn Island (n = 18 transects). For Swain Reef sites this value is a quarter of that recorded in a similar site in the far north GBR (0.04 items m^{-2} assuming a 10 m transect width, n = 15) (Haynes, 1997). Interestingly higher levels were recorded at West Hoskyn Island, than on the coast of Gladstone (0.09 items m^{-2}) (Wilson, 2012, n = 4). According to the Marine Debris Pollution Index (Chapter 2 Section 2.3.2.5), the Swain Reef beaches are considered "Green 8" and West Hoskyn "Green 7". Despite this, sites are sufficiently influenced with ~23 % of all nests across both survey areas contaminated by marine debris. Interestingly, the more contaminated nests are in the "very clean" Swain Reef areas, indicating that this designation may not be entirely accurate when assessing what potential influences debris on shorelines may have on wildlife and the environment. Consequently, the modification and application of a more comprehensive assessment index is needed, which is discussed further in Chapter 5.

HYPOTHESIS H_{XIII}: There was no difference in types, colours, and size of marine debris used as nesting material by brown boobies between sites (spatial).

Surveyed nests contained quite similar nest material between sites spatially, thus Hypothesis H_{XIII} was supported. The mean size and weight of debris items retrieved from nests at the different cays were quite similar both in size (range 3.1 – 17.0 cm) and mass (range 0.67 – 15.7 g). Using the nest classification data, no significant differences in the nest condition were found ($H_{[5]}$ = 9.854, p = 0.079) between cays, indicating that the birds were at similar nesting stages when the surveys occurred.

The nature of the debris items collected from these locations were similar, for instance hard plastic fragments and bits of rope were common in both (Table 4.14) and hence having comparable mass and size was not unexpected. The Swains debris items were larger (8.59 cm and 3.09 cm, respectively) but East Fairfax nest items were heavier (6.13 and 13.3 g, respectively) overall (Tables 4.7 and 4.9). East Fairfax nest debris items were of a similar weight to debris in nests recovered from the Ashmore reefs (8.8 g; Lavers, et al., 2013). The heavier weight of items in the East Fairfax nests is attributed to the presence of larger heavy items, such as glass bottles. Use of heavier items that appeared to be in place when the nest was created, was also seen in the Swains with items like timber. However more often items were of a weight that the bird could have transported to the nest on its own accord. The larger size of items in the Swains reflects the greater diversity of items recovered from these nests (Table 4.13). As is seen with the beach surveys, the size and weight of debris items recovered from the nest reflect the item type and material.

HYPOTHESIS H_{IV}: There was no difference in the types, colours and size of materials used in brown booby nesting material over time (temporal).

Differences were found in the nest material used by the brown booby between survey times, thus Hypothesis H_{IV} was not supported. The dynamics of nest building likely contributed to the differences seen in recovered amounts of debris objects between the sampling times (Tables 4.5 and 4.10). For instance, the majority of nest-building occur pre-and post-egg laying (Marchant and Higgins, 1990; Nelson and Baird, 2002). Although in the Swain Reefs and at Fairfax Island nesting can occurs year round (Queensland Government, 2013) there are localised peaks in nesting. Nests are not retained for more than one nesting season and as the chick grows the nest becomes less distinct, with items either blown away or stolen by conspecifics (Marchant and Higgins, 1990). Time between sampling in the Swains was found to be a significant factor affecting the mean number of marine debris items in nests ($F_{[2,10]}$= 13.015, p = 0.002) and the mean size of debris items ($\chi^2_{[2]}$= 22.728, p < 0.001). Additionally, it was shown that nest condition varied significantly between survey periods ($\chi^2_{[2]}$ = 11.270, p = 0.004). For both June 2012 and August 2013, the mean nest condition was at a Grade 2 indicating that they'd started to degrade, while in February 2013 nests were on average a Grade 1, indicating very new, intact nests (i.e., having eggs). These differences in the condition of the nests could also be a factor contributing to the differences in amounts and size of debris items collected at differing time periods if perhaps the fresher nests contained more items.

This does not appear to be the case for mean number of items however, with June 2012 (9.2 items) and August 2013 (3.2 items) having greater amounts of debris retrieved in nest material. The mean size of debris items in nests was only slightly greater in February (11.3 cm; June 8.1 cm and Aug 8.7 cm) so other influencing factors are contributing to differences between sampling times.

These factors could be the localised storm activity and long-term wind and wave action that influence the both composition and position of the cays within the Swain Reefs and their viability as seabird nesting areas (Flood and Heatwole, 1988; Queensland Government, 2013). Wind driven dispersal plays an important role in determining the movement and direction of floating objects in the surrounding marine environment (Smith, et al., 1990). So the differences in debris between time periods could be related to the seasonal wind and wave movement of debris on and off the cay or could be influenced by significant storm evens such as cyclones (Table 4.6). Bond et al. (2012) has also shown that storm activity influenced the debris usage in nest material of the northern gannet and accumulation upon beaches, as storms can affect the availability of material. In January 2013, the Category 1 Cyclone Oswald formed in the Gulf of Carpentaria and brought strong winds (>100 km/h) and heavy rains (BOM,

2013) down the Queensland coastline that would have removed a great deal of both natural and synthetic material off the cays. This may have removed or buried debris items and potentially reduced the availability of natural items (Tables 4.11 and 4.12). Even with the nests of best condition occurring in February 2013, the reduced debris levels in these nests may reflect the reduced availability of material at time of nest formation. This is supported by only three debris material types, the lowest of the three sampling times, occurring in February (Figure 4.11). The greatest feather presence in nests also occurred in February (~37 %), this occurs perhaps because other natural material had been removed from the storm activity. However, none of the differences in the range of natural materials utilised in nests between sampling times was found to be significant ($F_{[1,13]} = 0.196$, $p = 0.825$).

It was found that debris amounts and feather numbers were negatively correlated ($r = -0.533$, $p < 0.001$, $n = 64$). This relates to the low debris amounts in February when feather presence was at its highest. This may support the idea that nests that are graded as ‘2’ should be more preferentially surveyed over ‘1’ as the synthetic debris items may be more readily visible. Nest grading is needed as although breeding peaks do occur the breeding season is year round. Further surveying is needed to validate these grading suggestions.

As nesting occurs year-round, the weather patterns in the respective areas will likely influence the availability and amount of natural and synthetic material available for nest building. East Fairfax had only two sample times with more debris items recovered in the second sampling period. This however, may only be a reflection of the increased sampling effort. More frequent and longer term sampling (over a minimum of 4-years) is needed to determine the influence of seasonality upon debris amounts.

The debris materials used in nests of the brown boobies differed between sampling periods and locations. As mentioned above, storm activity in the area could account for some of this variation. Changing source activity could also be an influencing factor. For example, a study on the East Coast of Canada showed that when fishing activities stopped in an area the amount of fishing debris utilised in nearby northern gannet nests also decreased (Bond et al., 2012). Future studies in the Swains and Capricorn Bunker Group of Islands could examine the changes in debris types in response to things such as fishing season and gear changes and improved fishing waste capture initiatives (i.e. TAngler bins) as fishing was the sole greatest contributor to nest debris in study areas(Figure 4.10).

As mentioned above, other seabird nest studies have also shown offshore fishing activities as being the greatest contributor of marine debris items used within nests (Podolsky and Kress, 1989; Montevecchi, 1990; Nel and Nel, 1999; Hartwig, et al., 2007; Phillips, et al., 2010; Votier, et al., 2011; Bond, et al., 2012). The impacts of fishing within the GBR are poorly understood (GBRMPA, 2011), but this study indicates that allowed fishing activities are contributing sources of marine debris pollution (Figure 4.10) at the surveyed areas in this study.

Fishing industry related debris and uptake for use in nests is attributed to the similarity in appearance of fishing items to natural materials (Montevecchi, 1991; Votier, et al., 2011), such as seaweed, algae, seagrass species or other vegetative–like materials (Norman, et al., 1995). These natural looking materials may include items such as rope, line and strapping (Norman, et al., 1995; Votier, et al., 2011), and were items commonly found in brown booby nests in sampled areas in this study. The East Fairfax nest sites had greater levels of this material than at the Swain Reef sites (Figure 4.6) with colour differences apparent. Ropes in Swain Reef nests were primarily green (42 %), blue (16 %) and black (16 %), and those recovered on East Fairfax were blue (50 %), green (29 %), orange (14 %) and yellow (7 %). This colouring suggests that brown boobies in these areas may be purposefully selecting items due to their colouring and/or the resemblance to natural materials like seaweed, algae and other vegetative-like materials (Figure 4.5).

This concept is supported with colour differences between nest and transect items in the Swains being significantly different ($X^2_{[8]}$ = 17.625, p = 0.024). This however was not supported by colour differences at Fairfax Island, with no significant difference in colour between nests and transects ($X^2_{[8]}$ = 110.297, p = 0.245) indicating that item colours in nests are reflective of colours within the surrounding environment and are not necessarily being preferentially chosen. Colour is an important component of marine debris analysis due to the potential for colour to be a cue for uptake or interaction with marine wildlife (see Chapter 3 Hypothesis H_{IXI}); although information in terrestrial birds has shown that olfactory-cues can influence the uptake of green herbs for use in nests (Gwinner and Berger, 2008). In this study, the conclusions that can be drawn are quite narrow as information known about colour cues for these seabird species is very limited.

The amount and composition of materials are also important considerations when examining the (potential) severity of the birds' interaction with marine debris used as nest material or that may be encountered in the environment generally. Again, items such as rope and line can cause harm through entanglement leading to constriction of limbs, asphyxiation, a decreased ability to fly or forage, and often ultimately results in death (Phillips, et al., 2010; Votier, et al., 2011; Rodriguez, et al., 2013). Death from entanglement at nesting sites has been recorded in other studies (Podolsky and Kress, 1989; Hartwig, et al., 2007) such as northern gannet populations in Wales (Votier, et al., 2011), on the east coast of Canada (Montevecchi, 1990), and for Australian gannets in Victoria (Norman, et al., 1995). However, no live seabirds, or seabird remains (brown booby or other species) were found entangled within marine debris at the sites where beach and nest surveys occurred during the sampling periods.

So the brown boobies at these locations do not appear to be negatively impacted by marine debris used in the nests. In Chapter 5, the potential risk of marine debris used as nest material to the brown booby is discussed.

The size of rope material recovered from the nest debris in the Swains was likely not to be of a length that would readily entangle a chick or nesting bird (mean length 11.5±7.7 cm in Swains), but was longer (39.7±7.9 cm) on East Fairfax Island so there is potential for a negative interaction at that location. Rope material utilised in a nest may present a hazard but this was not evidenced in brown booby nests in this study. Another potential interaction is the possibility that hard plastic fragments in nests could be ingested either primarily by adults or secondarily by curious hungry chicks. However, further studies are required to determine the degree of risk of plastic ingestion in the Sulidaes in this region. Conversely, the use of marine debris could potentially be thought of as a positive thing in this instance as it does not appear to cause direct harm (i.e. via entanglement), and assists the birds in nest formation, which is an important part of strengthening the pair bond between mates (Nelson and Baird, 2002).

HYPOTHESIS H_{XV}: There was no difference in amounts of debris on cays in different Great Barrier Reef Marine Park zones.

An examination of debris loads in different Marine Park zoning areas found significant differences in the amount of debris on beaches ($U = 3.500$, $p = 0.031$), but not in nests ($U = 5.00$, $p = 0.110$). Therefore, Hypothesis H_{XV} was not supported. The lower debris levels were found in green zone sites (Distant and Riptide Cay) where limited recreational activities are allowed, but in the restricted access pink zone debris amounts were higher. Therefore, predictably at these isolated locations, marine park zoning does not influence marine debris levels. As most debris items are quite buoyant and can be readily transported in and around the marine environment park zones have no physical barriers but exist as “paper” barriers only. At more visited sites (such as the Capricorn Bunker Group of Islands) zoning may be more reflective of permitted activities, see Chapter 2.

By 2001, it was predicted that 81 % of all reefs and 87 % of all seabird islands would be within one day range of tourist vessels (Stokes, et al., 1996). This has likely increased even more with even greater developments in technology, fuel maximisation and vessel design. The GBRMPA has identified marine debris as one of the key threats to the GBR in their most recent Reef Trust Investment Strategy document (2014). Many difficulties exist in policing proper waste management by vessels at sea. An audit of waste facilities available at ports for both commercial and recreational vessels may be helpful with the end goal of developing strategies to encourage their use. The policing of correct waste disposal is incredibly limited, so strategies to address this issue could occur through improved facility utilisation at ports. See Chapter 5 for further strategies.

Other Threats to the Area

A great area of concern for the brown booby specifically (and other seabird species in the area) is from changing climatic factors (Heatwole, et al., 1996; Commonwealth of Australia, 2013). Increased storm and cyclone activity, coral bleaching and decreasing prey populations with anticipated sea level rises expected to have catastrophic impacts on these birds (Queensland Government, 2013). Already the population of brown boobies in the Swain Reefs has declined by 30% in recent years (Turner, 2002). Although marine debris may not be one of the most significant issues facing the brown booby it can further stress an already stressed system. Also as it is a direct anthropogenic source, it is perhaps one of the more readily addressed.

4.5 Conclusions and Recommendations

There was no observed detrimental impact to nesting brown boobies at surveyed sites from the Swain Reefs and at East Fairfax Island in the Capricorn Bunker Group of Islands. Low debris usage was observed in surveyed nests overall, and no instances of entanglement was detected. The use of marine debris items could possibly be conferring a benefit to these seabirds by providing substrate in which to nest with or against. However, certain items such as rope and monofilament line could pose an entanglement risk to brown boobies and other species nesting in the area. Other items such as glass and metal could also cause harm through cuts or punctures. Additionally, the presence of plastic fragments could be ingested by other nesting seabirds (or organisms) in the area. There was a limited relationship between what was recovered in the shoreline beach debris surveys and what was retrieved from nest, so the postulated idea that nest surveys could replace conducting shorelines surveys in, at least these areas, is not supported.

A photographic survey technique was developed for marine debris in nest material of the brown booby. A nest condition grading system was also created in the surveyed areas. These methods could be utilised by managers to help report upon debris interactions in this ecologically important area.

An understanding of where brown boobies source debris would be beneficial in fully understanding any potential threat and minimising interactions. As increased amounts of shipping traffic are expected through the GBR (from expanding ports in Gladstone and Bowen) the amount of debris potentially entering the water from this source can only increase. As maritime activities are the main source of marine debris in this area, studies to assess contributing factors to dumping by these ships and ways to reduce and/or prevent this behaviour would be beneficial.

CHAPTER 5

Data Synthesis and the Application of a Risk Matrix for Marine Debris

5.1 Introduction

The Great Barrier Reef (GBR) is under increased scrutiny locally, nationally and by the wider international community. This includes the United Nations Educational, Scientific and Cultural Organisation (UNESCO), that hosts the convention concerning the protection of the world's cultural and natural heritage areas of which the GBR is a part. The increased scrutiny and concern was a result of activities that may potentially impact the health of the reef and wildlife therein, and includes port expansions and dredging activities on the Queensland coast. Marine debris has been identified by the Australian Government in the State of The Environment Report (Indicator CO-32) as a knowledge gap that exists in regards to the possible impact of marine debris on marine animals through injury or fatality (Commonwealth of Australia, 2006a). Marine debris is also considered a key threatening process by the Australian Government (DEWHA, 2009), due to the interactions of marine debris with wildlife through ingestion and entanglement.

The outcomes of this research have the potential to contribute to addressing four of the objectives identified in the Governments harmful marine debris Threat Abatement Plan (Commonwealth of Australia, 2006a):

- Objective 1 - "contribute to the long-term prevention of the incidence of harmful marine debris";
- Objective 2 - "remove existing harmful marine debris from the marine environment";
- Objective 3 – develop tools to help "mitigate the potential impacts of harmful marine debris on marine species and ecological communities"; and
- Objective 4 - this project has "monitor(ed) the quantities, origins and potential interactions of marine debris" and if the sampling is continued it could, over time,

“assess the effectiveness of management arrangements … for the strategic reduction of debris”.

Further questions have been raised as a result of my research findings, with three of the most pertinent being:

- Are the interactions detected in this study of real risk to studied seabird species or are they present but represent negligible hazards;
- What role does secondary plastic ingestion have, and what is the interaction of seabird prey species with marine debris; and
- How can we effectively manage and lessen the marine debris threat, considering that Australia is relatively advanced in its environmental management and waste management practices?

A risk matrix was developed by modifying and applying the IMO’s “environmental risk and response benefit assessment form” and “impact assessment matrix” (IMO, 2014b) to help examine the local marine debris threat. With further conditions, such as increased sample size and more sampling seasons, it could be used as a tool to assist in addressing the questions above. The application of this modified IMO (2014b) risk matrix and assessment form is undertaken in this chapter to place in context the results of this study into a management framework (Section 5.2). The OSPAR bird ingestion data (van Franeker and the SNS Fulmar Study Group, 2013) is used along with local data to test the modified IMO risk matrix developed here. The outcomes of this risk matrix could help to develop strategies and recommendations to improve the management of marine debris at a local scale (Section 5.3). Considering the questions above and the findings of this research, a series of future research considerations are also presented and discussed (Section 5.3).

