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Understanding the effects of marine debris on wildlife

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Executive Summary

Marine debris is a global environmental issue of increasing concern. Marine ecosystems worldwide are affected by human-made refuse, much of which is plastic. The potential impacts of waste mismanagement are broad and deep. Marine debris comes from both land and sea-based sources and can travel immense distances. It can pose a navigation hazard, smother coral reefs, transport invasive species and negatively affect tourism. It also injures and kills wildlife, can transport chemical contaminants and may pose a threat to human health.

Marine debris includes consumer items such as glass or plastic bottles, cans, bags, balloons, rubber, metal, fibreglass, cigarettes and other manufactured materials that end up in the ocean and along the coast. It also includes fishing gear such as line, ropes, hooks, buoys and other materials lost on or near land, or intentionally or unintentionally discarded at sea.

The Australian government has recognised marine debris as a key threatening process, because of the potential harm it poses to wildlife. In 2003, 'injury and fatality to vertebrate marine life caused by ingestion of, or entanglement in, harmful marine debris' was listed as a key threatening process under the *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act). A key threatening process is defined as one that 'threatens or may threaten the survival, abundance or evolutionary development of a native species or ecological community'. Under the EPBC Act, the Australian government implemented the Threat Abatement Plan (TAP) which focuses on strategic approaches to reduce impacts and injuries to marine fauna and ecological communities.

CSIRO's national marine debris project set out to address knowledge gaps identified in the TAP. The project engaged with young Australians while collecting robust, scientific data relevant to the global marine litter problem. To understand the patterns and sources of marine debris and assess the potential harm posed to Australia's marine fauna, our research sought to address four questions:

1) What are the sources, distribution, and ultimate fate of marine debris?

2) What is the exposure of marine wildlife to debris?

3) When wildlife are exposed to debris, what factors determine whether animals ingest or are entangled by debris?

4) What is the effect of ingestion or entanglement on marine wildlife populations?

To address the first question, we carried out a national coastal marine debris survey at sites approximately every 100 km along the Australian coastline. Parts of this work and related research activities were incorporated into TeachWild, a national three-year marine debris research and education program developed by Earthwatch Australia together with CSIRO and Founding Partner Shell. This is the world's largest scale, integrated, rigorous collection of marine debris data.

As part of TeachWild, we engaged with more than 5,500 students, teachers and Shell employees in one-day research and training projects that helped to build knowledge, skills and to change attitudes in issues relating to ocean health. We engaged with more than 150 teachers and Shell employees in immersive, single and multi-day field-based research expeditions led by CSIRO scientists. We also developed curriculum content using marine debris as a teaching tool for science and mathematics to meet the Australian national curriculum guidelines. CSIRO scientists inspired students to explore their world through science in ways that were meaningful and relevant, motivated teachers through innovative learning, and helped increase

capacity and networks for educators and citizen scientists, in Australia and beyond. Staff scientists engaged in live-links and video calls that enabled students and Shell employees to ask questions, promoting deeper community engagement. Through this project we connected schools, communities and industry with scientists on a globally important conservation issue through extensive communication, outreach, interviews, webinars, video calls and face-to-face activities. Overall, we reached more than one million Australians, helping to educate them about and increase their understanding of marine debris.

Another key area of deep engagement for CSIRO scientists took place through mentoring and advising the next generation of researchers. CSIRO scientists have been mentors to eight international students who participated in the marine debris project. This included postgraduate students and undergraduates seeking experience in research institutions outside of their home institution as part of their undergraduate or post-graduate education. CSIRO scientists also supervised four Australian honours and PhD students whose research is focused on marine debris issues.

We also developed a public, online, national marine debris database. Here, members of the public can contribute data they collect about local beach litter, following our simple methodology that is freely available online. We also engaged with existing initiatives such as Clean Up Australia, Tangaroa Blue and Surf Rider Foundation, as well as other remarkable NGOs and state based organizations that are cleaning up Australia's beaches. Together, all of these organisations and citizen scientists contribute to the improved understanding of the types, amounts and sources of debris that arrives on Australia's coastline.

Type, source and quantity

We found that within Australia, approximately three-quarters of the rubbish along the coast is plastic. Most is derived from nearby sources, with some likely to be from overseas. In coastal and offshore waters, most floating debris is plastic and the density of plastic ranges from a few thousand pieces of plastic per km^2 to more than 40,000 of pieces of plastic per km^2. Debris is more highly concentrated around major cities, suggesting local source point pollution.

Threats to marine fauna

As the quantity of debris increases in the marine environment, so does the likelihood of impacts from debris to marine fauna. Plastic production rates are intensifying, and the volume of refuse humans release into marine systems is growing at an exponential rate. Litter impacts wildlife directly through entanglement and ingestion and indirectly through chemical affects. We have documented rates of each of these mechanisms through dissections, literature reviews, chemical analyses and modelling.

Ingestion risk to marine turtles

We found that the ingestion of anthropogenic debris by marine turtles has increased since plastic production began in the 1950s. Smaller, oceanic-stage turtles are more likely to ingest debris than coastal foragers, and carnivorous species are less likely to ingest debris than herbivores or gelatinovores. Our findings indicate oceanic leatherback turtles and green turtles are at the greatest risk of both lethal and sub-lethal effects from ingested marine debris. Benthic phase turtles favour soft, clear plastic, supporting the hypothesis that marine turtles ingest debris because it resembles natural prey items such as jellyfish. Most items ingested by turtles are plastic and positively buoyant. We estimated the risk of ingestion across turtle populations at the global scale, and identified regions, such as the north-eastern Indian Ocean, where risks appear to be particularly high.

Ingestion risk to seabirds

We developed a new simple, minimally invasive way of quantifying plastics exposure in seabirds. It can be applied at individual, population and species levels and it has no observed detrimental impacts. We also carried out a global risk analysis of seabirds and marine debris ingestion for nearly 200 species and found that 43% of seabirds and 65% of individuals within a species have plastic in their gut. Our analyses predict that plastics ingestion in seabirds may reach 95% of all species by 2050, given the steady increase of plastics production. We identified high risk regions for seabird impacts, finding a global hotspot in the Tasman Sea between Australia, New Zealand, and the Southern Ocean. In a species-specific study involving TeachWild participants, we found that 67% of short-tailed shearwaters (*Puffinus tenuirostris*) ingested litter. Juvenile birds were more likely to ingest debris than adult birds, and young birds ate more pieces of debris than adults. Birds ate everything from balloons to glow sticks, industrial plastic pellets, rubber, foam and string.

Entanglement risk to turtles and pinnipeds

Entanglement poses a significant risk to marine fauna. Seabirds, turtles, whales, dolphins, dugongs, fish, crabs and crocodiles and numerous other species are killed and maimed through entanglement. We estimate that between 5,000 and 15,000 turtles have become ensnared by derelict fishing nets in the Gulf of Carpentaria region. For pinnipeds in Victoria, the majority of seal entanglements involved plastic twine or rope, and seals become entangled in green items more than in any other colour. In general, young seals are entangled in greater numbers than adults.

Prevention and Recommendations

The most effective way to reduce and mitigate the harmful effects of marine debris is to prevent it from entering the marine environment: cleaning up our oceans is a much less practical solution. To reduce litter inputs requires incorporating an improved understanding of debris at the local, regional and national levels. Improved waste management efforts, targeted education and outreach activities, and technology solutions are also required.

We investigated drivers for releases of debris into the ocean and the potential effectiveness of responses in three contexts. Using our coastal survey data and interviews with more than 40 coastal councils around Australia we investigated the likely drivers for marine debris and effectiveness of local policy responses. We found evidence for two main drivers, general consumer/user behaviour and illegal dumping of refuse. Similarly, we found that local council outreach, which presumably affects user behaviour, and anti-dumping campaigns were both effective in reducing the debris found in coastal areas. We examined the drivers for lost fishing gear and found that they were a mix of overcrowding on fishing grounds, poor crew training, and enforcement evasion. We also evaluated the effectiveness of incentive schemes, such as South Australia's container deposit scheme, in reducing waste lost into the environment. The scheme appears to be very successful, reducing the number of beverage containers, the dominant plastic item in the environment, by a factor of three.

By garnering the information needed to identify sources and hotspots of debris, we can better develop effective solutions to tackle marine debris. For example, fisheries management aimed at reducing losses of fishing gear at sea would undoubtedly result in less wildlife harmed by entanglement and educating the next generation will improve our world for the future. Working together, scientists, industry partners, coastal managers and citizen scientists can make significant strides to reduce marine debris impacts in coastal areas and in the marine environment.

Part I Introduction

Marine debris poses a global threat to biodiversity of immense proportion. For instance, more than six million tons of fishing gear alone is lost in the ocean each year (Derraik, 2002). Despite this staggering amount of marine waste, fishing gear forms only a small percentage of the total volume of debris in the ocean: it does not even make the list of the top 10 most common items found during coastal clean-up operations (Ocean Conservancy, 2014). The impacts of this threat on biodiversity are both broad and deep. Marine debris has been reported to have direct impacts on invertebrates, fish, amphibians, birds, reptiles, and mammals (Good et al., 2010) and new work has demonstrated chemical impacts and hepatic stress to wildlife from plastic ingestion (Rochman et al. 2013). Some plastics also contain oestrogen mimics (xenoestrogens) which have been shown to disrupt reproductive development in fish (Rochman et al. 2014, Vadja et al. 2008) and may be associated with other potential health risks (sensu Le et al. 2008). These impacts are known to be a significant threat to the persistence of several threatened or endangered marine species, and likely to be affecting many others. For example, up to 40,000 fur seals are killed each year by entanglement in debris (Derraik, 2002) and entanglement and ingestion are major causes of population decline for some marine mammals. Generally speaking, the known impacts from debris in the marine environment are increasing, and the volume of refuse humans release into marine systems is growing at an exponential rate.

In 2011, a three year partnership was entered into by Shell, Earthwatch Australia and CSIRO. Together, TeachWild was developed to highlight the global problem of marine debris and engage the community in investigating the effects of marine debris on Australian wildlife. The goal of CSIRO’s research in this project was to develop a national risk assessment for wildlife species that are affected by marine debris, addressing a topic (marine debris) that has been identified as a ‘key threatening process’ to wildlife in Australia. The project integrated field, modelling and biochemical marker approaches to understand the impact of marine debris on fauna at both national and international scales. One of the critically important (and rewarding!) aspects of this work was that we collaborated and engaged intensively with school groups to promote science education and learning through a timely and relevant topic that is part of the national science curriculum. Using marine debris as a learning tool, there are opportunities for strong linkages to maths, chemistry, physics, biology, oceanography and other learning topics in the national curriculum.

The CSIRO national marine debris project sought to answer four fundamental questions:

1) What are the sources, distribution, and ultimate fate of marine debris?

2) What is the exposure of marine wildlife to debris?

3) When wildlife are exposed to debris, what factors determine whether animals ingest or are entangled by debris?

4) What is the effect of ingestion or entanglement on marine wildlife populations?

The aspirational aims of the project were to:

- Carry out a nation-wide risk analysis completed for focal species across multiple taxa
- See increased science learning and uptake for individuals, schools, communities and industry across the country
- Provide information to inform policy decisions based upon sound science
- Develop a priority list of 'at risk' species based upon distribution, encounter and impact of debris
- Engage with industries contributing to the marine debris issue (with potential solution-based approaches to resolving the issue) and
- Contribute to a change in behaviour resulting in decreased marine debris deposition across the country due to science learning at local scales.

The partnership has been an overwhelming success and the research has generated an overwhelming amount of public interest. In the course of three years of the project we successfully addressed the four fundamental questions (above). The project also successfully achieved the aspirational goals. To address question one, we completed coastal debris surveys around the country. While the initial proposed plan focused on coastal surveys at a reduced number of regions (Figure 1), we were able to extend the coastal debris surveys to collect data along the coastline in every state and territory (Figure 2).