5.1.1 Summary of Thesis Findings

Unsurprisingly, like in many remote locations, marine debris was present on all surveyed beaches (Chapter 2), but was at relatively low levels overall. The major findings of this research are as follows:

- The offshore GBR beaches had significantly lower levels of marine debris than surveyed near-shore beaches ($U = 5.500$, $p = 0.042$).
  - There were an average of 0.08 items m^{-2} at near-shore beaches and 0.04 items m^{-2} at offshore beaches and this is graded as 'very clean' by the Marine Debris Pollution Index;
- Accumulation rates were higher at near-shore sites (average 3.3 items d^{-1}) compared to offshore (average 1.1 items d^{-1}), with near-shore Alexandria Bay, QLD, having the highest daily accumulation rates of all surveyed sites (Table 2.5);
- Near-shore site debris loads were significantly higher during the second survey time in May 2013 ($F_{[2,16]} = 9.197$, $p = 0.011$), but there was no temporal difference in recovered debris amounts at offshore sites;
- All sites were dominated by hard plastic debris, but there was a significant difference in debris types between near-shore and offshore sites ($X^2_{[12]} = 68.187$, $p < 0.001$).
  - At near-shore sites more sheet (e.g. bags) and fibrous (e.g. cigarette butt) plastics were detected, and at offshore sites more foamed plastic, metal and glass-ceramic items were recovered (Figure 2.4);
  - Off/white-clear coloured debris items were the most common, followed by blue-purple coloured items (Figure 2.5) at both near-shore and offshore sites;

- o Significantly more debris originated from oceanic-sources at offshore sites (Figure 2.6), while near-shore sites were more influenced by land-based sources;

o Differences existed between the leeward and windward sides of Northwest Island, GBR.

Identifying the sources, amounts and types of marine debris within the study area has implications for the GBR sites in particular with regard to management. Monitoring of marine debris falls within the QPWS research and monitoring guideline in the management plan for the Capricorn and Bunker group of islands (QPWS, 2000), and the findings of this research highlights the need for continued monitoring due to the potential and realised interactions with fauna present in the area. The development of a Marine Debris Pollution Index (MDPI) appears to be a robust tool to determine the level of contamination in this area, and can be further developed in cooperation with environmental managers to help justify and to develop appropriate responses to marine debris.

This research is the first to have demonstrated seabird/plastic interactions in the southern GBR from ingestion (Chapter 3) and through the utilisation of marine debris within nest material (Chapter 4). This research is also novel in its assessment of both interactions and levels of marine debris in the nearby environment.

Ingestion levels were low overall (~13 %) in the wedge-tailed shearwater, but this species still has the potential to be used as a tool to monitor marine debris ingestion in this ecologically important area. The southern GBR hosts one of the most globally significant populations of nesting wedge-tailed shearwaters (Hill et al., 1992; 1995), and it is the only Procellariiform nesting in this area with the adults foraging in relatively close proximity to the nesting island (Congdon, et al., 2005; Cecere, et al., 2013).

This was the first study to detect plastic ingestion in the wedge-tailed shearwater species in the studied regions; although ingestion levels were at relatively low levels when compared to other shearwater species (Chapter 3).

- A greater proportion of birds ingested marine debris plastics and had significantly more plastic in their regurgitate at near-shore sites compared to offshore sites ($U = 40.000$, $p = 0.032$);
- Differences were found in amounts of ingested plastic, with significantly more plastic ingested in 2012 than in 2013 sampling seasons ($U = 10.000$, $p < 0.001$);
- No sampled adults were found to contain ingested plastics;
- Hard plastics were the most common plastic type ingested (~77 %) with only one instance of virgin plastic pellet ingestion and low incidences of fibrous and sheet plastic ingestion (Figures 3.4 and 3.5);
- Overall off/white-clear coloured plastic was the most common colour ingested in both near-shore and offshore birds (40 %) followed by green (23 %) and yellow (11 %) and grey-silver (11 %) (Figure 3.8);
- Current plastic ingestion levels did not appear to significantly influence the body condition of the birds ($U = 1091.00$, $p = 0.204$).

Further monitoring of the wedge-tailed shearwater over a longer time period (i.e., at least five-years) is needed to better assess temporal and spatial interactions, and to determine changing trends in marine debris plastic levels within the area. An increased sampling time per site would also allow for a more statistically robust number of birds to be sampled at all locations.

Marine debris was used as nest material by the brown booby at locations within the southern GBR. This was the first study to recognise this occurrence and quantify the amounts of debris in nest compared to that found within the nearby environment (Chapter 4). This chapter also introduced a new and novel photographic method to survey the nests of brown boobies in these locations for the presence of marine debris. A nest condition index was also created to enable standardised assessment of marine debris.

- There was a higher occurrence of debris used in nests at the more isolated Swain Reefs (~58 %) to that seen on East Fairfax Island in the Capricorn Bunker group of islands (~11 %);
- Hard plastics dominated all nests (82 %) in the Swain Reefs, while rope plastics were the dominant material type (44 %) in nests on East Fairfax Island (Figure 4.7a,b);
    - The majority of ropes utilised within the nests were of a size that could not cause entanglement (< 10 cm in length). However, the use of rope/rope-like material, metal and glass had the potential to cause physical injury but was not observed in this study;
- Hard plastic fragments were the most common item retrieved from beach shoreline surveys in the Swain Reefs (~40 %) and on West Hoskyn (~33 %) (Table 4.11);
- There was a significant difference in the types of material that were recovered from marine debris beach shoreline surveys and that used as nest material ($X^2_{[6]}$ = 14.092, p = 0.0029);
- In nests in the Swain Reefs and at East Fairfax Island blue-purple (28 and 30 %, respectively), and green (19 and 30 %, respectively) coloured debris items were the most commonly found (Figures 4.6a,b); while off/white-clear (35 and 28 %) and blue-purple (29 and 31%) were the most common colours recovered from beach transects at these nest sites in the Swain Reefs and West Hoskyn Island, respectively (Figures 4.11a,b);

- There was no significant relationship between the amount of debris recovered from shoreline marine debris beach surveys and that recovered from nests ($R^2_{[2]}$ = -0.86, p = 0.830);
- The most common source of nest debris in the Swain Reefs and East Fairfax Island was from commercial fishing (~31 and 32 %, respectively), while shoreline beach debris from these study sites was most commonly sourced to commercial shipping activities (33 and 33 %, respectively) (Figure 4.10).

The nest material within the surveyed areas did not reflect what was present in the corresponding beach-transect by amounts and for the majority of material types. This limits the use of nest material as a substitute for shoreline survey monitoring of marine debris pollution levels on beaches and vice versa as the two surveys were not correlated. However, nest surveys are still useful as a tool to monitor potential interactions with birds (i.e. entanglement) over time and to monitor sources of marine debris pollution within this ecologically important World Heritage Area.

The research in this thesis has clearly illustrated that marine debris is ubiquitous in ecologically significant/important areas (Chapter 2, 3 and 4) and that the presence of marine debris, particularly that of plastic, can potentially interact with nesting seabirds in the surveyed regions (Chapters 3 and 4). The main findings and interactions of this research on marine debris within the study area are summarised diagrammatically in Figure 5.1.

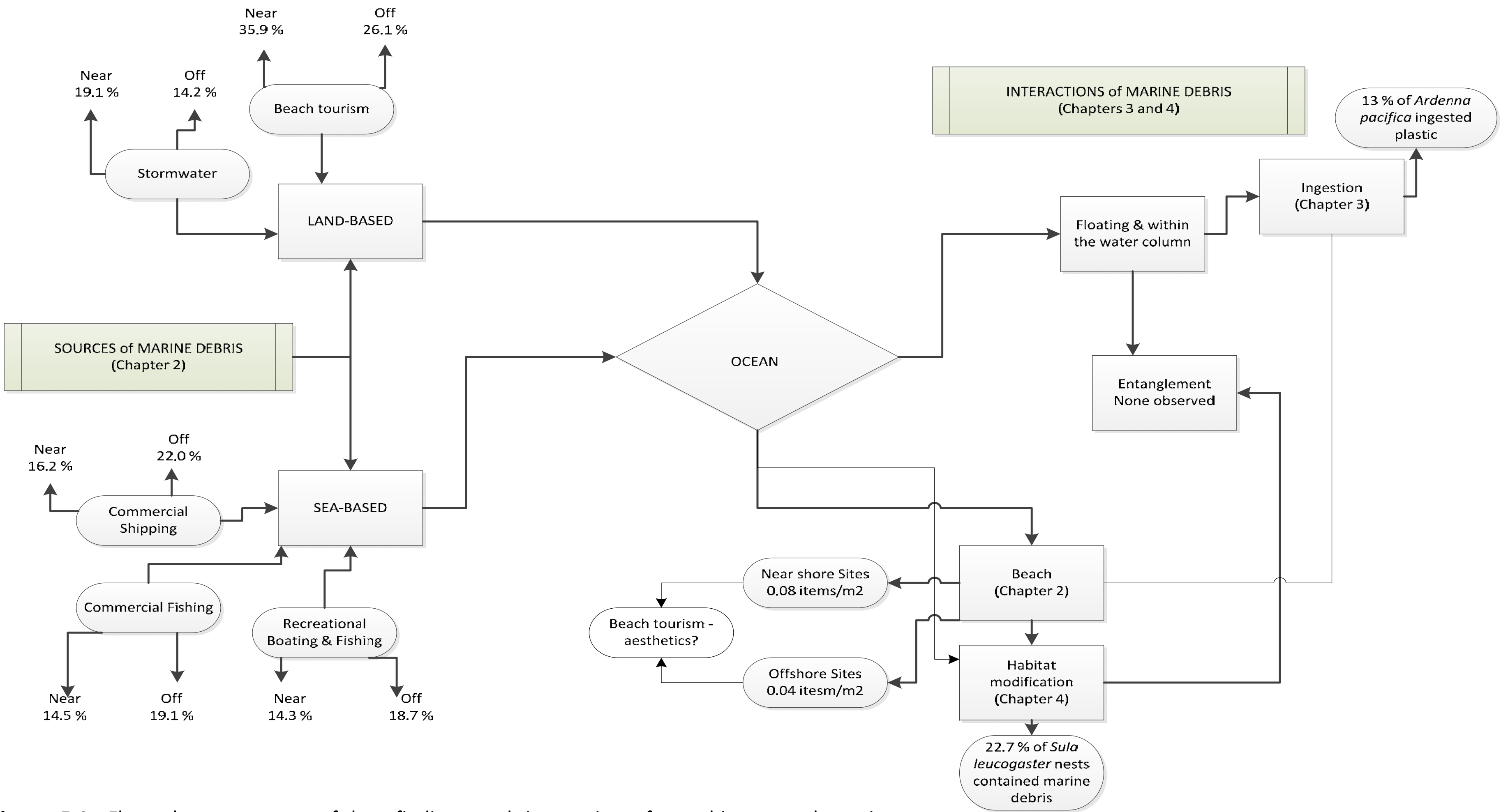


Figure 5.1: Flow chart summary of key findings and interactions from this research project

NB: near = near-shore and off = offshore

5.1.2 Study Limitations

A number of limitations were identified in this study and could be improved upon in future work going forward. These limitations included:

- Limited survey time. Ideally seasonal debris surveys should be conducted every three months for at least 4 years to enable a robust analysis of seasonal variability. The current research was limited with only having two sampling times and seasons to compare between. A greater budget and/or further research partnerships are needed to overcome the high access costs to these isolated sites. However, under the Australian PhD system it is rare that a PhD goes for longer than 3 to 4 years, and hence the expectation of 4 years of sampling to gather seasonal data is unrealistic and better suited to postdoctoral research.
- Sampling at different sites was restricted to neap or spring tides as access to sites were gained opportunistically. In addition, due to the isolated location of offshore sites, sampling trips occurred regardless of encountered weather conditions (i.e. high winds), with poor weather conditions often inhibiting the amount of sampling that could occur. In future studies, surveys should ideally not be conducted during high winds and with consistent tides (either spring or neap, not both unless sampling was adequate to compare spring and neap results). As a result of these factors the amount of recovered debris at sites may be biased.
- Different sampling effort was used at different sites due to logistical constraints. Ideally the experimental design should be that of a balanced sampling design. Yet, decisions in the field can obviate a balanced sampling design when conditions unexpectedly change and when access to sites is opportunistic.

- To gain a better understanding of the marine debris threat more birds should be sampled, over a longer period to reduce natural variability in the data (increase temporal sampling).
- More nests need to be sampled at different survey locations (increase spatial sampling) to give a better indication of nest debris usage and any ensuing interactions. Again poor (i.e. windy) weather conditions should be avoided whenever possible to reduce any potential bias in the recovered amounts of marine debris.

5.2 Application of the Risk Model-Matrix

Despite these limitations, sufficient data was gathered to apply to a risk model for marine debris management. Using the data gathered from this research, an assessment of the threat of marine debris pollution to seabirds in surveyed areas was developed through a risk based approach. This tool requires data on the marine debris present within the area (i.e. beach surveys, Chapter 2), and information on the ecological, social/cultural and economic impacts and/or interactions with the area in question (i.e. seabird ingestion surveys, Chapter 3). The ecological social, cultural and economic resources present within each of the surveyed areas were first identified on an IMO rapid assessment form (IMO, 2014; Table 5.1). Additionally, the category of presence of protected wildlife and habitat area are given on the form, as this can influence the response of environmental managers as the potential to impact upon a protected species is elevated.

Table 5.1: Rapid Assessment form of existing resources in surveyed areas (modified from IMO, 2014)

Site Name		**Capricorn-Bunker Group Islands**	**Swain Reefs**	**Sunshine Coast - Mudjimba Is.**	**Coffs Harbour - Muttonbird Is.**
Main shoreline type		3 and 13	3 and 13	3	3
Surrounding use		Natural	Natural	Residential	Residential
Protected Area		GBRMP / Nat'l Park	GBRMP	Nat'l Park	Nat'l Park Nature reserve
ECOLOGICAL	Presence of protected wildlife*				
Corals	X	x	x		x
Mangroves	X			x	x
Seaweed		x	x	x	x
Fish spawning		x	x	x	x
Coral spawning		x	x		
Shore bird	x	x	x	x	x
Birds on water	x	x	x	x	x
Swimming/diving bird	x	x	x	x	x
Nesting seabirds	x	x	x	x	x
Whale/dolphin/shark	x	x	x	x	x
Sea turtles swimming	x	x	x		
Sea turtles nesting	x	x	x		
Fish		x	x	x	x
Invertebrates		x	x	x	x
SOCIAL / CULTURAL					
Food gathering				x	x
Cultural significance		x		x	x
High aesthetic value		x	x		
Protected area		x	x		x
Recreational area		x		x	x
ECONOMIC					
Marina				x	x
Fishery – fish		x	x	x	x
Fishery – other		x	x	x	x
Infrastructure				x	x
Resort		x		x	x
Beach tourism		x		x	x

NB: *Presence of a resource within the area is designated by an 'x'.*
**Includes, migratory protection agreements such as those for birds between Australia and Japan (AMBA), China (CAMBA), Republic of Korea (ROKAMBA), and conventions such as the Bonn Convention, RAMSAR wetland convention.*

Shoreline Types:

1. Exposed rocky shores
2. Exposed wave-cut platform
3. Fine-to-med-grained sand beach
4. Coarse-grained sand beach
5. Mixed sand and gravel beach
6. Gravel beach
7. Rip rap
8. Exposed tidal flat
9. Sheltered rocky-shore
10. Sheltered rocky rubble slope
11. Sheltered tidal flat
12. Salt marsh
13. Coral rubble

Surrounding Use:

Natural
Agriculture
Commercial
Residential
Recreation

To aid with understanding the risk matrix model a number of terms and their associated definitions are provided.

A ***hazard*** is defined here as anything that can cause harm, and in this instance the hazard is marine debris. Specifically, it would be those items that can be ingested, can cause entanglement, or may result in physical injury or damage of any kind to a person, animal, or habitat. Although within the Commonwealth Government definition of threatening marine debris, only plastic items are identified (DEWHA, 2009), the assessment here goes beyond that definition to consider a more broad definition of marine debris as a hazard to encompass all potentially harmful anthropogenic marine debris items (Chapter 1 Section 1.1). Herein, a ***risk*** is the likelihood (or probability) of an event occurring (i.e. harm) and the consequences (i.e. potential interactions or impacts) from that event occurring (Standards Australia/Standards New Zealand, 2001). Seabirds are the subject of this risk assessment, with the risk of a seabird being harmed from marine debris and the severity of that harm from marine debris being examined. The risk end-point is an understanding of the potential interactions and/or harm that may result from marine debris to seabirds.

All surveyed sites were first assessed using the modified IMO (2014) rapid assessment method to determine the presence of ecologically important features (i.e. corals, seabirds nesting), any social or cultural activities within the area (i.e. recreational area, protected area), and economic features (i.e. aquaculture, fisheries)(Table 5.1). Marine debris is a multi-faceted issue and indeed has implications for the ecological, social and economic resources of an area. Undertaking a rapid assessment allows for each of these resources to be assessed within the matrix in a transparent and unweighted manner. As such the risk matrix, if used correctly can indicate sites that are at the greatest level of environmental risk or threat from marine debris pollution.

It must be noted however, that the full utilisation of the risk matrix is constrained in this present study because limited data on the different ecological, social and economic resources are currently available for the surveyed location. This lack of knowledge on all the resources present represents a data gap, and illustrates where further research is warranted to better inform management of the marine debris issue and resources within the surveyed areas. This is important because the Great Barrier Reef is a Marine Protected Area of national and international significance (World Heritage Area) that was established due to its ecological, social and economic importance. The Australian and Queensland Governments have identified marine debris as a significant pressure facing the reef (Commonwealth of Australia, 2015) and this risk assessment tool could be used as part of the initiatives developed to address this threat.