Results from the coastal debris surveys were analysed using a statistical model to infer how local conditions such as aspect, slope and substrate affect the density of debris. We also explored the role of explanatory variables such as population density and distance to cities to understand factors affecting debris distributions. The end result of these analyses is further discussed in 5.1 with implications from this work presented in Part VII and VIII.

Figure 1. Map depicting the initial proposed coastal debris survey sites. Note that Tasmania was not originally included in the plan and that portions of coastal Queensland, South Australia, Western Australia and the Northern Territory were also initially excluded.

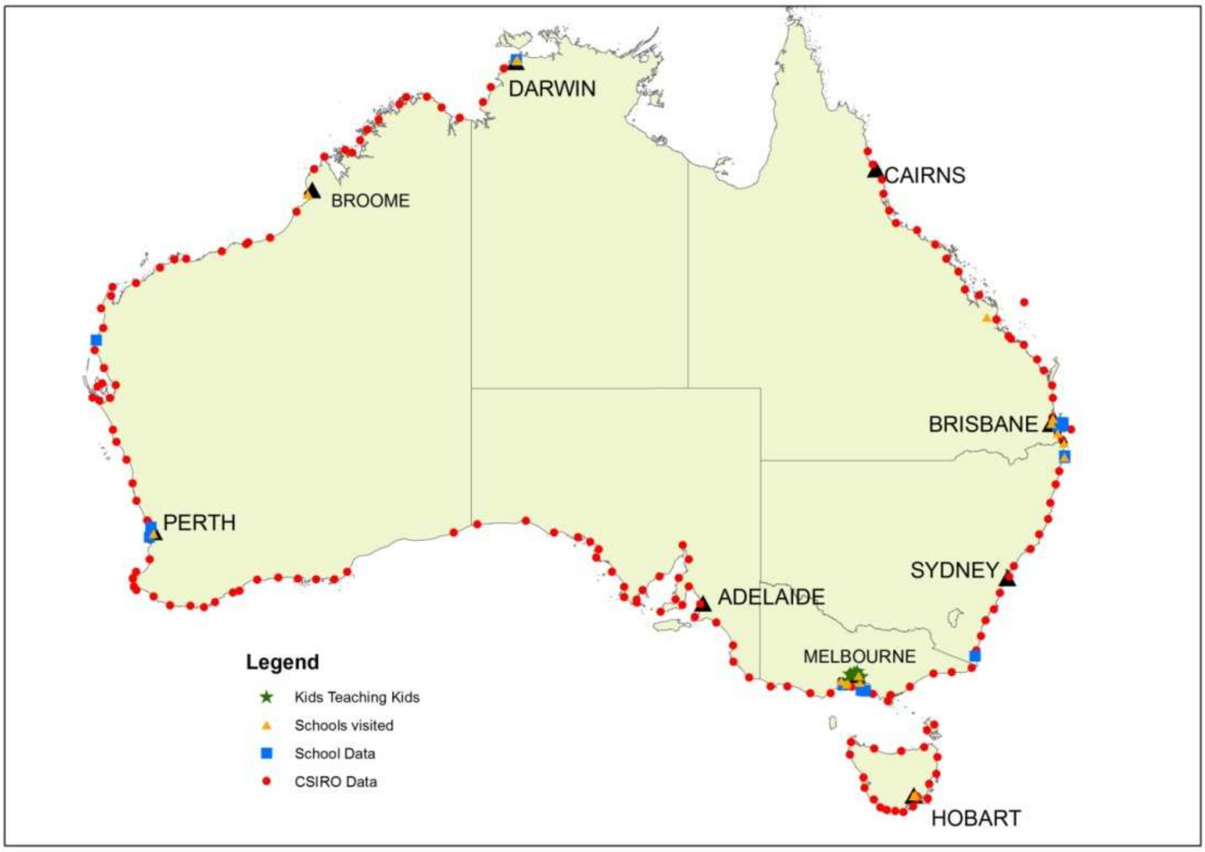

Figure 2. Map showing locations of coastal debris surveys around mainland Australia and the southern island state of Tasmania. This map includes locations of school debris surveys (blue squares), engagement with the 'Kids Teaching Kids' program (green stars) and CSIRO surveys (red circles).

To address question 2 'What is the exposure of marine wildlife to debris?' we overlaid the predicted distributions of debris in the ocean with known or predicted distributions of animals at sea. We validated these predictions for seabirds and turtle taxa based using published literature on plastic ingestion rates for these species, and supplemented the published knowledge with primary research. We were able to further investigate exposure and debris impacts on marine fauna using direct observations for focal taxa including seabirds (60+ species), turtles (3 of the 6 species that occur in Australian waters) and marine mammals (Australian fur seals).

Questions 3 and 4 were addressed through direct studies on focal taxa at breeding sites and at sea, depending on the taxa. To begin to estimate population level exposure of anthropogenic litter, we developed a new, minimally-invasive chemical assay method to assess plastics ingestion in seabirds (Section 6.1). We also developed the first robust estimation of the number of turtles likely to be killed through entanglement in derelict fishing gear, based upon a collaborative project with GhostNets Australia and Indigenous rangers (results presented in Section 6.2 and Appendices A and B).

In addition to developing new information which can be used to understand individual, population, and species level exposure to this anthropogenic threat, the project had a number of successful educational outcomes. Collaboration with Earthwatch Australia in developing school and citizen science engagement has greatly enhanced both the awareness of marine wildlife and the importance of this threat, along with enriching the educational experience of the students involved in the program. The research carried out by the CSIRO team with the support of TeachWild participants has been integrated to evaluate the risk marine debris poses to Australian wildlife. Findings from the work have also been provided to the Commonwealth government, to the science community, and to international organizations and to other interested parties. Overall, we met or exceeded each of our hopes and expectations and successfully built an inquiry-based learning environment for the next generation of leaders in Australia.

Finally, project staff were able to develop a number of outputs identifying opportunities and actions that could reduce the input of debris into the marine environment. We used the coastal survey data, supplemented with interviews with more than 40 coastal councils around the country to evaluate whether local policies had either a positive or negative effect on the rate of input of debris. We found that overall investment or facilities had little impact on debris. However, councils that had targeted part of their budget specifically to address debris were successful in reducing it. The most effective actions were those that involved waste facilities at coastal sites, but also prosecution of illegal dumping and outreach to the local populace. We also found a wide range of investments, facilities, and programs that did not have a demonstrable effect. However, councils where debris accumulated were generally aware of the issue, and generally had well target programs. One area of potential improvement would be addressing policies in councils that are sources of debris, as there was less evidence that these councils were aware or active with respect to this issue.

In addition to these research activities, project staff were involved in a wide range of scientific engagements and policy engagements. The research outputs are summarized throughout the relevant sections (particularly Parts V, VI and VII). There was significant interest at the local, national, international levels for a wide range of outputs from the project, ranging from professional advice to research tools and outputs. Project staff engaged with coastal councils, state governments, natural resources management bodies, the commonwealth government, foreign governments, NGOs involved in marine debris issues, and international policy and management bodies over the course of the project, in addition to Australian citizens who have a high level of interest in engaging scientists about this work. This interest in the research tools and outputs was unanticipated when the project was designed, and has added significant additional value to the planned outputs.

A further area of deep engagement for CSIRO scientists took place through mentoring and advising the next generation of scientists, managers and citizens. In the course of the national marine debris project, CSIRO scientists have served as supervisors and mentors for eight international students. These students included undergraduates seeking experience in research institutions outside of their home institution as part of their undergraduate or post-graduate training, as well as postgraduate students undertaking research on marine debris topics. CSIRO scientists also supervised four Australian honours and PhD students whose research is focused on marine debris issues. Students from Brazil, France, the Netherlands, Ecuador and Australia have been actively engaged in the marine debris project.

As the first phase of TeachWild comes to a close, a number of questions arise.

What will happen to the national marine debris data/database?

CSIRO will continue to host the national marine debris database for the time being. We are committed to ensuring that the citizen-science collected data are available for interested users. We hope that school groups and other volunteer citizen scientists will continue to contribute to the national database and will continue to collect information in a repeatable way. This will allow future analyses to look at changes in the amounts and types of rubbish deposited along the coastline at different seasons, in different years, and through time (particularly if or as different waste management policies are put into place). Repeated visits to the same sites and collecting consistent data (as happens at many sites around the country – look at the fantastic data being collected by a number of coastal council and volunteer groups in South Australia for some examples).

Can I still enter data in the database?

The answer is yes! The database will remain available for entering data and we will continue to try to answer questions as they arise. We are hopeful that citizen scientists will continue to clean up their local beaches/coastline and that information will continue to be shared. Perhaps future funding would allow increased direct engagement with schools in the future, as well as other follow on work from this project.

What is next for the marine debris project?

The next steps for the CSIRO national marine debris project are continuing to unfold. We continue to take a risk-based approach to understand marine debris impacts on wildlife, expanding on our recent work with seabirds and turtles (see publications provided in the Appendices). We are looking more deeply at population and species level impacts of plastic litter on several taxa and we are applying new methods we have recently developed to look at population level exposure to plastics in seabirds.

We are collaborating with colleagues around the world to improve the local, regional, and global understanding of marine litter inputs to the environment. We are particularly focused on evaluating waste management activities and policy effectiveness as part of our efforts to understand where, why, when and how litter is being lost in the supply chain and ending up along the coast. One of our key goals is to provide information that can help to reduce litter inputs into the environment prior to biodiversity impacts. We continue to try and work with managers, policy makers and other members of the public to provide meaningful information to help people, communities and industries make informed decisions.

Part II Year One in Review

2. A brief synopsis

Several key milestones were identified for the first year of the project in 2011-2012. These milestones included: 1) develop project curricula that fit into the national science curriculum; 2) develop a web based resource for public profile and community engagement; 3) identify potential schools with which to engage in the TeachWild program, particularly focusing on schools in important Shell-identified focal areas; 4) initiate data collection and input; 5) carry out 'Scientist for a Day' excursions with schools; 6) carry out seven-day research expeditions with teachers and, if possible, 7) carry out sea-based research expeditions with teachers.

We met each of the milestone objectives set out for year one (see progress report for year one, Appendix C). Not only did we contribute significantly to curriculum content that was developed for TeachWild, but we worked with teachers to develop specific lesson plans for targeted student groups, beyond the TeachWild curriculum, ensuring that these interactive inquiry-based lessons met the requirements of the national science curriculum.

We successfully developed an online data entry portal that utilised the Atlas of Living Australia's (ALA) Global Biodiversity Information Facility (GBIF). Through our CSIRO partnership with ALA, we were able to develop an open access and easily accessible national marine database that was available to volunteers, students, teachers, and citizen scientists. Here, data on beach surveys, incidental sightings and other site location information was initially collated. The data portal was established so that individuals and groups could input data and see summaries of information from across the country.

The important first step was to target schools with whom to engage. We achieved this through CSIRO's Scientist in Schools (SiS) networks by reaching out to schools that were involved in SiS. We also we developed and delivered the TeachWild "Scientist for a Day" program to more than 1,300 primary and secondary school aged students from around the country in the first year of the project. We also took teachers on intensive weeklong research expeditions in which they significantly contributed to our fundamental research aims for the national marine debris project (see Appendix C for details).

In year one of the project we carried out coastal debris surveys for a significant portion of the Australian coastline and we completed high-seas surveys to quantify marine debris offshore at more than 35 sites around the continent from a variety of research vessels.

Overall, the first year of the project was tremendously successful in meeting our stated targets. At the end of year one we were in a good position to meet or exceed our overall project aims.