The risk matrix consists of a measure of the level of pollution within the environment and a measure of potential interaction. Categories for the levels of pollution within the environment are based on the MDPI developed in Chapter 2 and the outcomes are summarised in Table 5.2. The MDPI was determined by running transects on beaches and then determining the amount of debris items per m^{-2} (Alkalay, et al., 2007) and then comparing that to a size measure of debris to determine a grading. Although it must be noted that transect sizes differed at Swain Reef sites due in some instances, to smaller cay size at these locations, the procedure to standardise the data was the same for all collections undertaken (determining the number of items of debris per m^2), and thus the outcomes of these chapters are comparable and were used in the MDPI. The beaches in this research study ranged from 0.01 to 0.2 items per m^2. Table 5.2 shows each of the research study sites and its derived MDPI. The majority of sites were graded as '2 - very clean', with only one graded as '4 – clean'.

Table 5.2: The Marine Debris Pollution Index for near-shore and offshore study sites. The Marine Debris Pollution Index number is derived from Table 2.14.

	Site name	Pollution Index Nov/Dec 2012	Pollution Index Apr/May 2013
Near-shore Sites	Diggers Beach, NSW	2 – Very clean	3 – Very clean
	Ocean View Beach, NSW	2 –Very clean	2 – Very clean
	Alexandria Bay, QLD	2 – Very clean	4 – Clean
Offshore Sites	Tryon Island, QLD	2 – Very clean	3 – Very clean
	Heron Island, QLD	2 – Very clean	2 – Very clean
	Northwest Island, QLD	2 – Very clean	2 – Very clean

Potential interactions with marine debris are based on nest data and are represented by four categories: Severe, with > 50 % (e.g. > 50 % of nests had marine debris present) (A) impact; Major with 30-50 % interaction (B); minor with 10-30 % interaction (C) and Slight with < 10% impact (D; Table 5.3). These measures (interaction and level of pollution) are then combined to create the risk matrix. Within the risk matrix a colour code of red, yellow, and green were used as an easy visual identification of the level of risk posed (Table 5.3). Red indicates an intolerable level of risk requiring immediate action. Yellow is a tolerable level with risk needing to be reduced as far is practical; and green is a broadly acceptable risk level that requires monitoring and when practical should be reduced further (JSAbuilder, 2013).

Table 5.3: Risk matrix for marine debris pollution within surveyed beach areas (modified from IMO, 2014) based on nest data

			Marine Debris Pollution Index Scores		
			Low (2-4)	**Moderate (5-6)**	**High (7-9)**
			1	2	3
Interaction Nests	**Severe > 50 %**	A	**1A**	**2A**	**3A**
	Major 30-50 %	B	**1B**	**2B**	**3B**
	Minor 10-30 %	C	**1C**	**2C**	**3C**
	Slight < 10 %	D	**1D**	**2D**	**3D**

The derived level of risk directs management and policy towards a mechanism of management prioritisation actions to control the identified risk (Health and Safety

Executive, 2014). For high accuracy a risk matrix requires extensive expertise for robust measures of the likelihood of harm to occur if qualitative assessment is relied upon. If the matrix has a low level of accuracy, this can result in control measures being unnecessarily applied (Type I error), or alternatively there could be a failure to undertake needed measures as the risk was not detected (Type II error) (Health and Safety Executive, 2014). Thus the matrix should be informed by research, and/or in conjunction with those that have expertise in the area under investigation. The data utilised in this matrix on interactions with seabirds and marine debris levels within the environment have been collected in a robust manner. Sample sizes were small at some sites; however, so caution in the interpretation is needed. In the interim the data generated from these matrices can be utilised by environmental managers, and when further data becomes available the risk analysis can be rerun so that adaptive actions can be undertaken.

5.2.1 Risk Posed to Nesting Seabirds

To assess the interactions of marine debris with nesting seabirds, the nest debris data from Chapter 4 were utilised (see also Appendix D: Verlis, et al., 2014). The number of brown booby nests that contained marine debris as a percentage of the overall nests surveyed at the specified locations and times was used to determine interactions in the risk matrix (Table 5.4). The interactions varied from minor to severe (Table 5.4). The percentage of nests that contained marine debris relative to the total number of nests surveyed for a particular site was determined for the Swain Reefs separate from Fairfax Island, due to their different geographical locations within the southern GBR (Figure 4.1).

Table 5.4: Interactions of marine debris pollution on nesting seabirds in the surveyed sites over time

Sample Time and Location	Number of contaminated nests (total number of nests examined)	Potential Impact
June 2012 Swains	10 (19) = 53 %	A Severe
February 2013 Swains	8 (24) = 33 %	B Major
March 2013 E Fairfax Is	7 (47) = 15 %	C Minor
August 2013 Swains	38 (51) = 75 %	A Severe
April 2014 E Fairfax Is	22 (187) = 12 %	C Minor

This interaction grading (Table 5.3) was then used to provide the impact ranking for seabirds in these two areas, and by matching this value to the determined level of debris (pollution) within the areas as determined by the Marine Debris Pollution Index (Table 5.2). From these two data sets risk could then be derived for nesting seabirds within the study areas (Table 5.5). Thus nests on Fairfax Island were at a minor level of risk from marine debris, and nests in the Swain Reefs were at either a moderate or minor level depending on the time of year, with an average rating of 'yellow' or moderate risk. The 'yellow'/moderate level indicates that while the locations are at a tolerable level of risk, measures should be undertaken to reduce the risk.

Table 5.5: Derived risk posed to nesting seabirds in the surveyed sites (from Table 5.3 and 5.4).

Sample Time and Location	Marine Debris Pollution Index*	Potential Impact from Nest Use	Derived Risk
June 2012 Swains	3 - Very clean	A Severe	**3A**
February 2013 Swains	3 - Very clean	B Major	**3B**
March 2013 W. Hoskyn	3 - Clean	C Minor	**3C**
August 2013 Swains	3 - Very clean	A Severe	**3A**
April 2014 W. Hoskyn	3 - Clean	C Minor	**3C**

*Derived from Table 2.14

5.2.2 Risk Posed to Seabirds via Ingestion

To assess the interactions of marine debris with wedge-tailed shearwaters from ingestion, the ingestion data from Chapter 3 was utilised. The threshold values (%) of potential interaction were reduced to take into account that ingestion can have a more direct effect then perhaps, when marine debris is used as nest material and that even lower rates of ingestion may still have negative repercussions. Thus, the potential impact categories were modified to: Severe, with > 5 % impact; Major with > 3-5 % impact; Minor with 1-3 % impact, and Slight with < 1 % impact (Table 5.6). The impact scale was based upon the OSPAR EcoQO objective, which takes into account weight of the plastic ingested (greater than or equal to 0.1 g) and the percentage of birds that have ingested that weight of ingested plastic. The weight of 0.04 g was used for this study as the northern fulmar for which the value was developed (van Franeker and the SNS Fulmar Study Group, 2013) was a heavier bird (850 g vs 350 g). Thus the 0.1 g utilised for the northern fulmar was reduced by 60 % for use with the wedge-tailed shearwater. This weight however is untested and further research is needed to confirm the amount of ingested plastic that would be appropriate to designate a harmful interaction in this species.

Table 5.6: Modified risk matrix for marine debris ingestion in the wedge-tailed shearwater at sampled sites

			Marine Debris Pollution Index Scores		
			Low (2-4)	**Moderate (5-6)**	**High (7-9)**
			1	2	3
Interaction Ingestion	**Severe >5 %**	A	**1A**	**2A**	**3A**
	Major >3-5 %	B	**1B**	**2B**	**3B**
	Minor 1-3 %	C	**1C**	**2C**	**3C**
	Slight < 1 %	D	**1D**	**2D**	**3D**

Thus, the risk at each location, regardless of survey time, was calculated based on the total number of birds surveyed from each site to determine a percentage of birds that had ingested greater than or equal to 0.04 g marine debris (Table 5.7). The interactions of birds from ingestion at the four survey sites ranged from slight to severe.

Table 5.7: Interactions with plastic marine debris by ingestion in the wedge-tailed shearwater late-stage chicks at sampled sites. The potential impact was derived using Table 5.6.

Site name	Contaminated birds with 0.1 g ingested (total number of birds sampled)	Interactions
Heron Island	6 (117)	A Severe
Northwest Island	0 (49)	D Slight
Mudjimba Island	1 (10)	A Severe
Muttonbird Island	1 (56)	C Minor

Consequently, the level of pollution for the risk assessment was based upon the Marine Debris Pollution Index (Table 5.6) and is summarised in Table 5.8. Risk was then derived using both the modified interaction (Table 5.6) and average level of pollution for each site (Table 5.7), with the risk outcomes summarised below in Table 5.8.

Table 5.8: Derived risk posed to wedge-tailed shearwaters by ingestion at the surveyed sites (based on outcomes in Tables 5.6 and 5.7).

Site name	Marine Debris Pollution Index	Ingestion Interaction	Derived risk
Heron Island	3 - Very clean	A Severe	**3A**
Northwest Island	3 - Very Clean	D Slight	**3D**
Mudjimba Island	3 - Clean	A Severe	**3A**
Muttonbird Island	3 - Very clean	C Minor	**3C**

From this table, the risk of marine debris to those wedge-tailed shearwaters nesting on the Sunshine Coast at Mudjimba Island and at Heron Island, GBR were at 'yellow' or tolerable level of risk. However, the sample size at Mudjimba Island site was quite low (n = 10). This limits the strength of this finding, but does indicate the need for more monitoring of ingestion levels in this species, especially in this area, as the derived risk would requires action to be taken to reduce marine debris in the area.

Those seabirds at Northwest Island, GBR and at Coffs Harbour (Muttonbird Island) were at a 'green' or tolerable risk. At a green level, even if tolerable, this threat should be reduced when possible. Heron Island was at a yellow level, meaning actions should be taken to reduce the risk. Due to the presence of a large number of ecologically important species within the surveyed areas, the presence of many important habitat areas and social and economic resources present (Table 5.9) strategies and measures to actively reduce marine debris would be recommended. However, again, more robust and sustained marine debris monitoring activities are needed to make more accurate use of these matrices. As stated earlier, the wedge-tailed shearwater is the most appropriate species for this monitoring within the southern GBR; as it is the only nesting Procellariiform, it is present in great numbers and when foraging for its young the adults do pursue prey in close proximity to the nesting island.

Table 5.9: Filled in Rapid Assessment form identifying existing resources in surveyed areas (modified from IMO, 2014)

Site Name		**Capricorn-Bunker Group Islands**	**Swain Reefs**	**Sunshine Coast -Mudjimba Is.**	**Coffs Harbour - Muttonbird Is.**
Main shoreline type		3 and 13	3 and 13	3	3
Surrounding use		Natural	Natural	Residential	Residential
Protected Area		GBRMP / Nat'l Park	GBRMP	Nat'l Park	Nat'l Park Nature reserve
ECOLOGICAL	Presence of protected wildlife*				
Corals	x	x	x		x
Mangroves	x			x	x
Seaweed		x	x	x	x
Fish spawning		x	x	x	x
Coral spawning		x	x		
Shore bird	x	x	x	x	x
Birds on water	x	x	x	x	x
Swimming/diving bird	x	**3A**	x	**3A**	**3C**
Nesting seabirds	x	**3C**	**3A**	x	x
Whale/dolphin/shark	x	x	x	x	x
Sea turtles swimming	x	x	x		
Sea turtles nesting	x	x	x		
Fish		x	x	x	x
Invertebrates		x	x	x	x
SOCIAL / CULTURAL					
Food gathering				x	x
Cultural significance		x		x	x
High aesthetic value		x	x		
Protected area		x	x		x
Recreational area		x		x	x
ECONOMIC					
Marina				x	x
Fishery – fish		x	x	x	x
Fishery – other		x	x	x	x
Infrastructure				x	x
Resort		x		x	x
Beach tourism		x		x	x

NB: *Presence of a resource within the area is designated by an 'x'.*
** Includes, migratory protection agreements such as those for birds between Australia and Japan (JAMBA), China (CAMBA), Republic of Korea (ROKAMBA), and conventions such as the Bonn Convention, RAMSAR wetland convention.*
***Risk grades are worse-case-scenario for each location*

Shoreline Types:

1. Exposed rocky shores
2. Exposed wave-cut platform
3. Fine-to-med-grained sand beach
4. Coarse-grained sand beach
5. Mixed sand and gravel beach
6. Gravel beach
7. Rip rap
8. Exposed tidal flat
9. Sheltered rocky-shore
10. Sheltered rocky rubble slope
11. Sheltered tidal flat
12. Salt marsh
13. Coral rubble

Surrounding Use:

Natural
Agriculture
Commercial
Residential
Recreation

5.2.2.1 Risk Matrix case study

To test the applicability of this risk approach a larger and more extensive data set was utilised. For this purpose, the OSPAR seabird ingestion data for the northern fulmar and corresponding shoreline debris data from locations in France were used (3,800 items m^{-1} (assuming a 5 m width) = 7.6 items m^{-2}). The ranking for ingestion in the northern fulmar was 60 % of birds having exceeded the 0.1 g level was Red-Severe (Table 5.6). The shoreline marine debris cleanliness rating of the beaches in France were ranked as Very Dirty - Red (Table 2.14) although no data was given on size (reporting was for items > 50 cm). One can assume items had an area > 25 cm^2 thus the Marine Debris Pollution Index result would still be a Very Dirty - Red. Combined in the Marine Debris Pollution Index, the result is Red 1A. This result calls for immediate action to be taken to reduce litter levels. This is already acknowledged in these countries and by OSPAR reports based on the ingestion data alone in the northern Fulmar species (OSPAR, 2007; van Franeker and the SNS Fulmar Study Group, 2013). This modified Marine Debris Pollution Risk Matrix findings are thus supported and demonstrates the versatility and broad applicability of this approach.

5.3 Recommendations for Management and Directions for Future Research

Marine debris is present within the surveyed areas, although at low levels compared to other more heavily polluted and populous areas of the North Pacific. Yet, the research in this thesis has demonstrated that the two studied seabird species are interacting with marine debris even at these lower environmental levels. This research was undertaken in locations that are recognised and legislated to protect ecologically significant values, with important habitat and wildlife present in the area. These areas also contain many social (e.g., recreational fishing, diving) and economic resources (e.g., commercial shipping passage, eco-tourism, fishing) (Table 5.9). This gives weight to the concept that marine debris has the potential to have wide-reaching impacts in these areas and management actions are needed to mitigate or ameliorate these impacts. It also highlights the importance of this research, which is the first study to identify the presence and interaction of marine debris with wildlife of the southern GBR and hence, is an informed 'call to action', per se. Yet, I also acknowledge that further research is still needed to better understand the impact of marine debris on other wildlife and resources of the study areas. The limited data collected on beach debris pollution, plastic ingestion and nest contamination all contribute to a risk model that shows that marine debris poses a threat to surveyed areas (Table 5.9).

Broadly addressing sources of pollution can be accomplished through management initiatives introduced by federal, state and local government, community groups and natural resource management groups (NRMs) that involve the general public. Marine debris is primarily the result of human behaviour and needs to include social and economic measures to address it (Kiessling, 2003), with preventative measures key to the solution. As marine debris is a multi-faceted issue that can result from actions of people both on land and at sea, this problem requires a multi-layered approach. There are a number of obvious key management recommendations that can be made to address these threats and a number of future research areas that can inform the marine debris issue within Australia.

5.3.1 Management Recommendations for Australia

Management actions to reduce and prevent the occurrence of marine debris may include activities and initiatives that will reduce the introduction of marine debris into the environment in the first place. These generic actions can involve:

- The introduction of deposit fees and reverse vending machines that can efficiently and effectively recover beverage bottles/containers by turning them into a valuable commodity (Moore, 2008). These machines were trialled in Sydney, NSW, to some success (Envirobank, 2014);
- Follow the examples of South Australia, Tasmania, and the Northern Territory, and ban LDPE plastic shopping bags across Queensland. Campaign is currently in place in QLD to raise awareness of this (Boyland, 2013) and the Environment Minister Steven Miles has said he will consider the ban (Higgins, 2015);
- Encourage and demand zero-waste and cradle-to-cradle production of products within Australia. Current examples of such products include construction items such as floor coverings(C/S Australia, 2015);
- Reduce plastic packaging in general, and single-use throw-away items like crockery and cutlery, drinking straws and move toward initiatives that encourage the use of reusable cups/containers/cutlery, and the use of natural compostable single-use materials; and
- Improve current waste management strategies to expand and promote recycling, and introduce mechanisms to reduce loss of waste at pick-up and at landfills. This can involve expanding the recycling capabilities to include a larger range of recyclable items, and placement of landfills away from waterways. This is especially relevant in Queensland, due to the high frequency of flood events in coastal regions. An example of this is TerraCycle that targets difficult to recycle items such as cigarette butts (Minns, 2015).

Further management measures to combat marine debris pollution could involve:

- The introduction of devices that capture marine debris before it reaches rivers and the ocean, such as stormwater catchment devices (Moore, 2008). Within the coastal regions adjacent to the southern GBR, there are few, if any, gross pollutant traps (GPTs) used on stormwater drains. It is up to the individual councils to introduce. Deriving local “hot spot” data will help in a targeted approach to installing these devices.