Working out the coastal survey details (from Left to Right: Andy Donnelly, formerly of Earthwatch Australia and CSIRO's Chris Wilcox and Denise Hardesty).

Part III Year Two in Review

3. A brief synopsis

At two years into the project we were on target in achieving our goals and addressing our four focal questions. We achieved and exceeded all of the key milestones identified for year two. The milestones included: 1) completing the coastal debris surveys, 2) carrying out the Scientist for a Day program in Victoria, Western Australia and Northern Territory, 3) carrying out a sea-based research expedition off the Western Australian coast, 4) conducting four multiple (generally 3-7) day intensive teacher expeditions, 5) significantly improving the National Data Portal and 6) carrying out initial, exploratory analyses of data. We are also beginning to realise new opportunities and the impact of our work, as evidenced through engagement with a variety of stakeholders around the country and overseas.

By the end of year two we had surveyed more than 170 sites around mainland Australia and the island state of Tasmania, completing the national survey for coastal debris (Figure 2). Many of the sites were remote and accessed by either car, foot, float plane (Broome to Darwin and west/southwest Tasmania) or boat (Figure 3).

In year two of the project we carried out Scientist for a Day activities in Northern Territory, Victoria, Western Australia, Tasmania and Queensland. We spent a week in the Melbourne surrounds in August 2012, a week in Exmouth, Carnarvon and surrounding areas in November 2012, a week in the greater Perth region in February 2013 and a week near Gladstone at the end of May 2013 working with school groups as part of the TeachWild education and science engagement. CSIRO staff also visited three schools in Tasmania (April/May 2013). In total, by the end of year two we had engaged with more than 3,000 students since the inception of the TeachWild program, exceeding our goal for numbers of students with whom to engage in the TeachWild Scientist for a Day program.

As part of the at-sea surveys, we were able to bring three science educators on board the Australian National Research Vessel, the Southern Surveyor, where they participated in an intensive 10-day voyage and collected marine debris data from Perth to Darwin. The science expedition was led by one of the lead CSIRO scientists. The teachers from Western Australia, South Australia and the Northern Territory collected surface trawl data at more than 20 locations between Perth and Darwin. This was a critically important trip with respect to marine debris data collection from surface trawls as it encompassed the largest geographic distance for surveys around mainland Australia (see Section 5.2 for details).

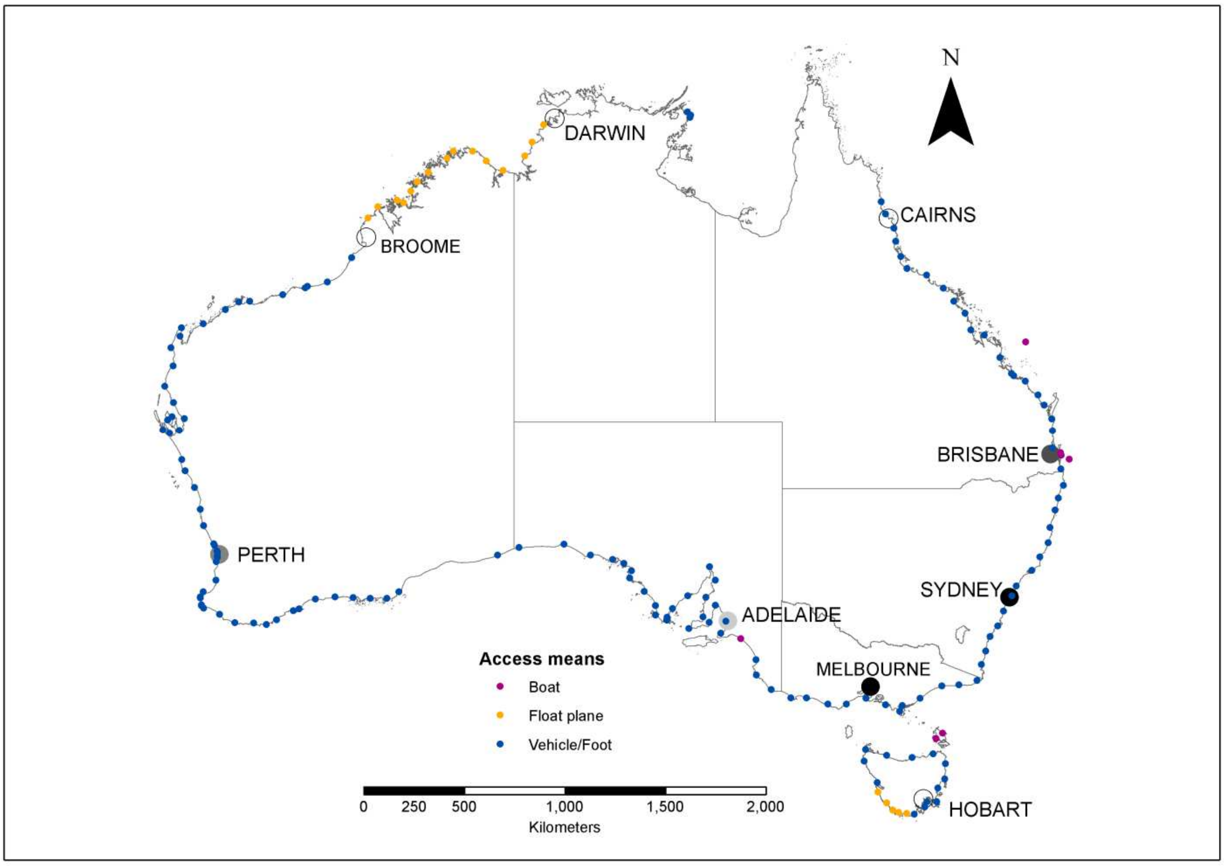

Figure 3. Map showing means of access to each CSIRO coastal debris survey site around mainland Australia and Tasmania.

In addition to the "Scientist for a Day" program, and the week long at-sea field excursion, we conducted four land based week long intensive field trips. These intensive trips included:

- North Stradbroke Island (24-30 September 2013) with 8 teachers/educators
- Phillip Island (11-14 October 2012) with 9 teachers/educators
- Phillip Island (9-13 April 2013) with 10 teachers/educators
- Rottnest Island (18-20 April 2013) with 8 Shell staff

Activities for the intensive expeditions were varied, but included coastal debris surveys, at-sea surface trawl surveys (and associated sorting of debris), necropsies of turtles and seabirds, spectrophotometry measurements to look at spectral characteristics of plastics, recording net and other material characteristics for items that have ensnared southern fur seals, and seabird colony surveys to look at debris levels in and near breeding colonies.

We exceeded the goals and obligations for intensive field expeditions in the second year of the TeachWild program, and with agreement of all partners, we were able to move some of the deliverables for the final year (year 3) forward to the second year. The intensive expeditions were very successful and contributed to important data collection needs by CSIRO staff and research partners. Importantly, these intensive excursions provided an inspiring and educational professional development opportunity for science teachers and Shell employees, as evidenced through the feedback provided by participants. Learnings were taken back to the classroom, the workplace and the community. For further detail of year 2 activities refer to the Year 2 Progress Report in Appendix D.

The data portal was established in the first year of the project so that individuals and groups could input data and see summaries of information from across the country. However, in the course of using the database, a number of issues arose with the Atlas of Living Australia data portal site. While it was not within our area of the project to do so, CSIRO staff revised the web portal data entry site (see Appendices E and F) to make the site more user friendly and intuitive. We also moved the database to a CSIRO server, maintaining full functionality through the www.TeachWild.org.au web link front end. The feedback from Earthwatch staff, CSIRO staff and TeachWild participants regarding the changes was overwhelmingly positive. While this additional work was outside the scope of the project commitment, we felt it critical to maintain and improve the front end accessibility and to have a user-friendly interface.

Using data collected on the CSIRO national coastal debris survey we estimated that there are more than 115 million bits of rubbish on Australia's coastline (including Tasmania but excluding the >8500 outlying islands). This is based upon a coastline estimate of 35,877 km in length and takes into account that we found an average of ca. 6.4 items of anthropogenic debris on each 2m wide transect we carried out. Given that the population of Australia is estimated at 22.32 million people (population clock: http://www.abs.gov .au/ausstats/abs@.nsf/0/1647509ef7e25faaca 2568a900154b63), this averages approximately six pieces of debris for every person in the country.

Our analyses show that about 75% of all waste is plastic, 24% is glass and metal, and 1% is cloth. Of the plastics, it looks like 2% of debris is discarded monofilament (and hence is associated with recreational fishing). Further information on the initial analysis can be found in the year two milestone report, (Appendix D).

During the second year of the project we also had intensive engagement with various interested parties from local, state and federal government and non-governmental organisations, and we had excellent interest in our work in the international arena as well (further description of our year 2 engagement can be found in the year two milestone report, Appendix D).

Teachwild participants engaged in a range of activities including coastal debris surveys and necropsies during intensive multi-day expeditions.

Part IV Year Three in Review

4. A brief synopsis

The final milestones for the project focused on a) ensuring completion of data collection and data quality assurance checks; 2) meeting project targets with respect to engagement and outreach; 3) analyses of data to address the four research questions initially identified in the project, and 4) dissemination of information through media, reports, international engagement and other means.

We met each of the objectives and milestones we set out to achieve in the final year of the project. Year three of the national marine debris project saw a shift in focus towards data analysis, and dissemination of information in multiple ways. First, we have been publishing results from this project in the scientific literature. Second, we have continued to engage with the general public through responding to media queries about the project. We have engaged in live web chat interactions with school groups where students can directly ask questions of CSIRO scientists, given public seminars to share information about TeachWild activities, and served as expert advisors on marine debris topics both domestically and overseas. We have also been active leaders in the international marine debris community through invited participation in working groups, international conferences and invited symposia.

In the final year of the project, we carried out analyses of the complete coastal dataset collected by CSIRO as well as the data collected by citizen scientists who engaged with the project and collected coastal debris survey data (Sections 5.2 and 8.3 respectively). To evaluate the effectiveness of citizen science collected data, we compared data from CSIRO scientists with the data collected by participants in the TeachWild program (See 8.3 for further detail).

A large proportion of the surface trawl data collected at sea has been included in the publication of two papers in the international peer-reviewed literature. These papers, led by PhD student Julia Reisser, focused on the characteristics, concentrations and pathways of plastic pollution in and around Australian waters; and described the pelagic communities of microorganisms and invertebrates found on millimeter sized plastics sampled at in Australian waters on research voyages (Appendices G and H, respectively). CSIRO scientists also contributed to a newly published article aimed to establish global research priorities for the management and mitigation of plastic pollution on marine fauna (Vegter et al. 2014, Appendix I) and three papers focusing on marine debris and sea turtles, led by PhD student Qamar Schuyler. The first of these publications analysed debris selectivity by two species of marine turtles and compared the types of debris ingested by turtles to the debris present in the marine environment (Schuyler et al. 2012, Appendix J). The next publication was a global analysis of anthropogenic litter ingestion by marine turtles which reviewed literature published since 1985 and asked whether the prevalence of litter ingestion has changed through time as well as which species are more likely to ingest debris and what times of debris are most commonly ingested (Schuyler et al. 2013, Appendix K). The third paper created a model sea turtle visual system and used it to analyse the colour, contrast and luminance of debris items ingested by turtles, asking whether turtles ingest plastic opportunistically or because it resembles their prey (Schuyler et al. 2014, Appendix L).

Another major focus for project staff in the final year was addressing the risk marine debris poses to seabirds. The at-sea ranges of one hundred and eighty-eight seabird species around the globe were combined with modelled distributions of marine debris at the global scale to analyse the threat marine debris poses to the world's seabirds. These analyses have resulted in a number of journal papers and articles (in process) which comprise additional sections of this report.