- The development of a water quality guideline or objective for marine debris within the local environment. This could provide greater power to communities and government to bring in reductive measures (like those mentioned above) and give support to research and management efforts in understanding and reducing any impacts and interactions with marine debris by both humans and wildlife.
    - This could include the use and/or further development of the Marine Debris Pollution index (see Chapter 2) alongside other water quality measures and/or ‘report cards’ (e.g. Gladstone Healthy Harbours Report Card; South East Waterway Report Card) that examines broader ecosystem health;
    - The development of regionally specific indicator items that are recorded from marine debris surveys. By identifying key marine debris items that are locally relevant this could help inform on the source of marine debris at surveyed sites and allow more engaged activities in citizen science marine debris programmes;
    - To assess the social and aesthetic impacts of marine debris, a ‘condom equivalent index’ that grades beaches based on the aesthetic value of recovered debris items (Chapter 2 Section 2.4 (Hypothesis H_X); Nelson, et al., 1999) could be developed. This technique involves social science techniques and surveying of local beach goers to develop the scores of commonly recovered items in order to generate these aesthetic values. The condom is considered the ‘worst’ item found by beachgoers and where the name of this technique originates. This aesthetic valuing of local

beaches could be a tool incorporated into the Marine Debris Pollution Index (Chapter 2) or for use alongside the index.

- Conduct and expand beach clean-up activities. These can be important tools in raising awareness of the marine debris issue among the general public, while removing harmful and aesthetically displeasing marine debris from the environment (Moore, 2008; Tangaroa Blue, 2014).
    - Currently a number of community supported organisations are involved in marine debris clean-ups around Australia, including Tangaroa Blue, Clean-Up Australia, Keep Australia Beautiful and Conservation Volunteers Australia;
    - A marine debris survey database has been developed by the Australian marine debris initiative and Tangaroa Blue (Tangaroa Blue, 2014). This should be continued and expanded to inform upon this key threatening process using standardised collection techniques.

The issue of marine debris has now become a priority item for the Great Barrier Reef Marine Park Authority (GBRMPA) (Commonwealth of Australia, 2015). Current management actions such as the Great Barrier Reef Marine Park (GBRMP) zoning measures may have an important role in reducing and maintaining low levels of beach tourism sourced debris. These zones restrict access to certain islands and are an important mechanism to not only protect sensitive populations of nesting seabirds, turtles and other wildlife, but can also serve to prevent the introduction of potentially harmful plant or insect life (i.e. destructive ants, prickly pear). This type of zoning (via integrated marine spatial planning) should be continued and supported, as this research has shown the great influence that beach tourism has upon marine debris levels present on surveyed beaches (Figures 2.9). Similarly, this type of zoning has a role in reducing land-based pollution at these environmentally sensitive locations.

However, the current zoning cannot address oceanic-sourced debris and the very mobile marine debris that can (and does) result from activities being undertaken within the area. Furthermore:

- Audits of current waste management facilities and activities in Ports operating along the Queensland coastline to determine usage and measures to improve and support ship-waste disposal could be undertaken.
- Clean-up activities and policing measures by rangers and other authorities (e.g. Australian Maritime Safety Authority) should be supported and expanded.
- Build on GBRMPA initiatives with the Reef Guardian school program and Reef Guardian Councils to increase awareness of the marine debris issue in the local areas. This has recently occurred with the expansion to Reef Guardian Fishers and Reef Guardian Farmers;
- Facilitate and enhance the current environmental programs or education information panels at national and state parks that highlight both the environmental and economic consequences of polluting both on land and while at sea;
- Further initiatives should be developed for the southern GBR in particular. On Heron Island for instance, the presence of both a resort and research station presents many opportunities for public involvement in educational and clean-up initiatives.
    - The development of debris/litter-wise programs for resorts operating within the GBR and at other environmentally sensitive areas could be created. These could assign a grade or ranking to resorts based on their compliance with good waste-management practices, clean-up activities and educational initiatives for both staff and guests.

The implementation and use of appropriate tools, actions and activities to address marine debris could help to reduce the marine debris issue on Australian beaches.

5.3.2 Research Recommendations

Properly addressing and reporting upon this key threatening process, as well as contributing to the objectives of the threat abatement plan can be achieved by continued research activities. Suggestions for further research include:

- Social marine debris studies: Human actions are the drivers of most marine debris. Social studies that increase the current knowledge of these social and individual motivators that drive littering behaviours and the product choice/use/reliance of plastic within society should be expanded upon. An understanding of the sociology and psychology of littering can help to advise on measures that may facilitate a reduction in this pollution problem. This could include both reduction of littering, but also in the development of legislative and other measures to reduce societal dependence on plastics, in particular single-use plastics and unnecessary plastics (i.e. microbeads in personal care products).
  - An exploration of the reasons that people continue to use plastics (and the lack of government intervention), despite all the known and demonstrated harmful chemicals present within them is warranted.
- Expand the monitoring of this pollution threat and conduct research to better understand the influences of marine debris upon the ecological, social and economic resources of an area (like those identified in Table 5.1) with collected data presented in a consistent way (i.e. per m^{-2}).
  - Conducting baseline marine debris surveys in areas of Australia, not just geographically, but in different habitat types will help in assessing the risk that marine debris poses. For instance, no benthic debris surveys and few

at-sea surveys for marine debris have been conducted within Australia with minimal work having been done on marine debris in river systems and coastal wetlands, known depositional areas, and their movement. A collaborative assessment (mass balance) of marine debris amounts for an area (e.g. water, benthic, beach) will ultimately inform on the risk this pollutant poses and their management.

  - A consistent quantified sampling method and resampling protocol (i.e. quarterly) should be widely disseminated. Ideally these should incorporate the above mentioned Marine Debris Pollution Index and indicators (Section 5.3.1). This can allow for a better understanding of the size, density and possible sources of marine debris within an area that can help inform mitigation measures (US EPA, 2011).

- Increased commercial shipping and cruiseline traffic is expected in the GBR and along the Queensland coastline with an associated expansion in ports and regional cities. As a result of these increasing activities, marine debris loads may also increase. To respond to this development:
  - Shoreline surveys should be continued and as they may monitor changing levels of debris within areas and the influence of different sources to amounts and types of recovered debris.
  - Surveys could also allow for recognition of the usefulness of any preventative initiatives (i.e. introduction of Gross Pollutant Traps (GPTs)) and can allow for modifications to be made if required (Kirkley and McConnell, 1997);
  - Further develop the wedge-tailed shearwater late-stage chicks (or other suitable species) as an indicator for plastic levels and interactions, similar to the northern fulmars in the EcoQO index in the North Sea as part of the OSPAR

monitoring. Longer term monitoring is needed (at least five years) to account for natural seasonal variation in detected plastic debris loads, and would allow for more statistically robust number of birds (and/or other species) to be sampled;

  - Investigate the effect of plastic ingestion on seabird survival, fitness and reproductive success through long-term, multi-season studies;

- Determine the presence and amount of microplastics in the Australian environment. At present there is a paucity of information on the prevalence of microplastics and the potential threat it may pose. The following studies are recommended:
  - Survey for microplastics within sediment of beaches, within the water column, and within wastewater (a major source) across the country.
    - Determination of the input of microplastics into the Australian environment from consumer products, such as linen, clothing and personal care products containing microplastic beads. Potential development and deployment of microplastics traps for personal washing machines and for water treatment facilities. The goal would be to reduce/prevent pollution from these sources.
  - Determination of the interaction of microplastics with marine organisms. Examine microplastic ingestion within a selection of species from different trophic levels, and the potential movement of these plastics through the food chain (i.e. plankton, bivalves and fish species). These have been studied in species in other areas of the world, but little work has been done in Australian species.

- An examination and development of possible chemical signatures within tissue/cell of an organism to indicate (micro)plastic ingestion. For instance, in blood, preen gland oil and/or in feathers. Preliminary work with preen gland oil and plastic ingestion has been undertaken in a number of Australian seabird species (Hardesty, et al., 2014).

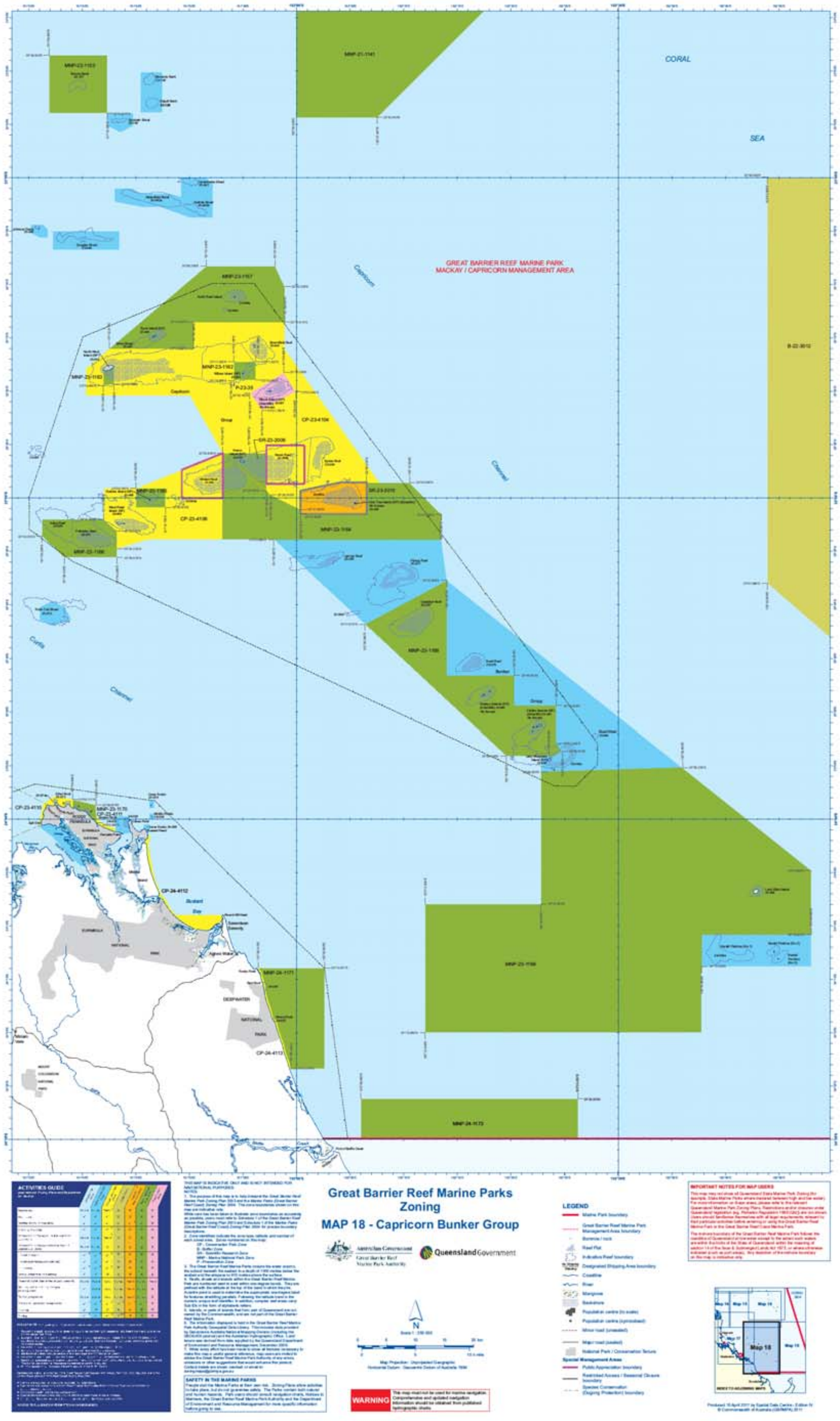
- Examining chemical contaminants in plastics in Australian marine debris plastics and what impacts or influences these might be having to marine fauna. This may include the following areas of study:
    - Ascertain what chemicals are accumulating on plastics locally;
    - Identify those chemicals transferred to organisms and whether those chemicals can accumulate within the tissues of selected indicator species;
    - Determine the toxicological and physiological effects of these chemicals upon the organism, or use current knowledge from other studies or species and apply this data to what is found in nature (Browne, et al., 2015). This may have implications for higher trophic level organisms, such as seabirds and humans. A better understanding of chemical transfer through the different trophic levels is needed.

5.4 Conclusion

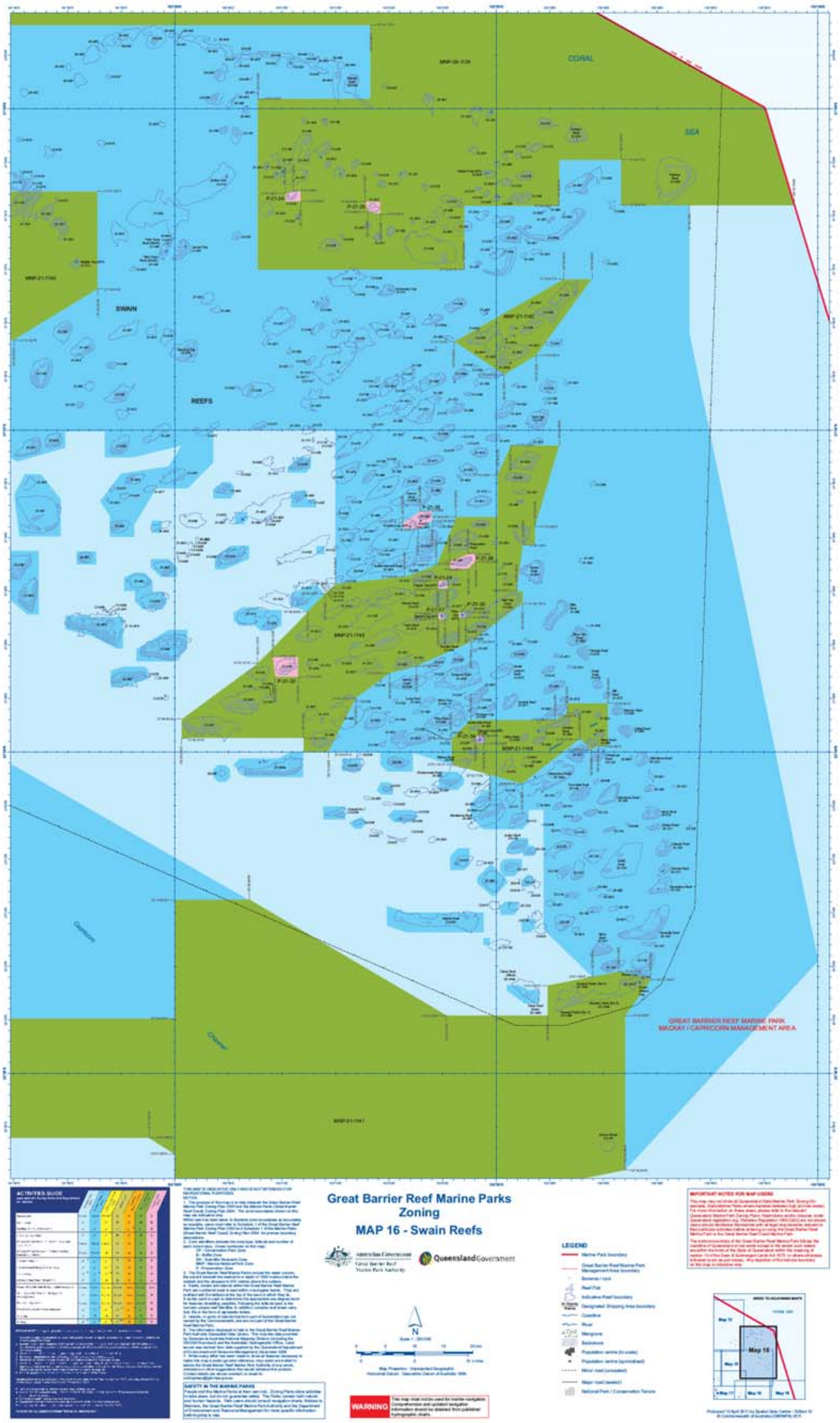
Marine debris is present within the surveyed areas and wildlife is interacting with this debris (via ingestion and use in nest material). Marine debris levels and interactions were relatively low at surveyed sites; however, the potential for harm from this interaction exists. Given the great importance of the World Heritage listed GBR and the significance of these areas for tourism, additional initiatives are warranted to monitor and protect this resource. This is acknowledged by the Great Barrier Reef

Marine Park Authority in their recognition of marine debris as one of the main threats to the reef (Commonwealth of Australia, 2015). This thesis can help inform upon this pollution threat, and the tools and survey techniques developed herein can be used by other researchers, government officials and community groups to help identify and monitor marine debris.

Appendix A: GBRMPA Capricorn Bunker Group (Map 18) Zoning Map (2011c)



Appendix B: GBRMPA Swain Reefs (Map 16) Zoning Map (2011d)



Appendix C:

Verlis, K.M., Campbell, M.L. and Wilson, S.P. (2013). Ingestion of marine debris plastic by *Ardenna pacifica* in the Great Barrier Reef, Australia. *Marine Pollution Bulletin, 72*, 244-249.