In total, we have now engaged over 5,700 school aged kids and 160 teachers/corporate citizens in the "Scientist for a Day" and week-long intensive field expeditions. The media interest and communications outreach of the project has far exceeded expectations. We estimate that we have reached at least 10% of the total population of Australia through television, print, radio and electronic media coverage of the marine debris research carried out by CSIRO.

Field equipment used for coastal debris surveys: clipboard, measuring tape, GPS, compass, safety gloves, bag for litter collection, size chart, etc.

Some of our major research findings include:

- The majority of coastal debris in Australia is from Australian sources, not the high seas. Debris is concentrated near urban centres.

- Consumer behaviour and illegal dumping are primary causes of marine debris in Australia.

- Debris has significant impacts on Australian wildlife. Derelict fishing gear has entangled between 5,000 and 15,000 turtles within the northern Gulf of Carpentaria region alone.

- Globally, approximately one third of marine turtles have likely ingested debris. Turtles ingest plastic debris that resembles their prey.

- Around the world, nearly half of all seabird species are likely to ingest debris. The greatest number of seabirds affected globally is in the Tasman Sea, southeast of Australia.

- Policies can reduce the problem. Incentives are effective: South Australia, which has a container deposit scheme, has one third as many beverage containers in its waste. Local initiatives are also effective; prosecution of dumping significantly reduces marine debris along a council's coastline.

- Individuals can make a difference! Inspiring and educating the next generation is an excellent means of changing human behaviour. For instance, students participating in the program instituted a voluntary deposit scheme for candy wrappers in the school canteen, resulting in a major littering reduction in their school. These inspiring students and teachers at Emerald Primary School in Victoria are demonstrating simple ways individuals and schools can make a difference (you can read more about their program at http://TeachWild.org.au/ what-is-your-school-doing; http://studentplanetsavers; global2.vic.edu.au/2013/03/05/emerald-primary-container-deposit-scheme/).

- Citizen scientist participants can make major contributions to understanding natural systems and environmental problems, gathering high quality data in a variety of contexts.

Citizen scientist participants at Rottnest Island. Teachwild activities during this intensive multi-day excursion included coastal debris surveys, debris identification and sorting, seabird colony surveys, necropsies, and other activities.

5. Overview

Marine debris is recognized as an increasingly important global issue that affects the environment and economics and can negatively impact wildlife, tourism, fishing and navigation. It has remained difficult to develop a synoptic description of the overall threat of marine debris to ecological systems. This uncertainty is due to three causes: an absence of a national map of the distribution of marine debris, comparative information on exposure of wildlife across taxa and regions, and a clear understanding of the effects of exposure to debris. This project provided an initial step in addressing this uncertainty by identifying available information on debris and developing preliminary analysis of its sources and distribution at a national scale.

5.1 Estimating quantities and sources of marine debris at a continental scale

The loss of plastic into the environment, and the oceans in particular, has effects on economic productivity, aesthetic values, and appears to be driving biodiversity losses. Plastic comes in a wide variety of shapes and sizes, from derelict industrial fishing nets that are kilometers long and can weight many tons, to beverage containers and other consumer items, to small fragments used as abrasives and from breakdown of larger items. Larger items represent a hazard to shipping, leading to fouling of propellers and water intakes. Estimates from a large study in Scotland suggest fouling rates of one event per vessel per year, and together with snagging and fouling of gear and contamination of catches, this costs the industry approximately 5% of its total revenue (Mouat et al. 2010). Beaches, harbors, and other sites that generate revenues from users are also significantly impacted. Removal of marine litter costs harbors in the UK €2.4 million each year, with substantially higher costs in other parts of Europe (Mouat et al. 2010). Coastal tourism is also significantly affected, and municipalities incur substantial costs to reduce these impacts. Municipalities in the Belgium, the Netherlands, and the UK spend between €10 and 20 million per year to reduce coastal debris (Mouat et al. 2010). A single period of heavy rainfall in South Korea during July 2011 increased coastal debris, resulting in a 63% decrease in tourism and lost revenue of $33 million (Jang et al. 2014). Similar results were observed in a US study of debris on the US east coast in 1987-1988, with economic losses estimated between $379 and $1,598 million (Ofiara and Brown 1999). In fact, there appears to be a direct relationship between marine debris and stated aesthetic values, with a study in South Africa suggesting that residents and tourists would not visit a beach with more than two litter items per meter (Ryan 1990).

Marine litter also appears to have major impacts on biodiversity. Entanglement in fishing gear has been implicated as a major threat to a number of marine vertebrates. For instance, it is estimated that between 5,000 and 15,000 turtles are entangled each year by derelict fishing gear washing ashore in northern Australia alone (Wilcox et al. 2014). Ingestion of plastics is also an issue, with over 600 species having been reported as ingesting plastic (Thompson et al. 2011). Ingestion appears to be having impacts, both directly through physical effects on animals and indirectly via concentration and transport of toxins into the digestive tract of marine species (Day et al. 1985, Tanaka et al. 2013, Rochman et al. 2013, Talsness et al 2009, Teuten et al. 2009).

While it is clear that plastic debris is an important and growing source of pollution, with a myriad of impacts, understanding its sources and trends remains difficult. Collection of data from surface sampling at sea remains limited, largely due to cost. Recent published work which estimated floating plastic debris at the global scale was based on plastics concentrations data from only 442 sites (Cozar et al. 2014): most sea surface data are sparse or geographically limited. In contrast, there are extensive coastal debris samples, largely from volunteer cleanup programs such as those run by Ocean Conservancy, project AWARE, or the Marine Conservation Society. While these projects sometimes have significant spatial and temporal coverage, they are typically focused on removal of debris and thus do not follow sampling designs that lend themselves to analysis. There have been some efforts to develop standardized coastal surveys, linked to environmental policy such as the beach litter surveys conducted for the Convention for the Protection of the Marine Environment North-East Atlantic (OSPAR 2010, Galgani et al. 2013). However, statistical analyses have been designed post hoc to evaluate trends and sources, which has been a major shortcoming in some programs (e.g. Schultz et al. 2013, Sheavly 2010). As governments make policies to address plastic pollution, such as the European Union Marine Strategy Framework Directive, large scale monitoring programs are emerging in Europe, Australia, the United States and elsewhere (Galgani et al. 2013, Department of Environment, Water, Heritage and the Arts 2009, Sheavly 2007). However, there is significant discussion over the design, cost, and utility of these monitoring programs (Galgani et al. 2013, Sheavly 2010).

Australia has developed a national policy to address marine debris, and in particular its impact on marine wildlife. While there were sporadic data on the distribution, abundance, and type of debris along the coastline, and to a lesser extent offshore, there was no large scale systematic dataset. In response to this need, we developed a large-scale statistically robust coastal survey of debris. Using this dataset we control for sampling bias to estimate the distribution of debris along the entire coastline of the Australian continent. Using this standardized dataset we investigate the factors influencing the contribution of terrestrial sources to coastal debris. Finally, we estimate the relative distribution of debris in the coastal marine environment, and compare that with a set of continental scale surveys at sea.

Methods

Spatial component (sites and site selection)

We selected an initial survey site in the northeastern part of the continent at random and then selected sites approximately every 100km in a clockwise fashion around Australia, using a smoothed version of the coastline capturing the major features. Due to accessibility, in some areas we were not always able to target selected sites exactly. In those instances we used the nearest site to which we could gain access. In the central region of the southern coast we were unable to carry out five surveys due to lack of access (Figure 3). Isolation varied widely among sites, with most accessible by vehicle or on foot, and the remaining sites (west coast of Tasmania, northwest coast of mainland Australia) accessed by floatplane (Figure 3). We completed a total of 575 transects at 122 coastal sites around Australia though we have a gap in the northernmost part of the continent (Figure 1). Surveys took place between October 2011 and May 2013.

Surveys were conducted according to a stratified random sampling approach. Upon accessing the coast, we randomly selected the direction from the access point (right or left) to where transects were conducted (except where there was insufficient coastline from the point of access. To avoid bias (e.g. the effect of higher traffic at the access point), wherever possible, we walked a minimum of 50 meters from the access point to the location where we would conduct the first transect. Each subsequent transect was a minimum of 50 meters distant from the previous transects. Transects were distributed evenly across the range of substrate types (beach, cobble, boulder, bare rock, mud, mangrove) at each site. At each site we carried out a minimum of three transects. If debris was not found in these first three transects we continued to add transects stratified across the habitat types until either debris was found or we reached the maximum of 6 transects. Transects are 2 meters in width, with one observer each reporting all items observed for a one meter wide swath. The two observers walk along a meter tape reporting all items observed from upright standing position, as per Year One report (Appendix C).

Data collected (covariates and nuisance variables)

At each site we recorded the GPS location of where we accessed the site (access point), date, observer, weather conditions, wind speed and direction, human visitors visible on the beach and time of day. For each transect we recorded the time it took to carry out each transect, the transect start and end location and the length of transect. To account for factors that may affect debris deposition and retention, we also recorded the exposure or shape, aspect, substrate and colour, gradient and backshore type at each transect. To consider the potential contribution of terrestrial inputs we also determined the population within 5km, 25 km, and 50 km of each site, and the distance from the access point to the nearest road. Each of the two observers was responsible for discerning and identifying items encountered within one meter wide of the transect tape that ran from the water line to two meters into the backshore vegetation. Hence, all transects were 2 meters in width. Only items detectable from the surface were recorded, and observers stood at height to look for debris. For a subset of data (items for each of ten equal distance length classes along the transect line) size was recorded based upon doubling size classes from <1cm^2, 2cm^2, 4 cm^2, 8cm^2, 16cm^2 and >16cm^2.

Statistical analyses

All analyses were implemented using R (version 2.15.3, 2012). We fit a generalized additive model (GAM in the mgcv package, Wood 2008) with a Poisson error to the coastal survey data using a continuous spatial surface for the mainland, and a separate continuous spatial surface for the coast of Tasmania with the site location as the spatial term. We implemented these continuous surfaces by using a cyclic spline fitted to the angle of rotation about the geographic center of the land mass. The transect length was treated as an offset term, given that we would expect the debris count on each transect to scale at a 1:1 ratio as transect length increases for a constant debris density. We separated covariates into two main categories:

1) sampling effects that related to transect characteristics (shape, substrate, gradient, and backshore type);
2) source effects related to potential land based sources of debris nearby (population within 5 km, 20 km, 50 km and distance from access point to nearest road).

We used a generalized additive model as described above, including separate spatial terms for mainland Australia and Tasmania. We incorporated sampling effects, but did not include the effects related to terrestrial sources as we wanted those to remain in the spatial component of the model. Thus, this spatial component gives a measure of the relative terrestrial inputs based on the ratio of glass to plastic, corrected for sampling bias due to site characteristics.

Results

We surveyed a total of 582 transects across 172 coastal sites, with an average of 3.3 transects per site (Figure 3). The sites covered a wide range of substrate types, including boulders (21 transects), gravel/pebble (10 transects), mud (8 transects), rock slab (81 transects), and sand (443 transects). Transects varied in length from 2 meters to 1.86 kilometers, with a median length of 70 meters. Total counts of items ranged from 0 to 360, with a median value of 2, yielding an average density of 0.147 items per square meter. Approximately three quarters of the nearly 5,000 pieces of litter found on survey transects were plastic 17% were glass, 6% were paper, 2% wood. Some identifiable items, such as cigarette butts (2%) and fishing line (1%), were present, but by far the majority of items were plastic fragments of indeterminate origin.

Based on the raw data, the greatest concentrations of debris occurred along the southwestern margin of the continent, with significant variation among other sites (Figure 4).

A model with just a spatial term explained 37.6% of the variation in the data. We found that the shape, substrate, gradient, and backshore type were all important in determining the amount of debris at a site and increased the deviance explained to 47.6% (Figure 5). Sites with convex shapes, such as headlands, had significantly less debris than linear or concave areas of coastline. Debris counts also differed among substrate types, with boulders having the highest counts, followed by sand, rock slabs, gravel, and mud in that order. Sites with either grass, shrubs, or seawalls behind them tended to have higher counts, while forested sites had lower ones.

The spatial term in the standardized model, i.e. correcting for site characteristics that affect sampling, shows that there are two regions that have particularly high concentrations of debris, the southwestern coast of the mainland, the central western coast of Tasmania (Figure 5). They are followed by a somewhat lower, but still elevated region of debris that runs from Brisbane south to Melbourne. By contrast, the north-western, northern, and north-eastern coasts of mainland Australia and the north and east coasts of Tasmania have relatively low debris concentrations.

Using this standardized model as a base, we explored a set of hypotheses related to terrestrial inputs of debris. We found that a model incorporating main effects for the local population (within 5 km of the survey site), regional population (within 50 km of the survey site), distance to the nearest road, and a regional population by road interaction term was the best performing model based on AIC scores, and captured 50.6% of the variation in the data. We found that debris along the coastline increased with the regional population, but decreased with the population living near the site. We also found that there was a significant interaction between the regional population and the distance to a road, indicating that isolated locations in populated regions tended to have higher debris counts.

The spatial terms in the full model, i.e. corrected for sampling bias and direct terrestrial inputs, give a relatively similar picture of the debris along the coastline. Overall, the southwest of the mainland and the west coast of Tasmania still have the highest values. However, the southeast coast of the mainland now has a slightly reduced spatial component, as the terrestrial inputs in this region have accounted for some of the pattern that was previously accounted for by the spatial terms. Overall the spatial term is still fairly faithful to the nominal data, but in regions with major populations such as that between Brisbane and Melbourne the full model and the standardized model differ.

We compared the spatial pattern in the full model, which represents a mix of the marine component of debris arriving at a site and other unknown sources of variation, with the ratio of glass to hard plastic found at a site. The spatial model of the glass ratio, including terms to correct for sampling bias such as substrate type, explained 62% of the deviance in the data. Comparing areas where the glass ratio is particularly low relative to its mean, and the spatial component from the full model is relatively high in comparison with its mean, we found supporting evidence for three areas of high marine input of debris, in the region between Brisbane and Melbourne, the south-western portion of the continent to the south of Perth, and on the western coast of Tasmania. We also found that the region between Melbourne and Adelaide, which has relatively high debris counts based on the full model, appears to have largely terrestrial sources when we compare the spatial component of the full model and the predicted glass ratio (not shown). A similar pattern occurs for the Tasmanian portion of the data, with marine sources indicated for sites on the west coast and terrestrial sources indicated on the north and east coast.

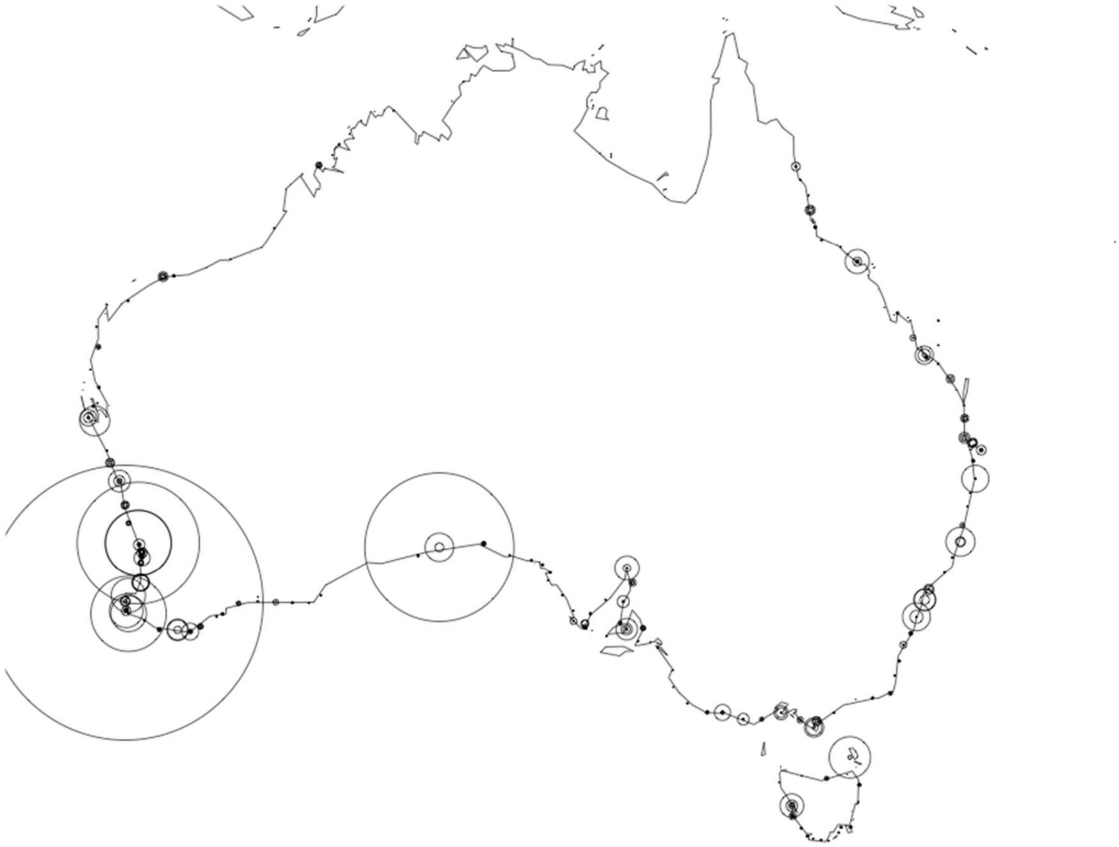

Figure 4. Debris density along the coastline with circle sizes proportionate to debris density for each transect at a site. Map is uncorrected for population, beach type, substrate, or other covariates.

5.2 At-sea surveys for marine microplastics and other anthropogenic litter

Anthropogenic litter occurs in all marine environments from coastlines to the open ocean and the sea surface to the sea floor. It is distributed according to its sources, transport by ocean currents, and the type of plastic material, which determines whether or not it is buoyant in seawater. The best-measured reservoir of plastic debris is that floating at the sea surface either as “macroplastics” measured by visual surveys or “microplastics” (smaller than 5 mm in size) measured using surface-towed plankton nets. We conducted surface trawls around the coast of Australia, between Fiji and Australia and between New Zealand and Australia (Figure 6) to estimate the density of plastics. At each survey site, nets were towed for 15 minutes at 3 knots three times. More than 230 trawls were carried out in total. This allowed us to develop a national map of sea surface plastic concentrations (Figure 7). For details regarding the findings from this work, see Reisser et al. 2013, 2014; Appendices G and H).

Figure 5. Relative density of anthropogenic debris along the Australian coast. Predicted densities are scaled with respect to the location with the highest density of debris (warmer colours [red] depicting relatively high densities of debris, corrected for shape, substrate, gradient and backshore sampling error terms). Black dots show actual coastal debris sampling sites. The map includes the combined terrestrial and marine anthropogenic debris inputs.

In general, we found that coastal and offshore distributions of debris have both concurrence and some notable differences. Our coastal surveys identified the southeast coast of the mainland and the west coast of Tasmania as having particularly high concentrations of debris (Figures 6, 7). These patterns are also reflected in the offshore data. It is notable that the higher concentrations in the offshore data extend further along the southeast coast, and to the south coast of the mainland, in comparison with the coastal surveys.

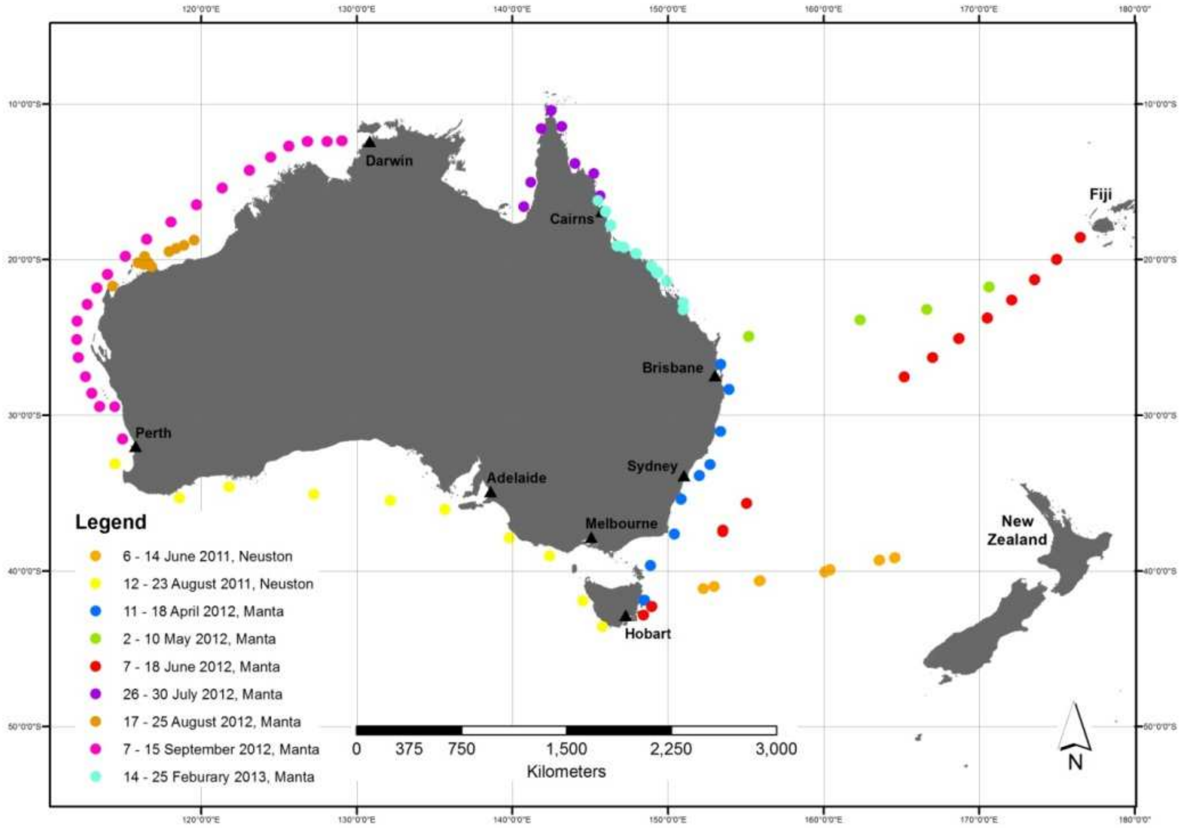

Figure 6. Map showing locations of surface trawls around the coast of Australia, between Fiji and Australia and between New Zealand and Australia.

However, there are some locations where the data differ. Coastal surveys along the southwest of the continent found high concentrations of debris, while these were not reflected in offshore samples (Figures 6, 7). This difference is likely driven by differences in winds and currents along the Western Australian coastline. There are strong onshore winds in Western Australia, which could potentially be driving strong coastal deposition, leading to a differing pattern between offshore and onshore densities with respect to other regions. A second notably different area between the coastal and offshore surveys is in northern Queensland. This is likely explained by a substantial flooding event just prior to the offshore sampling effort. This flooding transported large amounts of debris from land, leading to very elevated levels of debris in samples inside the Great Barrier Reef. A third point of difference is in the northwestern portion of the mainland coast. There was an area of elevated debris offshore in this region during two separate surveys. The driving force behind this difference is unclear, although it could be due to a local circulation pattern in the Leeuwin Current, which passes down the west coast of the continent, and generates some localized eddies which could concentrate floating debris.