Marine Pollution Bulletin 72 (2013) 244–249

Contents lists available at SciVerse ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Ingestion of marine debris plastic by the wedge-tailed shearwater *Ardenna pacifica* in the Great Barrier Reef, Australia

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ARTICLE INFO

Keywords:
Seabird
Plastic pollution
Bird health
Environmental impacts
UNESCO world heritage site
Chicks

ABSTRACT

We present the first evidence of ingestion of plastic by seabirds from the southern Great Barrier Reef (GBR), Australia. The occurrence of marine debris ingestion in the wedge-tailed shearwater, *Ardenna pacifica*, on Heron Island was the focus of this preliminary research. Our findings indicate that 21% of surveyed chicks are fed plastic fragments by their parents, having ingested 3.2 fragments on average. The most common colours of ingested plastic fragments were off/white (37.5%) and green (31.3%). Ingested fragments had a mean size of 10.17 ± 4.55 mm and a mean weight of 0.056 ± 0.051 g. Our results indicate that further research is critical to understanding the extent of ingestion, colour preferences, and what impacts ingestion may have on these and other seabird populations in the GBR.

1. Introduction

Marine debris is an internationally recognised problem in all of the world's oceans (UNEP, 2005). The effects of marine debris are widespread, ranging from impacts to human health, economics, tourism and beach aesthetics (Sheavly and Register, 2007; Thompson et al., 2009), to morbidity and mortality on marine wildlife (Derraik, 2002; Gregory, 2009). Impacts have increased in severity over the last sixty-odd years despite legislation such as the London Dumping Convention and Annex V of the Convention for the Prevention of Pollution from Ships MARPOL 73/78 (Lentz, 1987; Coe and Rogers, 1997). The increase in marine debris is thought to be due to things such as insufficient garbage and recycling facilities, and the introduction and mass production of plastics (Coe, 2000; Ten Brink et al., 2009). Plastics are consistently the most prevalent items found in marine debris surveys (Cunningham and Wilson, 2003; Barnes et al., 2009; Slavin et al., 2012), with this being attributed to their wide spread use and limited ability to fully degrade (Andrady, 2004, 2005).

Small plastic fragments (micro- and nano-plastics) are a growing concern due to their ability to impact on a wide array of species and habitats (Thompson et al., 2004; Barnes et al., 2009). For example smaller marine fauna, such as zooplankton (Moore, 2008), mussels (Browne et al., 2008), lugworms (Besseling et al., 2013) and fish (Boerger et al., 2010; Davison and Asch, 2011; Possatto et al., 2011) can indiscriminately ingest these plastic particles. These species can be prey to larger organisms and could possibly contribute to secondary ingestion in seabirds.

The impact of marine debris on other marine wildlife via ingestion and entanglement, and has also affected numerous megafauna such as pinnipeds (Fowler, 1985, 1987), dugongs (Ceccarelli, 2009), cetaceans (Denuncio et al., 2011; Williams et al., 2011), sharks (Sazima et al., 2002; Wegner and Cartamil, 2012), turtles (Schuyler et al., 2012), fur seals (Eriksson and Burton, 2003) and seabirds (Ainley et al., 1990; Moser and Lee, 1992; Brandao et al., 2011). More than 43% of studied seabirds are impacted by marine debris (Laist, 1997), with subsequent negative health effects observed in a number of seabird species. The evidence for these negative affects has been quite weak (Ryan and Jackson, 1986; Moser and Lee, 1992); but include suppressed appetite and reduced growth (Ryan, 1988a), decreased fat deposition (Connor and Smith, 1982), and lowered fledgling mass (Sievert and Sileo, 1993). Plastic ingestion has also been linked to satiation and dehydration in chicks of poor condition (Auman et al., 1997), damage to the digestive system (Pettit et al., 1981; Sileo and Fefer, 1987) and in extreme cases has caused blockages and starvation (Dickerman and Goelet, 1987; Pierce et al., 2004). The specific cues for intentional marine debris ingestion by seabirds however still remain unclear.

It is theorised by some researchers that the feeding behaviour of individual species and the resemblance of natural food items to debris may make some species more susceptible to debris ingestion (Moser and Lee, 1992; Robards et al., 1995). Ingestion is especially common in the Procellariiform order of seabird, due to their method and location of feeding, their stomach physiology and the limited ability of this order to regurgitate (Azzarello and Van Vleet, 1987; Fry et al., 1987; Colabuono et al., 2010).

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http://dx.doi.org/10.1016/j.marpolbul.2013.03.017

Ingestion may also expose birds (and other organisms) to chemical contaminants that may have been preferentially adsorbed to the plastic within the water, or from chemicals that are intrinsically part of the plastic from the manufacturing process (Derraik, 2002; Colabuono et al., 2010; van Franeker et al., 2011). Ingesting these toxic coated plastics may also affect bird health and wellbeing (Guruge et al., 2001; Colabuono et al., 2010; Yamashita et al., 2011), with the potential for these contaminants to be concentrated up the food chain (Endo et al., 2005; Teuten et al., 2009; Chen and Hale et al., 2010).

The wedge-tailed shearwater (*Ardenna pacifica*) is a Procellariiform seabird and is known to ingest plastics in locations around the Pacific Ocean, including Australia (Fry et al., 1987; Spears et al., 1995; Hutton et al., 2008). It is characterised by a long, slim body, wedge-shaped tail and a hooked bill, with no sex-specific differences or seasonal variation in plumage (Marchant and Higgins, 1990). They feed mostly on small fish and cephalopods (Harrison, 1983; Marchant and Higgins, 1990) and in some areas can be found hunting with schools of predatory fish and cetaceans that drive prey to the ocean surface. Feeding behaviour may consist of contact dipping, dipping, surface seizing and pursuit-plunging (Harrison, 1983; Marchant and Higgins, 1990), with birds also found scavenging behind trawlers and fishing boats (Marchant and Higgins, 1990).

The Great Barrier Reef (GBR) is home to more than 20 different seabird nesting species, with many of these species listed and protected under Australian migratory bird agreements with the Governments of Japan (JAMBA), China (CAMBA) and the Republic of Korea (ROKAMBA) (Commonwealth of Australia, 2009). Within the GBR's Capricorn-Bunker group of islands is the largest nesting population of wedge-tailed shearwaters in the Pacific Ocean. Heron Island alone hosts approximately 13,000 wedge-tailed shearwaters between September and May every year (Dyer et al., 2005).

Heron Island (23°27′S, 151°57′E) is one of the largest islands in the Capricorn-Bunker group within the GBR Marine Park and is located 72 km north east of Gladstone, Queensland (QLD) (Fig. 1). It is a major tourist destination and has a small research station. The GBR World Heritage Area extends from 10°40′55″S down to 24°29′54″S, and covers an area of 348,000 km^2 (Australian Government Department of Sustainability, Environment, Water, Population and Communities, 2012), with Heron Island located in the southern portion of the GBR. Despite the documented occurrence of marine debris on the northern reef (Haynes, 1997), no data exists on the occurrence of marine debris within the southern GBR. Consequently, no information on what impacts this debris may have on the nesting seabird populations exists. The presence of debris on coastal areas off of Gladstone and other central QLD locations is recognised (Wilson, unpublished) with a possibility of this debris migrating to the reef. The primary purpose of this study was to assess the occurrence of marine debris ingestion in wedge-tailed shearwater adults and late-stage chicks on Heron Island in the southern GBR. Inferred coloured 'prey' selection choice based on preferential ingestion of coloured plastics was also examined.

2. Materials and methods

Sampling occurred during two trips that took place in February and May, 2012, in the Austral summer and autumn period, at Heron Island. In February, only adult birds were sampled, while in May both adult and late-stage chicks were sampled. Birds were sampled on both trips within the *Pisonia grandis* forest. Different regions of the forest were chosen for sampling each day to try to eliminate the likelihood of resampling the same birds and to reduce stress in the other birds and organisms in the area by not maintaining the same position each night/day. Birds were not banded or marked in anyway.

A haphazard sampling design was used based on accessibility, with sites predominantly selected in areas that were clear overhead indicating likely landing areas. Note, however, that sites were chosen purposefully off-track as sampling during the day was required to be undertaken out of view of island visitors (human). Sampling sites were within the middle of the colony, avoiding peripheral nesting. Although edge effects may be prevalent, this study has focussed on noting the presence of ingested plastic. Further studies are currently underway to note nest edge effects on the ingestion of plastics. Care was taken to prevent damage to burrows when catching and sampling birds in the forest.

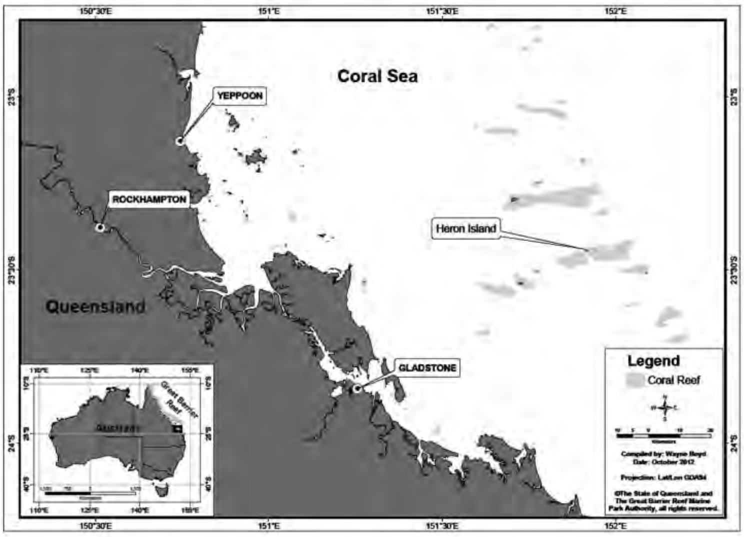

Fig. 1. Study area and location of nesting wedge-tailed shearwaters (*Ardenna pacifica*).

An approximate sampling area of 20 m by 20 m was used, with a different sampling area being haphazardly chosen each night. In total six different sampling areas were sampled in each experimental period. All *A. pacifica* burrows within the sampling areas were checked for chicks during the day, and any adults landing within or entering into burrows within this area were sampled in the evening. In total, 56 *A. pacifica* (32 live adults and 24 live late-stage chicks) were sampled for marine debris ingestion. All sampled birds were weighed using a spring scale (±0.1 g) and morphometric measures, such as culmen length were taken using Vernier callipers (±0.1 cm). Sampling used a standard stomach flushing protocol (Wilson, 1984), that involved two stomach flushing's of each individual. Samples were collected, frozen and stored frozen until analysis. Samples were maintained in individually labelled sample bags to ensure sample integrity was maintained.

In the laboratory, a modified protocol by van Franeker (2004) was used to analyse stomach samples. Briefly, the samples were thawed and run through a 1-mm sieve with plastic items being removed by forceps, and weighed using an analytical scale (accurate to 0.00001 g) and measured using callipers (accurate to 0.01 cm). Individual plastic items were counted, recorded and categorised as either user (i.e., fragments of large items, like bottles) or industrial (i.e., nurdles/virgin pellets; cleaning product scrubbers) plastic with any other characteristics also recorded (i.e., colour). Plastic fragments were assigned to one of eight broad colour groups (off/white–clear; grey–silver; black; blue–purple; green; orange–brown; red–pink, and yellow) by comparing individual pieces to an expanded colour wheel that included 72-colours (TigerColour, 2013). A scale that went from black to grey to white was also used. Colour gradients were used to determine a light or dark tone classification. Other material present within the sample (e.g., pumice stones) was noted for each sample then placed into a labelled open container, and dried out at 109 °C for up to 3-days. Dry weight of the sample less the plastic was then determined by weighing the containers.

A major limitation to this survey was the requirement of sampling adult birds immediately on their return, with this restricting the number of birds that could be sampled in one evening. Two stomach flushing's were undertaken per bird to ensure full stomach contents were removed. However, this may not have yielded full amounts from sampled adult birds due to the isthmus juncture between their proventriculus and gizzard potentially preventing the sampling of gizzard contents (Ryan and Jackson, 1986; Ryan, 1988b; Spears et al., 1995), with adults only yielding the most recently caught items from within their proventriculus.

Limited statistical analysis was conducted with the data, due to this being a preliminary investigation of marine debris ingestion in *A. pacifica* in the southern GBR, with low sample sizes and low number of birds found to have ingested plastic. Hence the statistical veracity of the data was poor.

3. Results and discussion

No plastics were found in adult wedge-tailed shearwaters in either the February or May sampling periods. However, plastics were found within (20.8%) late-stage chicks in May 2012 ($n = 24$). This level of plastic ingestion was similar to that recorded for *A. pacifica* at Midway Atoll (29%) (Sileo et al., 1990), but lower than that recorded on Lord Howe Island (43%) ($n = 30$) (Hutton et al., 2008) and on the Hawaiian Island of Manana (60%) ($n = 20$) (Fry et al., 1987). The colour of ingested plastic particles was examined to see if there were colour trends associated with ingestion. An examination of *A. pacifica* chicks indicated that the most common colours of ingested plastic were off-white/white (37.5%) and green (31.3%), with grey, black, yellow and red fragments also identified

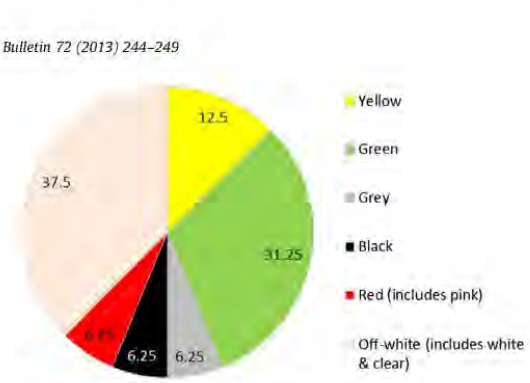

Fig. 2. Colours of plastic pieces (%) ingested by *Ardenna pacifica*.

(Fig. 2). White is often the most prominent colour of plastic ingested by many seabird species (Furness, 1985; Ogi, 1990; Eriksson and Burton, 2003; Carey, 2011; Titmus and Hyrenbach, 2011), and similar to this study, Sileo et al. (1990) found the most commonly ingested colour by wedge-tailed shearwaters is off/white (84%) followed by green (29%). The trend in colour selection may be a result of the prevalence of plastics with these colours in the environment, or an actual colour preference by the adult seabirds when feeding.

Plastics light in tone were most frequently ingested by the wedge-tailed shearwaters (62.5%) in this study. This could be related to their diet which consists mainly of small fish (e.g. goat fish, mackerel skad and flying fish) and cephalopods that live in warmer waters. Most prey items are taken from the sea surface (Harrison, 1983; Baduini, 2002), or are driven to the surface by predatory fish, with these birds pursuing active prey sources (Ainley et al., 1990). It has already been shown that birds that feed at the surface in more contaminated oceanic waters by surface seizing, dipping, or by scavenging are commonly found to have ingested plastic and this is thought to be related to the increased likelihood of contact with plastics floating on the ocean surface (Day, 1980; Furness, 1984; Ryan, 1987; Nel and Nel, 1999). The prominence of lighter tones (off/white, yellow, green) being ingested could be related to these plastic fragments resembling the colour of the natural prey, with fish reflecting light and being light in colour, and squid flesh having an off-white colour. The grey and black coloured particles may be ingested due to their similarity in size and colour to pumice stones. We found that 75% of late-stage chicks on Heron Island had ingested pumice stones, with an average of 2.8 stones per bird (mean size of 9.74 ± 3.57 mm SD). Yet, only one surveyed adult contained a pumice stone (6.00 mm length). All the pumice stones floated when placed into a beaker of water, which indicates that they were likely ingested at the water surface.

The stomach content of one chick in the present study was 48% plastic by weight. A total of 16-particles were collected from all sampled birds, with five-particles being the greatest number found within any one bird and a mean number of 3.2 ± 1.6 SD particles being ingested per individual. These findings were similar to that of Spears et al. (1995), with 3.5 particles ingested by 24% of the dark phase wedge-tailed shearwaters in the tropical Pacific Ocean; with other studies finding that wedge-tailed shearwaters on average contained 2–6 fragments (Fry et al., 1987).

All ingested plastics floated when placed into a beaker of water, with the heaviest particle weighing 0.18 g, indicating that the particles were likely at or near the surface of the ocean when taken up by the bird; with the wedge-tailed shearwater known to feed by dipping and surface seizing (Marchant and Higgins, 1990). Ability of the ingested particles to float would indicate that they are more than likely either polypropylene or polyethylene due to the low density of these polymers (Blumberg, 1993). Many studies have

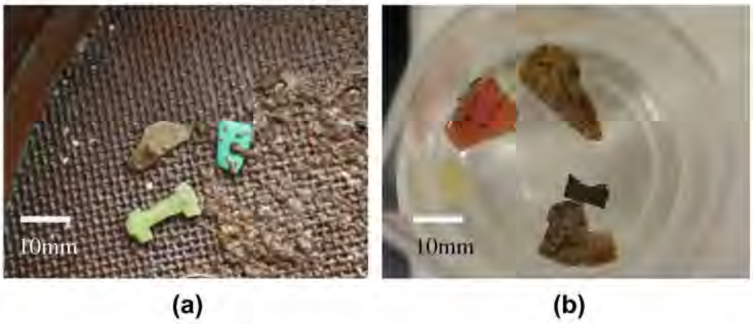

Fig. 3. Plastic pieces from regurgitate of two separate wedge-tailed shearwater (*Ardenna pacifica*) chicks: (a) chick 1 with three green fragments; and (b) chick 2 with two yellow, one red, one off-white and one grey fragment.

also found that the most commonly collected plastic pieces are small bits of polypropylene, and polyethylene (Day et al., 1985; van Franeker, 1985; Engler, 2012).