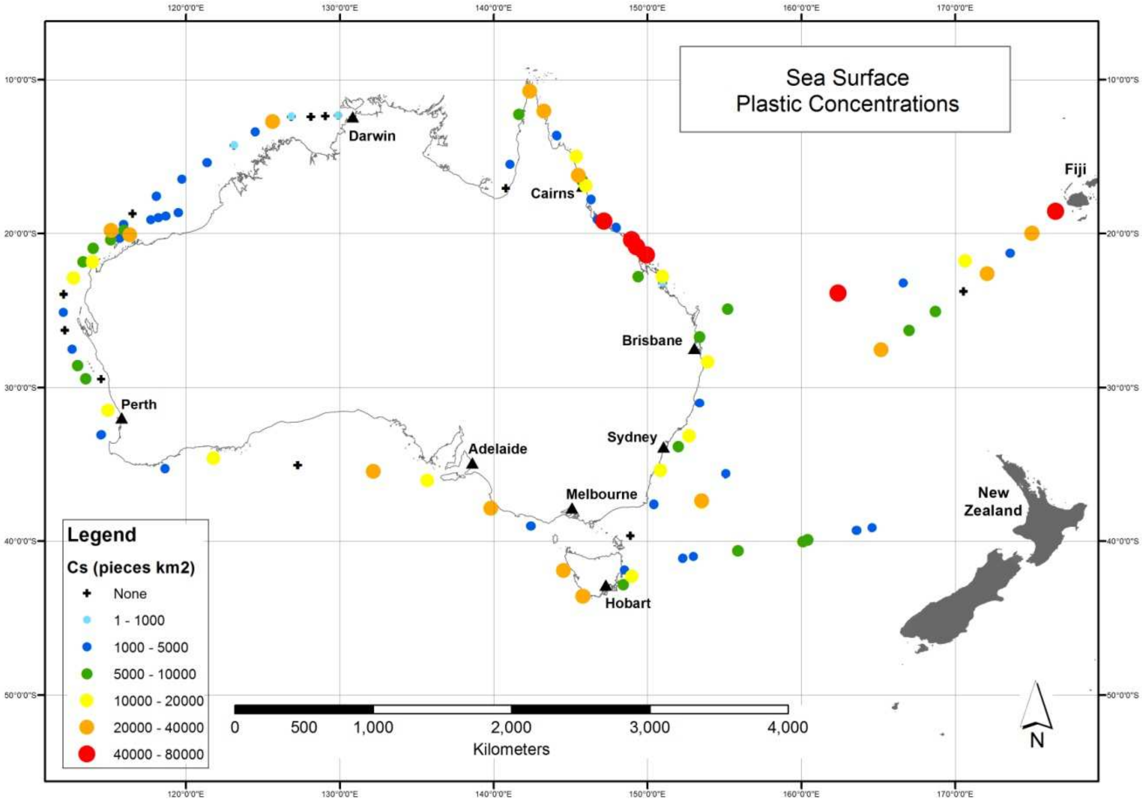

Figure 7. Map showing locations of sea surface plastic concentrations, corrected following methods in Reisser et al. 2013).

Other sources of marine debris include lost, abandoned or discarded fishing gear; estimates are around 640,000 tons per annum. These ‘ghostnets’ can fish unattended for decades, killing huge numbers of threatened or commercially valuable species. Large numbers of ghost nets wash up in northern

Australia, reaching densities as high as, or higher than those reported anywhere else in the world. These abandoned nets and other fishing gear are of substantial concern. Understanding the magnitude of the impact and the areas where the impact is the greatest is critical for both addressing the issue of abandoned fishing gear and for prioritizing conservation actions to address the species and populations most at risk. For further detail see published results from this work, included as Appendices A and B.

Part VI Threat to Wildlife

6. Overview

Marine debris has been identified as a key threatening process that may impact numerous wildlife species. As the quantity of debris increases in the marine environment, so increases the likelihood of impacts from debris in the marine environment. Plastic production rates are intensifying, and the volume of refuse humans release into marine systems is growing at an exponential rate. Understanding the impact of marine debris on threatened species is particularly of concern for seabirds, turtles, and other marine fauna that may ingest or become entangled. Impacts of marine debris can include reduced mobility, increased energetic costs, physical disruption of feeding, introduction of contaminants from the plastic itself or chemicals adsorbed to it.

Ingestion of marine debris is of major concern for both Australian seabird and turtle species. For seabirds, chicks appear to be at greater risk of mortality by marine debris ingestion than adults because of their high rates of ingestion and low frequency of regurgitated casting of indigestible material. When the plastics are regurgitated to chicks by parents during feeding, the physical impact and internal ulceration are likely to lower survival. In addition, the chick receives less food, lowering its nutrient intake, reducing its fat stores and increasing its chances of starvation. The rate of this source of mortality remains completely unknown for Australian seabird species. Ingestion of marine debris can have lethal and sub-lethal effects on sea turtles. Although researchers have reported on ingestion of anthropogenic debris by marine turtles and implied incidences of debris ingestion have increased over time, there has not been a global synthesis of the phenomenon since 1985. It seems life history stage is the best predictor of debris ingestion by sea turtles, based upon a recent global review of debris ingestion (see Schuyler et al. 2013, Appendix K for detail).

In addition to impacts from ingestion, wildlife can be maimed, injured or killed after becoming entangled in marine debris. Such entanglement can constrict growth and circulation, leading to asphyxiation. Entanglement may also increase the animals drag coefficient through the water, increasing energetic costs which can reduce body condition, reproduction, or survival. In extreme cases entanglement can cause the animal to die, either due to drowning, or due to its reduced ability to catch prey or avoid predators.

Other secondary impacts of marine debris ingestion to wildlife result from the potential transfer of chemical compounds from plastics to wildlife. This is a growing area of research, and the transfer of chemical pollutants from plastics to wildlife has recently been demonstrated in fish (Rochman et al. 2013).

Microplastics have the potential to affect organisms ranging from plankton and small fish to megafauna. The full implications of health impacts on wildlife due to chemical transfer from plastics are unknown impact but may include endocrine disruption, cell necrosis, tumour development, liver stress and mortality (Rochman et al. 2013).

To address the potential impacts of marine litter on Australian wildlife, we investigated the likelihood of marine debris impacts on seabird species that breed on and around Australia's coastal regions. We looked at ingestion and entanglement risks to sea turtles and entanglement dangers to the Australian fur seal.

The following three sections describe taxa-specific work in progress or published works. Those included as appendices to this report are noted therein.

6.1 Seabirds and debris ingestion

To better understand the extent of potential impacts to seabirds due to ingestion of plastic litter, we carried out a risk analysis for the impact of plastic ingestion on seabirds by modeling exposure to debris for 188 seabird species at the global scale. We adjusted the model using published data on plastic ingestion by seabirds. Globally, forty-three percent of seabirds and 65% of individuals within a species have plastic in their gut. The highest expected impact occurs at the Southern Ocean boundary in the Tasman Sea between Australia and New Zealand. This contrasts with previous work on human pressures on biodiversity, which suggested that the southern ocean boundary is a region of low impact in comparison with other areas of the globe. We predict plastics ingestion is increasing in seabirds and will reach 95% of all species by 2050. (Please contact the authors of this report for further detail).

Few studies have compared ingestion rates between adults and juveniles of the same species. We investigated marine debris ingestion by short-tailed shearwaters (*Puffinus tenuirostris*) obtained through two stranding events on North Stradbroke Island, Australia in 2010 ($n = 102$; adult) and 2012 ($n = 27$; juveniles). Over 67% of birds ingested anthropogenic debris: 399 pieces of debris were identified. Juvenile birds were more likely to ingest debris than were adult birds and juveniles ingested significantly more pieces of debris than did adults. We also found evidence that *P. tenuirostris* actively selects for hard plastic, rubber and balloons. For further information please see Appendix M of this report (Acampora et al. 2014).

The global use of plastics is continuing to rise and there is increasing interest in understanding the prevalence and risk associated with exposure of wildlife to plastics, particularly in the marine environment.

In order to facilitate an assessment of ingestion of plastics in seabird populations we developed a minimally invasive tool that allows for detection of exposure to plastics. Using a simple technique in which we can sample live, apparently healthy members of a population, we successfully tested for the presence of three common plasticisers; dimethyl, dibutyl and diethylhexyl phthalate (DMP, DBP and DEHP respectively). These plasticisers are prevalent in the manufacturing of plastic end-user items which often end up in the marine environment. Using gas chromatography-mass spectrometry and protocols to reduce background contamination, we were confidently able to detect targeted plasticisers at low levels. The method described has broad applicability for quantifying plastics exposure in wildlife at individual, population and species levels. Furthermore, the approach can be readily modified as needed to survey for plastics exposure in taxa other than seabirds. Applying the simple, minimally invasive approach we developed is particularly appealing for quantifying plastics exposure at population and species levels and it has no observed detrimental impacts to wildlife. For further information and detail please contact the authors of this report (manuscript has been accepted for publication; Hardesty et al. 2014).

6.2 Turtles and debris ingestion and entanglement

Marine debris is a growing problem for wildlife, and has been documented to affect more than 600 species worldwide (Thompson et al. 2011). To understand the frequency and potential impact of marine debris ingestion in marine turtles in Australia, we investigated the prevalence of marine debris ingestion in sea turtles stranded in Queensland between 2006 and 2011. In this paper we asked whether plastic ingestion rates differ between species (*Eretmochelys imbricata* vs. *Chelonia mydas*) and by turtle size class (smaller oceanic feeders vs. larger benthic feeders). We compared the debris ingested by turtles to the amounts and types of debris that were found during 25 coastal debris surveys carried out within the region. We used these surveys as a proxy measurement of debris availability and we modelled turtles' debris preferences (colour and type) using a resource selection function. We found no significant difference in the overall probability of ingesting debris between the two marine turtle species studied, both of which have similar life histories. Curved carapace length, however, was inversely correlated with the probability of ingesting debris; 54.5% of pelagic sized turtles had ingested debris, whereas only 25% of benthic feeding turtles were found with debris in their gastrointestinal system. Benthic and pelagic sized turtles also exhibited different selectivity ratios for debris ingestion. Benthic phase turtles demonstrated a strong selectivity for soft, clear plastic, lending support to the hypothesis that sea turtles ingest debris because it resembles natural prey items such as jellyfish. Pelagic turtles were much less selective in their consumption of plastic, although they showed a trend towards selectivity for rubber items such as balloons. Most ingested items were plastic and were positively buoyant. This published paper, led by CSIRO-supported PhD student Qamar Schuyler, highlights the need to address increasing amounts of plastic in the marine environment.

Importantly, it provides evidence for the disproportionate ingestion of balloons by marine turtles. For further detail see Appendix J (Schuyler et al. 2012).

To understand whether plastic ingestion has been increasing in marine fauna, we carried out a global literature review of all turtle diet studies that have been published between 1985 and 2012. Collectively, these papers reported on information on turtle diet studies from before 1900 through 2011. Specifically, we investigated whether ingestion in anthropogenic debris has changed through time. We also asked what types of debris are most commonly ingested, what is the geographic distribution of debris ingestion by marine turtles relative to global debris distribution, and which species and life-history stages are most likely to ingest debris. The probability of green (*Chelonia mydas*) and leatherback turtles (*Dermochelys coriacea*) ingesting debris increased significantly over time, and plastic was the most commonly ingested type of anthropogenic litter. Turtles in nearly all regions studied ingested anthropogenic debris, but the probability of ingestion was not related to modelled debris densities. Smaller, oceanic-stage turtles were more likely to ingest debris than were coastally foraging turtles, and carnivorous species of marine turtle were less likely to ingest debris than herbivores or gelatinovores. The results from this work suggest that oceanic leatherback turtles and green turtles are at the greatest risk of both lethal and sub-lethal effects from ingested marine debris. To reduce this risk, reducing anthropogenic debris inputs to the marine environment are critical. For further detail see the published paper in Appendix K (Schuyler et al. 2013).

As part of addressing project aims 3 and 4, work was undertaken to understand why marine turtles ingest plastic. There are two predominant hypotheses as to why animals ingest plastic: 1) they are opportunistic feeders, eating plastic when they encounter it, and 2) they eat plastic because it resembles prey items. To assess which hypothesis is most likely, we created a model sea turtle visual system and used it to analyse debris samples from beach surveys and from necropsied turtles. We investigated colour, contrast, and luminance of the debris items as they would appear to the turtle. We also incorporated measures of texture and translucency to determine which of the two hypotheses is more plausible as a driver of selectivity in green sea turtles. Turtles preferred more flexible and translucent items to what was available in the environment, lending support to the hypothesis that they prefer debris that resembles prey, particularly jellyfish. They also ate fewer blue items, suggesting that such items may be less conspicuous against the background of open water where they forage. Using visual modelling we determined the characteristics that drive ingestion of marine debris by sea turtles, from the point of view of the turtles themselves. This technique can be utilized to determine debris preferences of other visual predators, and help to more effectively focus management or remediation actions. For more information see the publication resulting from this work in Appendix L (Schuyler et al. 2014).

As human population growth continues, so too does our waste, often with unintended consequences for wildlife. The estimated 640,000 tons of fishing gear lost, abandoned, or discarded annually exerts a large but uncertain impact on marine species. These derelict fishing nets or “ghostnets” drift in the ocean and can fish unattended for decades (ghost fishing), killing untold numbers of commercially valuable or threatened species. We developed an integrated analysis combining physical models of oceanic drift with ecological data on marine turtle species distribution and vulnerability to make quantitative predictions of threat. Using data from beach cleanups and fisheries in northern Australia, we assessed this biodiversity threat in an area where high densities of ghostnets encounter globally threatened turtles. Entanglement risk was well-predicted by our model, and was verified using independent strandings data from the region. We were able to also identify a number of previously unknown high-risk areas. From our work we were are also able to recommend efficient locations for surveillance and interception of abandoned fishing gear. Our work points the way forward for understanding the global threat from marine debris and making predictions that can guide regulation, enforcement, and conservation action. See Appendix A for this published work (Wilcox et al. 2013).

6.3 Pinnipeds and entanglement

Previous studies of pinnipeds in Australian waters have found that seals are vulnerable to entanglement in marine debris (Page, *et al.* 2004; Pemberton, *et al.* 1992; Shaughnessy, *et al.* 2000). Entanglement occurs when two items are entwined together and may range from single hooks to full body entanglements (Department of the Environment, 2014a). In order of severity, some of the known examples of entanglement impacts include wounding, causing infection, maiming, amputation, restricted movement, smothering or choking of the animal leading to starvation, reduced fitness, and drowning (Department of the Environment 2014b).

Pinnipeds are found in nearshore waters around the Australian coast from Victoria to Tasmania and across the south of the continent into South Australia. Large breeding colonies of Australian fur seals occur along the Victorian coastline near Phillip Island. To better understand the frequency and impact of marine debris entanglement on Australian wildlife, we collaborated with researchers from Phillip Island Nature Parks to ask questions about seal entanglement. We focused our efforts on two islands in Bass Strait, Seal Rock which is located only 1.5 km from Phillip Island and comprises two small islands and Lady Julia Percy Island which is approximately 6km off the Southern Victorian coastline in Australia. We worked with data collected from more than 100 items in which Australian fur seals had been entangled and which were subsequently removed from seals on Seal Rocks and Lady Julia Percy Island, Victoria, Australia from 1997 to 2012.

We set out to ask if pinnipeds in Southern Victorian waters are subject to entanglement dangers, and if so, in what types of material? We present entanglement data collected over 15 years (1997-2012). From this we can describe types of entanglement items most likely to ensnare pinnipeds in the region and detect if there is a correlation between age and the likelihood of entanglement.

We recorded material type, colour, overall size, mesh size, diameter, number of threads, whether the item was braided, twisted, knotted, if it was monofilament and number of strands for all entanglement items. We also noted the date, seal age (pup, juvenile, adult), location (Seal Rock, Lady Julia Percy Island, Kanowa Island, Berry Beach, Cowes jetty or Western Port Bay), and severity of injury (wether cutting deep or surface wound), whenever possible.

We estimated entanglement rates using the observations of entanglement during the excursions to the colonies. In the sixteen years of data we were able to analyse, we had information for 138 individual entanglement items. Fifty percent (n=69) were made of plastic twine or rope, 20% (n=27) were made of other plastics such as plastic bags, packing straps, balloon ribbon etc., 17% (n=24) were monofilament line, including gill nets and 8% (n=11) were comprised of rubber. The remaining 5% (n=7) consisted of metal items (such as hooks and lures) and cotton (a baseball cap that resulted in a neck constriction).

Seventy-two (n=64) percent of recorded seal entanglements occurred at Seal Rocks, with Lady Julia Percy Island accounting for 17% (n=15). The remaining 11% (n=10) were spread over other areas of the coastline including Kanowa Island, Berry Beach, Cowes jetty and Western Port Bay.

In assessing whether animals are entangled in all colour of items, we found that for twine/rope entanglements, 61% (n=43) involved green material. Grey and white coloured items accounted for 10% (n=7) and 9% (n=6) respectively. When examining monofilament line, clear and green (52% and 26% (n=12) (n=6) were recorded more than other colours as having entangled seals. White plastic strapping formed the majority (67%, n=6) of the strap entanglements.

Age of seal entangled was only recorded on 49 (35.5%) of the entanglement samples. An overwhelming 94% (n=46) of entanglement events involved young (juvenile or pup) seals, with more pups (53%) than juveniles (41%) being recorded as entangled.

Entanglements were primarily observed between July and September. Most entanglements were recorded at Seal Rocks which had a particularly large portion of the observations with location information (N=138). Seal Rocks also had observations in every month except January, based on the 95 records with dates.

Seals in the Bass Strait are subject to entanglement dangers from a variety of objects, most of which are associated with fishing activities. Net characteristics such as material type correlate with strongly with seal entanglement. Our results are consistent with other researchers finding of predominant entangling materials, i.e. trawl nets, monofilament lines and packing straps (Croxall, et al. 1990; Pemberton, et al. 1992; Fowler, 1988). We also found incidental entangling items such as plastic bags, plastic sheet, rubber "o" rings and cloth described in other entanglement studies (Shaughnessy, 1980; Fowler, 1988; Croxall, et al. 1990).

Net colour also plays an important role in ensnaring Australian fur seals, with green nets being the most common coloured net entangling seals in the region. It is unclear whether this is due to the type of fishing industries conducted in Bass Strait or because there are more green nets used by the fishing industry in general. It has been noted that green nets can be bought very cheaply and are now used widely (J. Bulbrook, pers. comm., 5 Feb 2014) suggesting the latter. In a sample of nearly 9,000 nets washed ashore in northern Australia, Wilcox, et al. (2014) found that green nets were overwhelmingly common. With regard to monofilament, seals were most frequently entangled in clear monofilament line. Clear monofilament is used widely in both the recreational (hand line, gill net) and commercial (gill nets, long line) fishing industries in southern Australian waters.

We found that young seals were more likely to be observed as entangled than adult seals, similar to results from other entanglement studies in Australia (Pemberton, et al. 1992; Page, et. al, 2004) and around the world (Fowler 1988; Croxall, et al. 1990; Fowler, et al. 1990). This may be because of curiosity and playfulness of young animals (Pemberton, et al. 1992). It could also be a function of mesh size (smaller necks and limbs pass through easier) (Fowler, 1987; Bengtson, et al. 1988; Fowler, et al. 1990; Pemberton, et al. 1992).

Resighting data suggests that on any given survey one would see only a fraction of the animals that are entangled, adding to possible under estimation of entanglement rate. Nine of the sites had resight data with resighting rates between 32 and 64 percent. So, on any given day between half and two thirds of entangled seals may not be seen. However, if seals are entangled for long enough, and if the animals remain at the colony for an extended period, these animals will have additional chances of being seen. Pups and juveniles are more susceptible to entanglement. Nevertheless, they comprise a smaller proportion of the population which means that in addition to being smaller in size (and hence more difficult to observe), they may have a reduced chance of being observed during surveys.

Our findings suggest that there is not a significant population level consequence of seal entanglement in Victoria. Overall, population numbers at these sites are increasing and combined with the expansion in breeding colonies the Australian fur seals, vulnerability is likely to be reduced. While this does not mean that entanglement is not a relevant issue, there are clearly other factors at play. We have not observed an overall change in entanglement rates through time. Given that population numbers are increasing however, it may be that a lower proportion or percentage of animals in the population, are being impacted – or it could be that seals entangled in marine debris do not haul out as often as free seals as they need to spend more time foraging due to extra energy expended whilst entangled (Feldkamp, 1985).

Reducing the incidence of entanglement on marine wildlife through policy and governance decisions is critical in Victoria. We suggest that fisheries operating in the area using the mesh sizes within the range of entangling items found in this study be suspended from making repairs to or discarding nets while out at sea, as this will reduce the incidence of these entangling items in the environment. Also, as seals are less likely to become entangled in highly visible nets such as red and yellow, creating policies implementing the use of only highly visible nets in Australian waters may further reduce the impact of entanglement to Australian marine wildlife. For further information and detail please contact the authors of this report.

Part VII Citizen Science

7. Overview

In 2011, a three year partnership was entered into by Shell, Earthwatch Australia and CSIRO with specific outreach goals. These included: 1) increased science learning and uptake for individuals, schools, communities and industry across the country and 2) contribute to a change in behaviour resulting in decreased marine debris deposition across the country due to science learning at local scales.

In order to achieve these goals CSIRO and Earthwatch staff developed and led engagement with primary and secondary age students, as well as community groups and Shell employees through the TeachWild “Scientist for a Day” program. This program involved classroom and field based excursions whereby participants learned about marine debris impacts on wildlife and collected data to contribute to the national state of knowledge on the locations, density and types of marine debris that occurs on the Australian coastline. CSIRO staff also led science educators, artists and Shell employees on week-long field expeditions to learn about the project and how the science was conducted and carried back to their classrooms, workplaces, and communities.

7.1 Scientist for a Day

The highly successful Scientist for a Day program has resulted in engagement with more than 5,700 students to date. With Earthwatch staff, scientists from CSIRO have worked with teachers and schools from all states (excluding the ACT) on the 1 Day Scientist for a Day program. The scientist for a day program involved a presentation of marine debris (what it is, where it comes from) and its effects on wildlife. The excitement and enthusiasm from schools around the country has been impressive. Schools have developed their own videos based upon their learning experiences and the program has led to engagement in state and national kids teaching kids participation from schools in two states using their learnings in the Scientist for a Day program to teach other students about the TeachWild program and the marine debris issue. Teachers and students have together developed waste reduction programs at their schools and have developed innovative practices to change school, community and home practices, particularly around plastic waste.

In addition to these live face-to-face interactions with school groups, we have increased our Skype/videoconferencing interactions with school groups. CSIRO staff have had some fantastic Skype/web chats with numerous other primary and secondary school kids throughout the year. Having live chats with students while in the field allows us to not only teach kids about marine debris, but also shows them some of the opportunities available for careers in science.

Feedback from schools has been very positive and it is heartening to see and learn about some of the creative solutions to reducing rubbish that are being established and gaining traction in schools and communities around Australia.