The mean size of plastic particles ingested was 10.17 ± 4.55 mm SD, with a mean weight of 0.056 ± 0.051 g SD. These ingested pieces were larger than those seen in Hawaiian wedge-tailed shearwaters that had ingested smaller user plastic fragments (1–3 mm in diameter) (Sileo et al., 1990) and 2–4 mm in diameter (Fry et al., 1987). Unlike in this study, most recovered plastics in those Hawaiian birds were rounded raw pellets of polyethylene or polypropylene, with only 20% being worn user plastic fragments of polystyrene (Fry et al., 1987). In this study, only user plastic fragments having originated from larger plastic items were ingested with no industrial pellets found in the regurgitate (Fig. 3).

There was no significant difference in the bird weight and culmen length of the wedge-tailed shearwater chicks found to have ingested plastic and those that had not in this study (Mann Whitney *U*-test $p = 0.406$ and 0.891, respectively). It should however be noted that the sample size was small ($n = 5$) and further sampling is required to ascertain any health related effects. Spears et al. (1995) showed a negative correlation between the number of plastic particles and body weight. Heavier birds had ingested more pieces and this was attributed to them being more efficient foragers and feeding at areas like convergence zones where both plastic and prey accumulate (Spears et al., 1995; Nevins et al., 2005).

Natural behaviour of the seabird may contribute to uptake with plastic possibly being mistaken for cuttlebones that are naturally pecked to obtain calcium carbonate (Cadee, 2002). Plastic particles may also have entered a seabird diet via secondary mechanisms. For example, incidental observations and analysis of regurgitate from a masked booby (*Sula dactylatra*) found that an ingested fish contained a plastic fragment (size 6.3 × 3.8 mm) (Verlis, unpublished). No whole fish were found in our wedge-tailed shearwater regurgitate but this observation suggests that some of the plastic pieces observed in the chicks could be from secondary ingestion, possibly from prey items like fish. It is not unreasonable to suggest that those smaller plastic fragments (below 8 mm) may have originated from secondary ingestion. To further investigate this possibility, the rate of ingestion of plastics by fish within the birds feeding grounds is required.

None of the 32 sampled adults were found to have ingested plastics. This is thought to be related to the physiology of the bird, and the low likelihood of sampling an adult bird that had just fed upon plastic during its last foraging trip. However, since plastics were found within sampled chicks this does indicate that adults of this species are taking up plastics and feeding it to their young either directly or indirectly. Feeding plastics to chicks has previously been documented in wedge-tailed shearwaters (Fry et al., 1987; Hutton et al., 2008) in other locations, and is thought to contribute to the higher level of ingestion occurrence seen in some young seabird species (Ryan, 1988, 1990; van Franeker and Meijboom, 2002). Although this contradicts the finding of Spear et al. (1995), which showed a statistical pattern of increasing ingestion with age.

Many birds locate their prey by sight and forage most actively during the day, and to a lesser extent rely on olfaction and sound to locate their prey (Shealer, 2002). Procellariiformes are unique in their use of olfaction to forage and in other behavioural tasks, like mate identification and nest locating (Hutchinson and Wenzel, 1980; Verheyden and Jouventin, 1994). Birds are tetrachromats meaning they have four retinal cones that contain at least five different oil droplets that reduce chromatic aberrations and contribute to the utilisation of almost the entire radiation spectrum available for vision providing for a greater spectral range that includes UV vision (Bowmaker, 1980; Cuthill et al., 2000). We suggest that this increased visual range may be a factor in the selection of ingested plastic that was found in this study, as different plastics can be absorbers of UV light, with UV information being shown to be used in foraging and signalling behaviours in many avian species (Cuthill et al., 2000). In addition, the olfactory cues often employed by Procellariiformes may have a role in the uptake of marine debris if the debris items have sorbed fish or other prey-like odour compounds from being in the oceanic environment for extended periods of time, similar to the sorption of persistent organic pollutants (Endo et al., 2005; Teuten et al., 2007; Rios et al., 2010).

Ingestion of marine debris plastic is occurring in the wedge-tailed shearwaters within the Great Barrier Reef. At this time it is not known what impact this may be having on this species although ingestion is not occurring at levels seen in species that are more greatly impacted such as the short-tailed shearwater (Carey, 2011) and flesh-footed shearwater (Hutton et al., 2008). Further sampling is needed to investigate the preference and size differential of ingested plastics and the potential for secondary transfer of these items. Additional analysis of the plastics for chemicals (both natural odours and contaminants) could also provide evidence for potential cues for uptake and suggest possible impacts on the health and wellbeing of these seabirds.

Acknowledgments

This research was funded by a Birds Queensland grant and a Strategic Research Scholarship from Central Queensland University. Research had an animal ethics research approval (Approval

Number A11/09-276) from Central Queensland University and all sampling and handling of animals conformed to the ethical standards pertained within our ethics approval. The funding bodies were not involved in the design, collection or analysis of data, or in the interpretation or writing of this article.

This research was conducted under the following permits from the Queensland Government Department of Environment and Resource Management (WITK10514111 and NCPI03548412) and the Great Barrier Reef Marine Park Authority (QC11/045).

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Appendix D:

Verlis, K.M., Campbell, M.L. and Wilson, S.P. (2014). Marine debris is selected as nesting material by the brown booby (Sula leucogaster) within the Swain Reefs, Great Barrier Reef, Australia. Marine Pollution Bulletin, 87, 180-190.

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Marine Pollution Bulletin 87 (2014) 180–190

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Marine debris is selected as nesting material by the brown booby (*Sula leucogaster*) within the Swain Reefs, Great Barrier Reef, Australia

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ARTICLE INFO

Article history:
Available online 15 August 2014

Keywords:
Seabird
Plastic pollution
Threat
Beach survey
Environmental indicator

ABSTRACT

Many seabirds are impacted by marine debris through its presence in foraging and nesting areas. To determine the extent of this problem, marine debris use in nest material of the brown booby (*Sula leucogaster*) in the Great Barrier Reef, Australia, was investigated. Nine cays were examined using beach and nest surveys. On average, four marine debris items were found per nest ($n = 96$) with 58.3% of surveyed nests containing marine debris. The source of marine debris in nests and transects were primarily oceanic. Hard plastic items dominated both nest (56.8%) and surveyed beaches (72.8%), however only two item types were significantly correlated between these surveys. Nest surveys indicated higher levels of black and green items compared to beach transects. This selectivity for colours and items suggest these nests are not good indicators of environmental loads. This is the first study to examine *S. leucogaster* nests for marine debris in this location.

1. Introduction

Marine debris is one the main global threats facing oceans due to its varying and far reaching impacts on the users and inhabitants of the marine and coastal environment. Marine debris items being those things made or used by man (synthetic or anthropogenic), and are either purposefully or accidental released into marine or freshwater environment (Galgani et al., 2010). Impacts can be on the environment, the economy and the health and safety of humans and animals (Sheavly, 2005; Ceccarelli, 2009;Gregory, 2009; Ten Brink et al., 2009; Slavin et al., 2012). Although marine debris can be composed of a wide variety of materials, plastics dominate and pose the greatest threat to marine life due to its longevity and persistence in the environment (Andrady, 2005; Moore, 2008; Ryan et al., 2009; Thompson et al., 2009). Despite global conventions such as MARPOL Annex V that regulates the disposal of all plastics while at sea, the problem persists. Certain types of marine debris, such as plastic fragments and discarded fishing gear can be especially detrimental to seabirds and other wildlife (Kiessling, 2003; STAP-GEF, 2012).

Seabirds are impacted by a range of environmental pollutants, and are well suited to act as indicator species for contamination (Furness and Camphuysen, 1997; Burger and Gochfeld, 2004; Nevins et al., 2005). For instance, plastic ingestion is monitored in seabirds in the North Sea, with plastic levels indicating the intensity of pollution within an area (Van Franeker and Meijboom, 2002; OSPAR, 2008). Often seabirds are brought into close association with marine debris items through their foraging behaviours in convergence zones where marine debris accumulates (Carr, 1987; Ainley et al., 1990; Nevins et al., 2005). Anthropogenic activities in a given area also influence the type and nature of marine debris items that amass (Merrell, 1980; Canadian Council of Ministers for the Environment, 1999; Ribic et al., 2010). More than 44% of seabird species studied have been shown to be impacted by marine debris via ingestion and entanglement (Laist, 1997). The brown booby (*Sula leucogaster*) is part of the order Pelecaniformes, which include Sulidaes (boobies and gannets) and is an order known for entanglement in marine debris both at sea (Laist, 1987,1997; Schrey and Vauk, 1987; Rodriguez et al., 2013) and at nesting sites (Conant, 1984). Boobies are not known for ingestion of plastic marine debris with zero to low incidences recorded (Sileo et al., 1990; Spear et al., 1995). These birds feed by pursuit-diving or plunge-diving and preferentially forage in turbid waters, which would limit the attraction, contact and opportunity this species would have to directly ingest plastics (Shealer, 2002).

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http://dx.doi.org/10.1016/j.marpolbul.2014.07.060
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Marine debris has been found in nests of Sulidae species, with items found within the nests reflecting the activities occurring in the surrounding marine environment (Nel and Nel, 1999; Votier et al., 2011; Bond et al., 2012). There is evidence of marine debris use by *S. leucogaster*, however this is limited (Ostrowski et al., 2005; Lavers et al., 2013). Bird reference guides also refer to the use of marine debris and other items such as plant remains, twigs, seaweed, bones, and turtle egg shells as nesting material by this species (Marchant and Higgins, 1990). Nest building in the Sulidaes can be undertaken to form a functional structure, or it can be symbolic in nature (Nelson and Baird, 2002). In both instances, it involves close mate interactions that likely serve to strengthen the pair bond, with males presenting the female material in a ritualized manner and the female doing the majority of the nest building (Marchant and Higgins, 1990; Nelson and Baird, 2002). The aim of this study was to examine the amount, characteristics and types of marine debris used in *S. leucogaster* nests in the Southern Great Barrier Reef (GBR), and potential impacts resulting from its presence.

2. Methods

2.1. Study sites

The GBR is a World Heritage Area due to its natural universal value and encompasses an area of 348,000 km^2 which encompasses over 600 continental islands and 300 coral cays (GBRMPA, 2011). It stretches parallel to the north-eastern Australian coastline for nearly 2000 km on the edge of the continental shelf (Mather and Bennett, 1994). It is home to many globally significant fauna groups and is an important breeding area for sea turtles and many seabird species (GBRMPA, 2011). The Swain Reefs are located in the most south-easterly part of the GBR, north-east off the coast of Gladstone, Queensland, and are the farthest reefs from the Australian mainland (Smith et al., 1990). The Swain Reefs are composed of a series of small cays and approximately 370 patch reefs, with an overall land mass of 9 ha (Queensland Government, 2013).

This study examined nine coral cays in the Swain Reefs. At all sites both nest and marine debris surveys were conducted, as time allowed. The sites are: (1) Bell Cay (1.5 ha); (2) Price Cay (1.6 ha); (3) Bacchi Cay (0.5 ha); (4) Frigate Cay (2 ha); (5) Distant Cay (0.25 ha); (6) Riptide Cay (0.25 ha); (7) Gannet Cay (1.7 ha); (8) Bylund Cay (0.6 ha); and (9) Thomas Cay (1 ha) (Fig. 1). Price and Bell Cays were vegetated, with all others sites composed of either coral sand and/or rubble (Queensland Government, 2013). Bell and Bylund Cays had no nesting *S. leucogaster* present during sampling but had beach marine debris surveys conducted on their windward sides.

2.2. Nest debris surveys

Surveys of *S. leucogaster* nests were undertaken between June 2012 and August 2013 across the Swain Reefs. Nests were opportunistically surveyed, with every second or third nest surveyed on more densely populated cays, and every nest being surveyed on less dense cays as time allowed. To survey individual nests, a 0.25 m^2 (50 cm by 50 cm) quadrat was placed over unoccupied nests and photographs were taken from ~1 m above the nest. Any marine debris in the nest was collected in labelled plastic bags (site name, date, nest number) ensuring that minimal physical disturbance of the nest occurred. Surveys targeted nests that contained egg(s), or that were readily identified as having been nests due to accumulation of materials (Fig. 2a, b, c).

Collected marine debris nest items were categorised by material and type of object, with weight, size and characteristics such as colour recorded. The classification of material debris by material and type was based on Cheshire et al. (2009) with additions of additional plastic categories of fibrous (e.g. cigarette butt, face wipe), rope (e.g. rope, line, net, strapping), medical (bandaid, needle) and sheet (e.g. bags, wrappers, sheeting, labels). Colour coding was the same as that used in Verlis et al. (2013), with the modification of an additional colour category of 'natural' to designate unpainted/unstained processed wood items. This colour coding was also used on recovered shoreline marine debris items (collected from beach surveys).

Determining the source of the marine debris was accomplished using a percentage allocation scoring technique (Whiting, 1998; Tudor and Williams, 2004), with identified sources being land (beach tourism), commercial shipping, commercial fishing, recreational boating/fishing, and stormwater discharge. An exponential scoring system was used to assign a weighted value to the likelihood of an item originating from each of the sources (0.25 = very unlikely, 1 = unlikely, 2 = possible, 4 = likely, 16 = very likely). No zeroes were assigned as no source could absolutely be ruled out as having made a contribution to the recovered marine debris items (Tudor and Williams, 2004). To help decrease the subjectivity of assigning source, multiple sources are allotted a score and the allocation of scores to marine debris items was based on observational data that included the presence of biofouling and fading, the likely use of the item, and if it could be purchased within Australia, or was of foreign origin. This same sourcing method was also used on marine debris collected from shoreline debris surveys.

2.3. Shoreline debris surveys

On each cay where nest surveys were completed, three 10 m wide belt transects were conducted just above the high tide line on the windward shore. The length of the transect was determined by cay size and ranged from 10 to 50 m (total area of 300 m^2 to 1500 m^2) with total transect area recorded. Reduced transects were conducted on Bell and Bylund cays. Transects were spaced to sample the two ends and middle of the beach. All surface marine debris items present (>1 cm) were collected from within the belt transects. In June 2012, transect widths of only 5 m (total area of 750 m^2 and [225 m^2 Bylund]) were utilised due to time constraints. To overcome the differences in sampling effort (sample area surveyed) the data was standardised to amount per m^2. All marine debris items were classified according to the material type (e.g. hard plastic, glass, metal), object type (e.g. bottle, fragment), with the weight (using an AND GF-10 K balance accurate to 0.01 g) and greatest-length size measurements (using a metal ruler accurate to 0.1 cm) also recorded.

2.4. Data analysis

The mean (±1 standard deviation) for size and weight of all marine debris items was determined for transect and nest debris. The percentage use of different marine debris material types, items, and colours of debris items in transects and within nest material were determined for each sample period. Statistical analyses were undertaken using SPSS statistical package (version 20.0.0.1). For all statistical tests run, significance was represented by a $p < 0.05$.

A linear regression analysis was used to determine the nature of the relationship that existed between marine debris types found on the beach and within nests using the number of items of a particular marine debris type and colour within transect and within nest. This was also used to determine any correlation between amounts of marine debris in nests and that recovered from the beach at the same time and location. A chi square (χ^2) analysis was undertaken to determine if differences existed between the colours of nest marine debris items to those found in transect. A

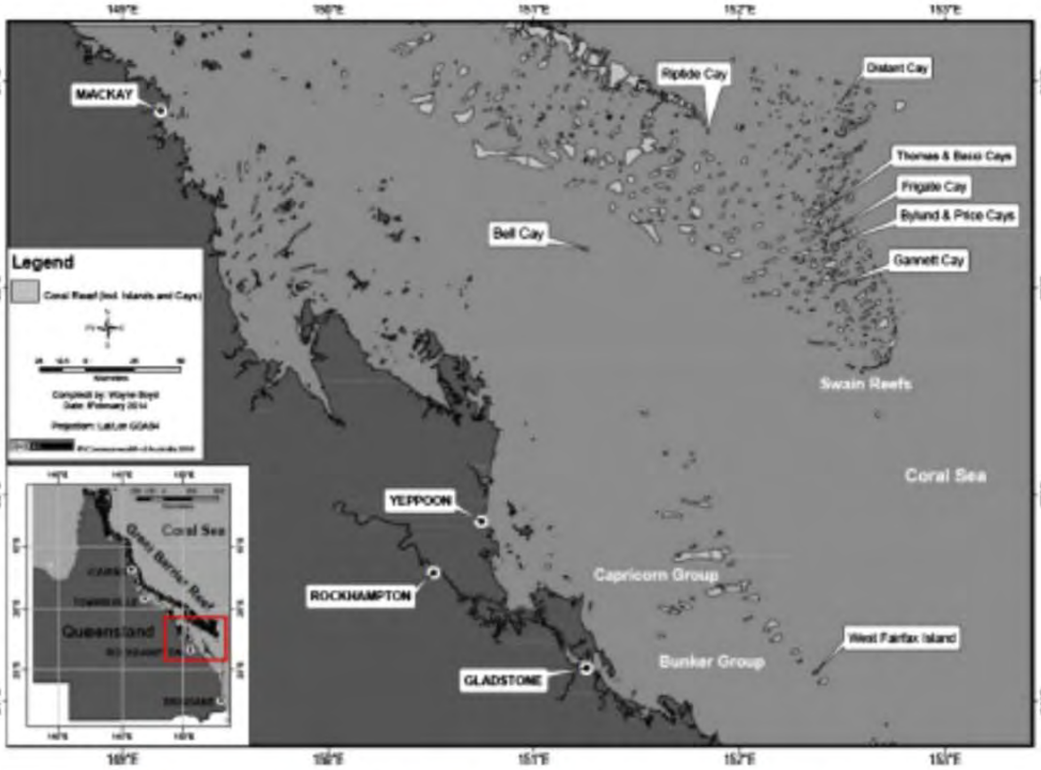

Fig. 1. Surveyed beach and *Sula leucogaster* nest locations in the Swain Reef Cays, Great Barrier Reef, Australia.

Fig. 2. Brown Booby (*Sula leucogaster*) nests at: a) Frigate Cay, August 2013; b) Thomas Cay, June 2012; c) Thomas Cay, August 2013; and d) Riptide Cay, February 2013 (note the dead common noddy (*Anous stolidus*) used as nest material in this nest).

one-way ANOVA with Tukey post hoc test were used to determine significant differences between marine debris prevalence at different time periods in nest and beach; to determine any differences in natural material items over different sampling times, and the influence of marine park zoning on debris accumulation in nest and on beach. Again number of items was used. Data was first tested for heterogeneity with a Levene statistic and normality with Kolmogorov–Smirnov test.

For analysis of nest photographs, a modified Coral Point Count with Excel extensions version 4.1 (CPCe4.1) (Kohler and Gill, 2006) was used. To determine the appropriate number of random points required to accurately reflect the quantity of material (both organic and anthropogenic) used in the nest material a trial was run. Ten nest photographs from each time period that represented different levels of marine debris load were randomly selected and used in the trial. Point sample sizes of 10, 20, 40, 60, 80, 100, 120, and 200 points were randomly generated on the photos and the material under the points classified according to one of 27 predetermined material types (Supplemental Table S1). The mean percent of marine debris from each sample size were plotted and the asymptote determined to identify the lowest number of overlayed points required to accurately reflect nest contents. Based on the trial, 60 randomly placed points were subsequently used to determine the percent coverage of anthropogenic and organic material. The results were analysed with the background materials of sand, vegetative matter and coral rubble being removed.

3. Results

3.1. Nest debris

Of the 96 nests surveyed, across all Swain Reefs for all sampling times, 58.3% contained marine debris. The greatest amount of marine debris was found at surveyed nest sites in August 2013, with 74.5% of surveyed nests containing plastic (Table 1). However, this was not significantly different to other survey times ($F_{[3,11]} = 1.786$, $p = 0.208$). The highest percent coverage of nest material composed of marine debris was seen in June 2012 (7.1%), with nests primarily composed of natural materials (96.7%) at all sampling times. The most common natural material found in nests on these cays were coral pieces (41.1%) and feathers (20.1%) (Table 2). Interestingly, dead animals, such as birds and fish were used as nest material (Fig. 2d). The natural materials utilised in nests between sampling times did not differ significantly ($F_{[2,11]} = 0.196$, $p = 0.825$). The percent cover of marine debris found in nest photos was positively correlated to the number of individual marine debris items retrieved from nests ($R^2 = 0.975$, $p = 0.0001$) giving strength to the use of this technique to quantify the presence and cover of marine debris items in nest material when items cannot be physically collected.

Overall, a mean number of 4.1 ± 4.7 marine debris items per nest were found within the Swain Reefs. However, nearly half (41.1%) of all nests contained only one marine debris item. In June 2012, the greatest mean number of marine debris items was detected in nests (9.2 ± 7.9 items per nest). During that sampling period, Price Cay had the greatest number of items ($n = 23$) detected in any one nest of all surveyed sites. February 2013 had the lowest number of items recovered from nests at all surveyed locations (Table 1). The overall amounts of marine debris in nest material did not statistically correlate with levels recovered in beach surveys ($R^2 = -0.86$, $p = 0.830$).

Table 2
Overall percent coverage of material used in *S. leucogaster* nests both natural items and marine debris.

Natural material (%)		Synthetic material (%)	
Coral	41.12	Plastics	
Feather	20.05	Plastic Hard	2.05
Seaweed/Algae	12.96	Plastic Rope	0.33
Shell	9.84	Plastic Sheet	0.09
Pumice	5.73	Non-Plastics	
Wood (not timber)	1.86	Processed Wood	0.33
Seed	1.77	Glass	0.51
Animal-matter/non-bird	0.61	Metal	0.05
Twig/branch	0.37	Rubber	0.05
Bird bones	0.37		
Leaves/needles	0.05		

Nb: Background materials of sand, coral rubble and vegetative matter were removed prior to analysis.

The overall mean size and weight of marine debris items from all surveyed nests was 8.61 cm ± 7.18 and 6.16 g ± 10.89, respectively (Table 1). The most common marine debris items are summarised in Fig. 5, with hard plastic fragments originating from the breakdown of larger plastic items dominating. Hard plastic items dominated individual nests (81.6%), and with rope plastic (9.4%) and sheet plastic (1.3%) accounted for nearly 93% of all material types found in nests. No fibrous, foamed or medical plastic were found in nest material, nor were any paper or cardboard items. A number of toiletry items, such as toothbrushes, razors and combs (4.3%), and stationary items, such as pens and markers (3.5%) were also detected in nests.

The most common colour of marine debris used by *S. leucogaster* in its nests was blue-purple (28.3%) followed by green (19.1%) (Fig. 4). Slightly higher levels of yellow and silver/grey coloured items were seen in nests compared to transect debris. A chi square analysis showed a significant difference between the colours of marine debris items in nest and that in transect ($\chi^2_{[8]} = 17.68$, $p = 0.024$).

The sources of nest marine debris were primarily marine based (Fig. 6), with commercial fishing debris being the greatest contributor (30.8%). Land-sourced items only accounted for 26.4% of marine debris items. No difference were found in the amount of marine debris in nests or on beaches of cays in different marine park zones (Marine National Park (Green) zone, Preservation (Pink) zone, General use (light Blue) zone) ($F_{[2,15]} = 0.943$, $p = 0.411$; $F_{[2,15]} = 3.265$, $p = 0.66$, respectively).

3.2. Shoreline transect debris

An average of 0.01 marine debris items m^{-2} was found on the shorelines of Swain Reef Cays. June 2012 had the greatest number

Table 1
Summary of individual nest marine debris findings from Swain Reef Locations.

	Nests containing plastics	Percent-coverage marine debris (%)	Size (cm) mean ± S.D.	Weight (g) mean ± S.D.	Number of items in nest mean ± S.D.
June 2012	52.6% (n = 19)	7.06	8.14 ± 7.04	6.10 ± 12.38	9.2 ± 7.93
February 2013	30.8% (n = 26)	1.05	11.26 ± 15.97	10.20 ± 22.66	1.5 ± 0.756
August 2013	74.5% (n = 51)	3.47	8.70 ± 5.89	5.80 ± 7.60	3.24 ± 2.94
Overall	47.9% (n = 96)	3.26	8.61 ± 7.18	6.16 ± 10.89	4.05 ± 4.73

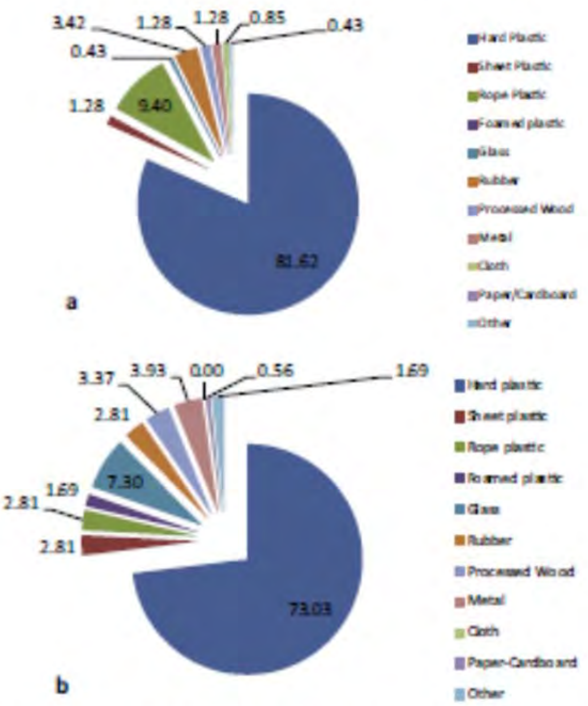

Fig. 3. The proportion of marine debris material types present in: a) nests; and b) beach surveys at all surveyed locations in the Swain Reef Cays and all sampling times.

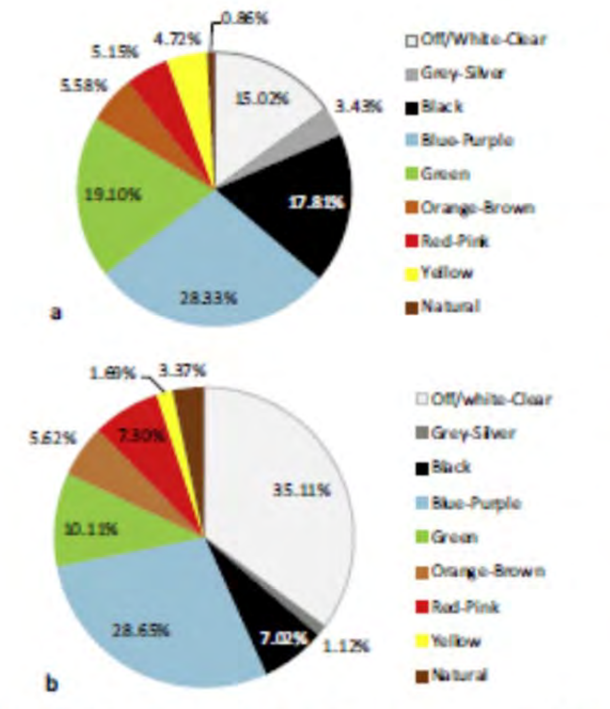

Fig. 4. Colour of synthetic marine debris used in: a) *S. leucogaster* nests; and b) on surveyed beaches in the Swain Reef Cays, Great Barrier Reef, Australia.

of items detected in transects (0.03 items m^{-2}) and February 2013 the lowest number (0.005 items m^{-2}) (Table 3). On average, Price, Frigate and Bylund Cays had the greatest number of items collected in beach transects (Table 4). In August 2013, the greatest range (type) of materials was found on beaches; while only two types of anthropogenic material (hard plastic and metal) were collected in February 2013 (Table 5).

The overall mean length and weight of marine debris items in transects across all time periods was 14.95 ± 34.22 cm and 78.16 ± 251.16 g, respectively (Table 3). Hard plastic (75.1%) was the most common material type found in all shoreline transects, with sheet plastic (2.8%), rope plastic (2.8%), and foamed plastic (1.7%) having much smaller contributions to marine debris loads (Fig. 3b). Glass/ceramic (7.3%) and metal (3.9%) were the non-plastic materials that dominated the surveys. Neither cloth items nor any medical or fibrous plastic marine debris items were found on shoreline transects. The most common items found in transects were hard plastic fragments (39.6%), plastic bottles (12.4%), and plastic caps/lids (7.69%). There was a positive correlation between rope plastic used in nests and that found in transect ($R^2 = 0.606$, $p = 0.002$) and to a lesser extent this was evident with rubber ($R^2 = 0.407$, $p = 0.019$). No other correlations with marine debris items were observed.

Shoreline transect marine debris was predominately off/white-clear in colour (35.1%), although blue-purple (28.7%) coloured debris was the second most common colour found in transect debris and was similar to levels seen in the nests (Fig. 4a,b). There were far less black and green coloured items in transect marine debris with more natural (wood) items than that seen in nest marine debris.

Commercial shipping was the main source of marine debris detected on shoreline transects (33.0%). Oceanic sources dominated, with beach and stormwater only being attributed to 26.6% of recovered items (Fig. 6).

4. Discussion

Marine debris is found in heavily urbanised (e.g. Cunningham and Wilson, 2003; Eriksen et al., 2013; Jayasiri et al., 2013; Morritt et al., 2014) and pristine (e.g. Haynes, 1997; Whiting, 1998; Edyvane et al., 2004; Slavin et al., 2012) locations. This study provides further evidence that remote areas such as offshore reefs are also affected by marine debris, specifically plastic pollution. This finding has implications for seabirds that use remote locations to nest. Hence, this study aimed to determine the extent of marine debris usage by *S. leucogaster* in their nests, any impacts of this usage, and if the degree of usage in nests is reflected by the background level of marine debris available upon the cay shorelines examined.

The surveyed beaches in the Swain Reefs had on average 0.01 items m^{-2} ($n = 9$). This level was much lower to that seen in the nearby onshore beaches in the Gladstone Queensland Region in 2012 (0.09 items m^{-2}, $n = 4$) (Wilson, 2012), and a quarter of the amount recorded in the far North GBR (0.04 items m^{-2} assuming a 10 m transect width, $n = 15$) (Haynes, 1997). The average size of marine debris items in nests was relatively small (Table 1) and was half the weight of debris (6.2 g, $n = 96$) recovered in brown booby nests in Ashmore Reef (11.1 g, $n = 37$) (Lavers et al., 2013). We do note that the Lavers et al. (2013) data is based on a single sampling period (April 2013) and hence represents a restricted temporal scale compared to this study. Although the higher weight of marine debris items at Ashmore Reef was similar to that seen in our February 2013 (16.0 g, $n = 12$) samples, the differing geographic locations may be a factor in the differences. The Ashmore Reefs for instance, are close to the Indonesian Islands and could theoretically be more influenced by land-sourced marine debris items.

Of the 96 nests sampled in the Swain Reefs over the three sampling time periods, more than half contained marine debris

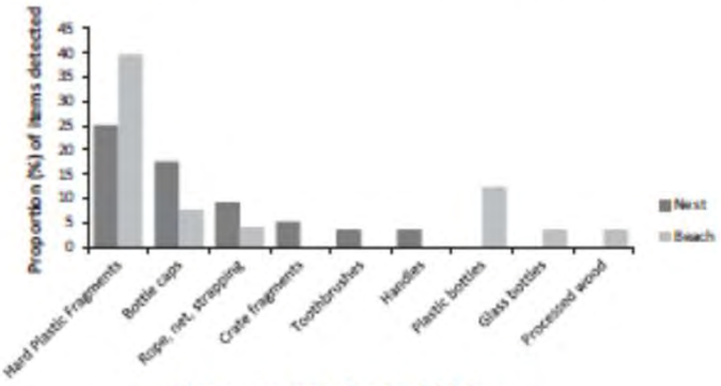

Fig. 5. The most common marine debris items in nests and on beaches.

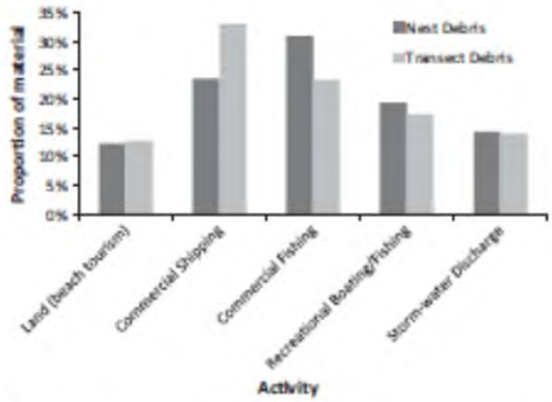

Fig. 6. Sources of marine debris in nests and on beaches for all surveyed sites.

Table 5
Percentage contribution of non-plastic and plastic synthetic debris items on beaches.

Non-plastic (%)	June 2012	February 2013	August 2013	Overall
Cloth	0	0	0	0.0
Glass/Ceramic	3.23	0	12.3	5.35
Metal	3.23	9.09	4.62	5.82
Paper/Cardboard	0	0	1.28	0.43
Rubber	1.08	0	6.15	2.07
Wood	1.08	0	7.69	2.07
Other	0	0	4.62	2.14
Plastic (%)				
Hard plastic	87.1	90.9	49.2	76.8
Sheet plastic	1.08	0	6.15	2.07
Medic plastic	0	0	0	0.0
Rope plastic	2.15	0	4.62	2
Foamed plastic	1.08	0	3.08	1.21
Fibrous plastic	0	0	0	0.0

Table 3
Summary of marine debris beach surveys at all locations and surveyed time periods.

	No. of transects	Size mean (cm) ± S.D.	Weight mean (g) ± S.D.	Weight (g^{-2})	Count (items^{-2})
June 2012	12	10.24 ± 38.43	31.02 ± 165.10	0.7312	0.03
February 2013	12	24.63 ± 44.94	33.81 ± 60.65	0.0758	0.005
August 2013	24	20.05 ± 23.68	144.90 ± 331.16	0.9363	0.007
Overall	48	14.95 ± 34.22	78.16 ± 251.16	0.7725	0.01

NB: Weight does not include items left on beach which could not be weighed.

Table 4
Number of items of debris collected from sampled belt transects at nine Swain Reef Cays.

Beach	Count (items/m^2)	Size mean (cm) ± S.D.	Weight mean (g) ± S.D.
Bell Cay	0.005	28.93 ± 45.75	37.77 ± 51.39
Riptide Cay	0.003	23.4	22.19
Price Cay	0.03	18.54 ± 46.38	78.41 ± 182.43
Bylund Cay	0.01	10.55 ± 8.76	64.49 ± 166.95
Thomas Cay	0.003	24.91 ± 32.78	231.93 ± 501.34
Bacchi Cay	0.004	31.32 ± 31.47	305.07 ± 637.52
Frigate Cay	0.02	5.78 ± 15.55	8.70 ± 46.90
Gannett Cay	0.003	10.12 ± 3.12	93.56 ± 60.15
Distant Cay	0.007	14.85 ± 8.77	139.12 ± 252.97

NB: Weight does not include items left on beach which could not be weighed.

(58.3%). This was similar to levels seen in Kittiwake (*Rissa tridactyla*) nests in Denmark (57.2%) (Hartwig et al., 2007), but was higher than that seen in *S. leucogaster* nests at Ashmore Reef (3–39%) (Lavers et al., 2013) and in cormorant nests in the Gulf of Maine (36–39%) (Podolsky and Kress, 1989). Although 4.1 marine debris items are expected to be present within nests, of all items used only 3.3% were marine debris (Table 1), with natural materials such as coral pieces, feather and seaweed-algae accounting for the majority of nest material (Table 2). Coral and shells have been theorised to be used by terns due to their ability to camouflage the egg against predation (Kotliar and Burger, 1986). Similar protective qualities could be obtained by *S. leucogaster* with the use of natural materials.

The dynamics of nest building are likely to play a part in the differences seen in recovered amounts of marine debris objects detected between the different sampling time periods (Table 1). Yet, none of the differences in the range of natural materials utilised in nests between sampling times differed significantly ($F_{[2,11]} = 0.196$, $p = 0.825$). The majority of nest building occurs pre-and post-egg laying (Marchant and Higgins, 1990; Nelson and Baird, 2002), and nesting can occur year round in the Swain Reefs (Commonwealth of Australia, 2013; Queensland Government, 2013). Nests are not however retained for more than one nesting season, and as the chick grow the nest becomes less distinct, with items blown or stolen by conspecifics (Marchant and Higgins, 1990). The age of the nest likely had a role in the amount of marine debris present when surveyed, with older nests potentially biased toward containing fewer marine debris items due to natural removal processes.

All but one of these Swain Reef sites where nest surveys were conducted were un-vegetated with most cays having a base substrate of sand and/or coral rubble. Lavers et al. (2013), suggested that if natural vegetative debris is scarce that birds may rely more on marine debris for nest material. This study detected greater amounts of marine debris on the only vegetated cay, Price Cay, for two of the sampling periods (June 2012, $n = 44$ total nest items; and August 2013, $n = 16$ total nest items). As such, this may not support Laver's et al (2013) idea in this region. Therefore, in the GBR region examined it seems unlikely that the presence of native vegetation would reduce the use of marine debris items in nests. Field observations indicate that the vegetation present on Price Cay acted more as an insulating buffer against the elements, rather than as nest substrate (i.e. nests were situated close to but did not incorporate vegetative matter) with vegetation likely acting to trap debris items. Presence of vegetation and other factors, such as slope, position of the cay, and substrate appear to influence upon marine debris use in nests.

The overall amount of marine debris available on the beach does not appear to be an influencing factor to debris use in nest material, as overall levels in nests did not correlate with availability of debris on beaches ($R^2 = -0.86$, $p = 0.830$). Hence, marine debris beach surveys cannot be replaced by monitoring the nest material of *S. leucogaster*, because the birds appear to selectively take-up items. As such, the amounts of debris present within their nests may not accurately reflect the level of contamination in the surrounding environment. In certain species, this situation may be different. For instance, in Denmark, the levels of marine debris incorporated in Kittiwake nests corresponded to the amounts of those debris items types (i.e. strings and netting, foil) found on shoreline surveys surrounding the colony (Hartwig et al., 2007). Also gannets are known to collect nearly all of their nest material from the surrounding sea (Montevecchi, 1991) with levels thought to reflect levels of marine debris in the adjacent marine environment.

In the present study correlations between nests and transects for type of debris were found only for rope and rubber ($R^2 = 0.606$, $p = 0.002$; $R^2 = 0.407$, $p = 0.019$, respectively. This could support the assertion that some items are sourced directly from the surrounding environment (Lavers et al., 2013) and may indicate *S. leucogaster* has a preference for these items since levels were consistent over time. Overall, the level of marine debris contamination in the Swain Reefs where *S. leucogaster* nests do not appear to influence the amounts and types (in most instances) of items used as nest material, therefore limiting the use of nest surveys as an indicator for marine debris loads in this area. However, regionally specific studies should be conducted to further evaluate the applicability of this technique.

Seabird nest material studies often focus specifically on fishing industry related debris as this is seen as an industry that can be regulated or managed to reduce the problem. In such instances uptake of fishing debris items appears to be related to the similarity in appearance of these items to natural materials (Podolsky and Kress, 1989; Votier et al., 2011; Bond et al., 2012). These natural looking materials include items such as rope and strapping (Votier et al., 2011), and were items also taken up by *S. leucogaster* in the Swain Reefs for use as nest material (Fig. 5). Interestingly, rope materials found in nests in the Swain Reefs were primarily green, blue, and black, which may suggest that the studied birds in the Swain Reefs are purposefully choosing these items, due to their colouring and/or the resemblance to natural materials such as seaweed that are commonly utilised (Table 2). However, the presence could also be reflecting the prevalence of these items in the environment.

The colour of marine debris items used by *S. leucogaster* in nests and that found on beaches appeared similar (Figs. 2a and b), although no statistical correlation was evident ($\chi^2 = 17.68$, $p = 0.024$). The nest debris had higher levels of green and black items present than seen in the beach transects. This may indicate that the birds are purposefully choosing these coloured debris items from beach transects hence these coloured items are less available from the transects.

In some bird species, the selection of specific coloured items, like green nest material, can also act as a function in mate attraction (Brouwer and Komdeur, 2004). As *S. leucogaster* is a monogamous species with the males presenting females with items for nest building, perhaps these are preferred colour for nest building and these function in strengthening the pair bond, and/or signalling the birds for nesting. For example, in some species, the presence of the mate and of nest material provided the stimulant for incubation behaviour and signals the release of gonadotropin in females which brings about oviduct growth and ovulation (Lehrman et al., 1961).

The high levels of blue, green and black items in nests from the Swain Reefs (Fig. 2a) (which were also the most common colours of rope utilised by *S. leucogaster*: green (42.1%), blue (16.3%), and black (15.8%)) differed to colours of debris in *S. leucogaster* nests and in transect data at Ashmore Reef (Lavers et al., 2013). At Ashmore Reef, black (30%) and white (28%) items dominated nests and blue items (60%) dominated beach debris (Lavers et al., 2013). In contrast, in this study white items dominated beach debris (Fig. 2b). White objects are often taken up and ingested by seabirds due to their resemblance to prey items (Furness, 1985; Carey, 2011; Verlis et al., 2013), and white items are the fourth most common colour found used in nest debris in this study. These items may be utilised due to their resemblance to natural items such as cuttlebones, and light coloured coral pieces and shells but is not likely attributable to prey resemblance. The presence of white coloured marine debris items in nests was also not surprising due to the high prevalence in the environment as indicated by colour of beach debris items (50.8%; Fig. 2b). The colour prevalence of items in the nests are most likely influenced by both availability of different coloured items in the surrounding environment and weather patterns in the region.

Table 6
Foreign-sourced marine debris from nest and transect.

Country	Nest	Transect
Indonesia	X	X
Peru	X	
Philippines		X
Papua new guinea		X
Vanuatu		X
Thailand		X
China		X
Japan		X

Any long-term changes in wind direction and consequent alteration of sediment movement onto cays will alter cay shape (Flood and Heatwole, 1986; Queensland Government, 2013), and hence it is expected that these factors would influence the deposition and erosion of debris items upon cays. Storm activity has also been shown to impact upon debris usage in nest material and accumulation upon beaches, by altering the availability of material (Bond et al., 2012), with wind having an important role in determining the movement and direction of floating objects in the surrounding marine environment (Smith et al., 1990; Bond et al., 2012). Annual differences in debris coverage in nests and on beaches, like those seen in Austral winter June 2012 and August 2013, could be related to these longer-term factors of wind and wave movement of debris on and off the cay (Table 1).

The larger size and heavier weight of debris items (Table 1) and highest level of feather usage in February compared to other time periods (37.4%) may relate, at least in part, to the weather conditions at the time and the clearing of both natural and debris items. In January 2013, the Category 1 Cyclone Oswald formed in the Gulf of Carpentaria and brought strong winds (>100 km/h), large swells and heavy rains (BOM, 2013a) down the Queensland coastline would have removed a great deal of both natural and anthropogenic material from the cays. Nesting occurs year-round in the Swain Reefs for *S. leucogaster* (Queensland Government, 2013) and hence the weather patterns experienced in the area will likely influence the availability and amount of natural and anthropogenic material available for nest building.

Other potential factors that influence the available nest material are nearby anthropogenic activities occurring offshore that can affect the nature and type of material deposited on beaches. The greatest contribution of nest marine debris originated from marine based sources, which was not unexpected due to the isolation of the Swain Reefs from mainland Australia (up to 200 km offshore). Both beach and nest debris items were most heavily sourced (Fig. 6) from commercial shipping (33.0%) and commercial fishing (30.8%), with 74% of debris sourced to oceanic sources. This is similar to findings in Fog Bay, Northern Australia where 85% of debris items were oceanic in origin (Whiting, 1998).

Many studies of seabird nests in different locations have shown offshore fishing activities as the greatest contributor to nest marine debris usage (Podolsky and Kress, 1989; Montevecchi, 1991; Nel and Nel, 1999; Hartwig et al., 2007; Phillips et al., 2010; Votier et al., 2011; Bond et al., 2012). Some items in nests and within shoreline transects in the Swains were of foreign-origin (Table 6). These items could have originated from foreign commercial vessels travelling through the GBR area and/or from foreign commercial fishers operating in the region. Studies in Northern Australia, found glass bottles from Japan that were attributed to longline and tuna fisheries (Smith, 1992; Wace, 1995), with some of the rubber items recovered in this study, likely to be from Indonesian fishing vessels (Kiessling, 2003). The East Australian Current flows southward directly by the Swain Reefs (Smith et al., 1990; Smith, 1992) and most likely transports items from the South Pacific equatorial current down from the North-East and through the Torres Strait, as evidenced from a hard plastic cocktail stick originating from a Balinese resort and a water bottle from Vanuatu that was found in this study.

Of the nine surveyed sites, two were within marine national park (green) zones (Thomas and Bacchi Cays), with green zones being no-take areas for fisherman with only low-impact activities permitted within those waters, and the remainder were within preservation (pink) zones, with pink zones being no-go zones with only permitted activities allowed (GBRMPA, 2004). No statistical difference was found in the amount of debris on beaches or in nests on the cays on the basis of this zoning (Green, Pink) ($F_{[2,15]} = 3.265$, $p = 0.66$,). This indicates that marine park zoning is not effective for protecting against marine debris pollution, due to the buoyancy of debris items, the transference of debris by birds, and the subsequent ability of items to be readily transported in the marine environment.

Impacts of fishing within this ecologically important area is poorly understood (GBRMPA, 2011), but this study indicates that allowed fishing activities (and commercial shipping) within the area are the major sources of marine debris pollution (Fig. 6). To manage this problem, we recommend that further enforcement of maritime laws governing disposable of rubbish on-board ships and boats is needed, along with education and awareness initiatives of mariners to improve the obvious pollution that is entering the surveyed environments from commercial activities. As shipping traffic is set to increase in the GBR due to the expansion of the ports in Gladstone and Abbott Point, the amount of marine debris that will be entering the environment from commercial shipping (the major source identified on cays) could also potentially be increasing.

In June, the smallest sized beach debris items were recovered, and in August the heaviest. The heavy beach debris items recovered in August 2013, relate to the presence of large pieces of processed wood present in the survey. The considerably smaller size of objects found in June 2012, relates to the large number of debris fragments collected. June had the greatest number of fragments recovered than any other time period. The larger mean size of items recovered on the beaches compared to that found in nests; likely reflect the item type, with plastic bottles for instance being the second most common item in shoreline surveys (12.4%).

Beach debris surveys in the northern GBR also showed common items of plastic water and laundry bottles and glass alcohol beverage bottles (Haynes, 1997) like what was seen on Swain Reef beaches. The size and weight of recovered items reflect the nature of the debris items available in the local marine system at that point in time and subsequently retrieved. It is obvious that temporal changes are occurring in this system, and are likely to occur in other systems. This lends weight to the need for more comprehensive temporal debris surveys being needed if correlations between type, weight and amount are to be fully elucidated.

The amount and composition of materials are important considerations when determining the severity of impact that this marine debris may inflict upon the nest users (e.g. through entanglement) and the impact that occurs in the environment in general (e.g. smothering and damage of corals). Plastics, in particular hard plastic fragments, accounted for the majority of debris types both in nests and on beaches (Figs. 3 and 5). Hard plastic fragments have been recovered within other seabird nests (Hartwig et al., 2007; Lavers et al., 2013), and this is a common finding in many debris shoreline surveys within Australia (Frost and Cullen, 1997; Whiting, 1998; Cunningham and Wilson, 2003; Slavin et al., 2012; Smith and Markic, 2013) and around the world (Barnes et al., 2009; Costa et al., 2010).

Marine debris can pose a risk from both ingestion, as plastics break apart into progressively smaller fragments (Andrady, 2000; Costa et al., 2010), and from entanglement. Hence it is recognised as a Key Threatening Process by the Australian Federal Government under the Environmental Protection Biodiversity Conservation Act, 1999 (DEWHA, 2009). This study has shown that the remote, offshore location of the Swain Reefs has high levels of hard plastic and rope items in the nest material (Fig. 3) and seabirds in the southern GBR region are consuming plastics either primarily or secondarily (Verlis et al., 2013). However, no live seabirds, or seabird remains were found to be entangled with marine debris at the sites in the present study. This may be due to the size of rope material recovered from nest debris unlikely to be of a length that would readily entangle a chick or nesting bird (mean length 11.53 ± 7.73 cm). However, further studies are warranted to determine the risk of plastic ingestion in the Sulidae family in this region.

There have been population declines of *S. leucogaster* within the southern GBR in recent years (Congdon et al., 2007). The role of marine debris upon this decline is not known, but it is not expected to be great at this time due to limited evidence of ingestion, entanglement and use in nest material. As shipping traffic, the most significant source of marine debris in the region (Fig. 6), is expected to increase due to the expansion of ports along the Queensland coast (GPC, 2011; North Queensland Bulk Ports Corp Ltd, 2012) this will likely lead to a corresponding increase in marine debris pollution. Despite this, direct physiological impacts from ingestion are not expected in *S. leucogaster* due to their method of feeding, at least not from primary ingestion. However, studies have shown that transference of chemicals of concern, such as bisphenol A (BPA) are possible through the skin (Geens et al., 2011; Zalko et al., 2011). BPA and other chemical components of plastic are thought to cause a number of sexual development abnormalities, behavioural problems, and may impact upon the endocrine system leading to reproductive difficulties and cancers (vom Saal et al., 2007; Talsness et al., 2009). We postulate that nesting on top of certain plastic items could potentially lead to absorption of contaminants through the birds' skin. If marine debris levels increase within the area, this could lead to more marine debris items being used within nests and potentially exposing birds to harmful contaminants through a dermal exposure route. Marine debris monitoring is therefore necessary to identify changes and determine future impacts, especially as other stressors such as climate change will likely have a significant effect on this species (Nelson and Baird, 2002; Congdon, 2008).

5. Conclusion

Marine debris is present in the nest material of *S. leucogaster* and on the beaches of surveyed Swain Reef cays, in the Great Barrier Reef, Queensland. Similar trends in debris amounts were observed between nest and beach debris, but these were not significant and no correlations exist between debris colours, or with the majority of debris types that are available. Only filamentous type material of rope and rubber showed correlation to levels found in transects. It would appear that *S. leucogaster* is specifically selecting for particular debris items, therefore limiting the use of nest surveys as a replacement for beach surveys for marine debris assessments and thus utility as an indicator of pollution within an area. However, nest surveys aid the understanding of potential threats to this species and others. Further knowledge of where *S. leucogaster* obtains its debris would be beneficial in fully understanding any potential threat and minimising impacts. As shipping traffic increases, the amount of debris potentially entering the water from this source can only increase. Effective monitoring of marine debris levels in the area are needed to best manage this marine debris source, along with greater controls and enforcement of legislation that governs marine debris pollution.

Acknowledgements

A huge thank you to the Queensland Parks and Wildlife Service (Gladstone Branch) for their continued and invaluable assistance, with specific thanks to Andrew McDougall, Sascha Taylor, Andrew Congram, Damon Shearer, Jessie Moore and Dean Bosworth. Thank you also to the various funding agencies that have supported the lead author in her PhD research: Birds Queensland, Birdlife Australia Stuart Leslie Bird Research Award, Wildlife Preservation Society of QLD, and CQ University's Strategic Research Scholarship and CQ University's High Cost Student funding. Thank you to my associate supervisor Prof Owen Nevin for commenting on this manuscript, and to the independent reviewers for their helpful suggestions. Thank you Dr Wayne Boyd for your assistance putting my maps together and for all your helpful advice.

Animal ethics approval (Approval Number A11/09-276) was given for this research from CQUniversity, and was conducted under the following permits from the Queensland Government Department of Environment and Resource Management (WITK10514111 and NCPI03548412) and the Great Barrier Reef Marine Park Authority (QC11/045).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2014.07.060.

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