In addition to school engagement, we delivered the TeachWild program to more than 30 Shell Graduates. These day long engagements have provided us with an excellent opportunity to promote learnings from TeachWild to Shell staff, increasing their understanding of the marine debris issue and Shell's role in supporting leading research efforts and their commitment to social investment on extremely relevant and timely topics. The interest and enthusiasm from Shell employee participants has been overwhelmingly positive.

The clear message from Shell employees is that they appreciate the company they work for and they are excited about the opportunities provided by Shell. Learning about marine debris impacts on wildlife has been quite an eye opening experience for many of the participants (or so we understand from feedback from participants). It has been rewarding for us to see some of the personal and professional changes that some of the participants have been interested in developing and implementing at work, home and in their communities.

7.2 Intensive Field Expeditions

The multiple day (typically weeklong) TeachWild excursions were tremendously successful. The feedback from teachers has been overwhelmingly positive with several teachers remarking that this has been the best professional development opportunity of their careers. To date we have engaged 160 teachers/corporate citizens (Shell employees) in multiple day research expeditions led by CSIRO scientists.

Activities for the intensive expeditions have been varied but have included coastal debris surveys, debris identification and sorting, at-sea surface trawl surveys (and associated sorting of debris), necropsies of turtles and seabirds, spectrophotometry measurements to look at spectral characteristics of plastics, recording net and other material characteristics for items that have ensnared southern fur seals, and seabird colony surveys to look at debris levels in and near breeding colonies. These activities and the immersion in a hands-on learning environment was enriching for participants. The opportunity to teach back live to classrooms and communities enables educators to bring their students 'to the field'. This teach live component with video web chat sessions between teachers, scientists and the classroom was an exciting addition to the intensive expeditions.

Teachers have made real contributions to the science whilst learning new skills. Importantly, while doing so they have been able to Skype or blog back to their classrooms, communicating with students in words, photos and in live video feeds about their experiences in the TeachWild program. The intensive expeditions have been very successful and have contributed to important data collection needs by CSIRO staff and research partners.

7.3 Effectiveness of Citizen Science

Is citizen science data worth our investment?

Public participation in scientific research (Citizen Science), has long been used to tackle research questions that would otherwise not have been addressed (Couvet et al. 2008, Dickinson et al. 2010, Irwin 2001, Silvertown 2009). Citizen science projects can involve volunteer participants from school children to adults and citizen scientists may be involved in many steps along the way including participating in data design, collection, processing and analysis, and dissemination to the broader community. Citizen Scientists now participate in projects ranging from population ecology to astronomy. Bird monitoring in Europe goes back as far as 1749 (Greenwood 2007) and now bird monitoring programs are running in most countries engaging citizen scientists including the monitoring of Australian birds (Blakers et al. 1984). Astronomy has the largest participation rate by citizen scientists, with engaged volunteers discovering new stars and sky objects (Dickinson et al 2010). This citizen scientist engagement has enabled collection of data that can potentially go beyond the normal scope of a conventional research project by greatly increasing the sampling power.

The National Marine Debris project was established to quantify the amount and types of rubbish that are entering our marine environment, and the potential impacts this waste may have on Australian wildlife. The project integrated field, modelling, genetic and biochemical marker approaches to understand the impact of marine debris on fauna at the national scale. One of the critical aspects of this work was to collaborate and engage with school groups to promote science education and learning through a timely and relevant topic that is part of the national science curriculum. Importantly, the marine debris issue fits in well with mathematics, chemistry, physics, biology, oceanography and other parts of the national curriculum and it is of interest to the general public. Engaging citizen scientists (school children, teachers and the general public) also enabled more data collection which significantly strengthened the scientific output.

Our objectives were to investigate the utility of citizen science data contributing to a rigorous scientific study. In addressing this question we focused on if or how training makes a difference to the precision and accuracy of public surveys.

Methods:

School identification

CSIRO education made contact with prospective teachers through the national Scientists in Schools (SiS) program to identify potential schools and promote the project and the TeachWild program. Additional schools interested in participating were identified by Earthwatch Australia staff. Teachers and students at schools from Queensland, New South Wales, Victoria, South Australia, Western Australia and Tasmania who enrolled in the 'Scientist for a Day' program were given training by CSIRO scientific staff.

Teacher Training

There were two levels of training for teachers who enrolled in the 'Scientist for a Day' program (a one-day training session or a multi-day training block (typically 5-7 days). The more intensive training involved dedicated multi-day TeachWild excursions during which teachers received intensive class-based and field training in marine debris issues and data collection. Teachers carried out coastal debris surveys to look for plastics and other anthropogenic debris. They assisted in necropsies for turtles and seabirds and they learnt to use spectrophotometers to record spectral characteristics for debris. The 'Scientist for a Day' program was a two part session that typically took place over a single day. The first component of the session engaged school children and teachers together to learn about marine debris as a topic and the second component of the program involved the training and carrying out of coastal debris surveys. This was often followed by data sorting activities. The 'Scientist for a Day' program typically involved 1-2 trained professionals from CSIRO and Earthwatch.

Citizen science coastal surveys

Transect surveys

At the selected coastal location, wherever possible, groups randomly selected the direction from the access point (right or left) to where transects were conducted. In some cases this may not have been possible due to insufficient coastline from the point of access. To avoid bias (e.g. the effect of higher traffic at the access point), wherever possible, participants were asked to walk a minimum of 50 meters from the access point to the location of the first transect. Participants were also asked to locate each subsequent transect a minimum of 50 meters distant from the previous transects. Transects were distributed evenly across the range of substrate types (beach, cobble, boulder, bare rock, mud, mangrove) at each site. At each site groups were asked to carry out a minimum of three transects. If debris was not found in these first three transects, groups should have continued to add transects until either debris was found or a maximum of six transects was reached. Transects ran perpendicular from the water to two meters into the backshore vegetation. Transects were two meters in width, and schools typically had two observers looking for debris on each one meter wide swath (for a total of four observers per transect). An additional (fifth) student would record debris items noted. One student photo documented the process, transects and litter, another student collected litter in a collection bag, and another student would help keep track of distance along the transect line. The observers walked along a meter tape running from the water to the backshore vegetation, reporting all items observed from upright standing position, as per Year One report (Appendix C). The total number of observers searching for debris items was also recorded for observer effort reporting. Upon return to the classroom, transect data were then entered into the national marine debris online database.

Emu Parade surveys

The Emu Parade is a simpler method for sampling marine debris than is the more detailed transect methodology and works effectively for primary and junior secondary groups and for larger groups. For an 'Emu Parade' coastal debris survey, students were typically divided into groups of 10 or fewer, with each group designated a specific section of the beach. Instead of surveying a 2 m wide transect there is a fixed area which is searched by citizen scientists. These areas or wide 'transects' are typically 30m wide (can be wider) along the beach. The length of each transect was variable, but followed the consistent methodology of transects (e.g. from the water line up to two meters into the continuous backshore vegetation). To remain consistent with the transect methodology, the emu parade survey is carried out at least 50 m from the main beach access point, wherever possible. Where multiple surveys are conducted, they are placed at least 25 m apart. Typically debris from each 'parade survey' was collected and returned to the classroom for identification and sorting. These data were then entered into the national marine debris online database.

Results

Comparison between citizen science and scientist conducted transects

CSIRO scientific staff completed 575 transects at 172 coastal sites around Australia (Figure 8). 156 transects and 41 emu parades over 56 sites were undertaken by citizen scientists (Table 1). The citizen scientist transects involved adults, primary and secondary school students. The adults were mostly Shell employees or teachers who had undertaken a one-day or a one-week training program on marine debris and data collection and interpretation (Table 1). Project staff attended field excursions and participated in all transects and emu parades made by citizen scientists. However, most were led by the teaching staff from the school or institution involved.

Density of debris

The density of debris detected and counted during citizen scientist and project transects were similar ($P>0.7$) (Figure 9). However, on emu parades a higher density of debris was observed than was observed by professional and citizen scientists undertaking transects ($P<0.05$). When these data are separated into age groups, the data show that density of debris found during emu parades undertaken by adults were similar to those by all groups who undertook transects (Figure 10). The higher overall density found during emu parades was entirely due to surveys carried out by primary school students. Secondary school students detected a significantly lower density of marine debris than other groups ($P<0.05$) (Figure 10).

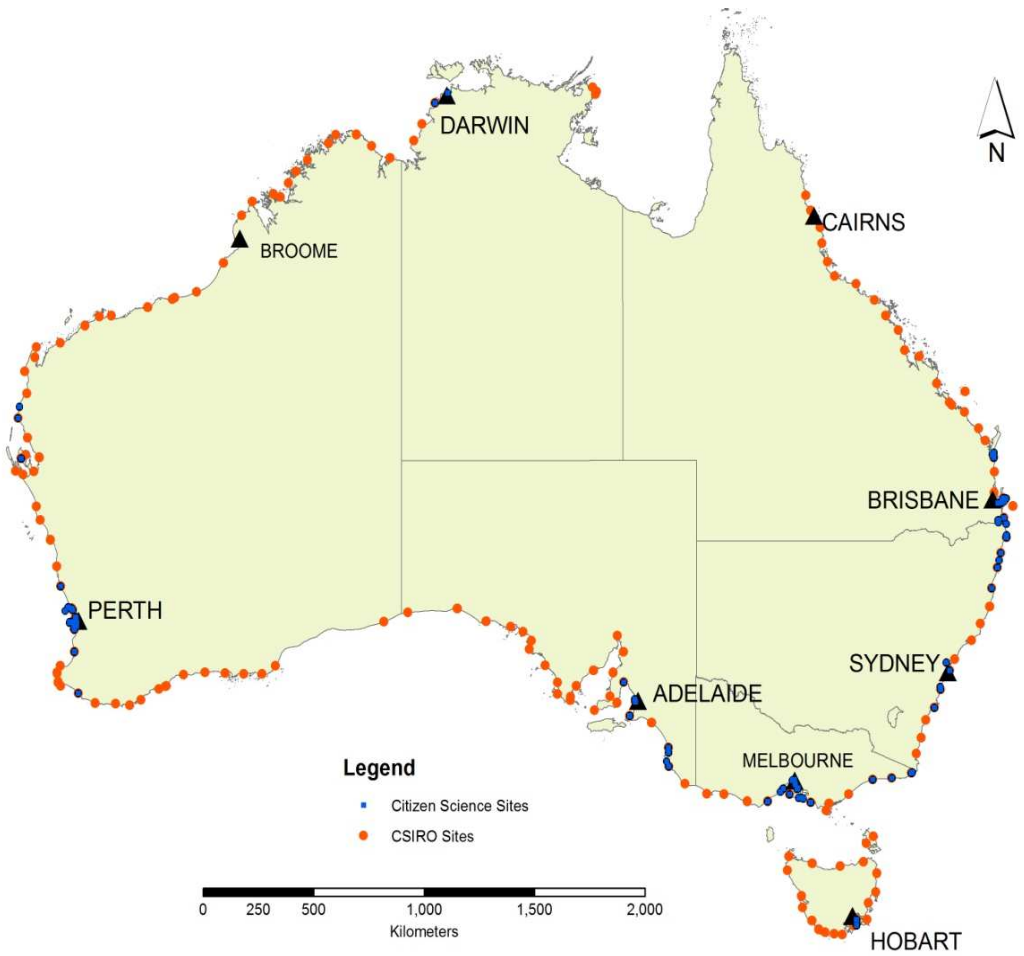

Figure 8. Map of Australia showing (a) the location of citizen science transects and emu parades (blue dots) and transects carried out by project staff (orange dots).

Training

Teachers from Queensland, Victoria, Tasmania, New South Wales and Western Australia participated in the 7-day TeachWild program. The level of training did not appear to effect the density of marine debris recorded by each group during transects (Figure 11): there was no significant difference in data collection between groups receiving one week or one day of training. Both groups found comparable quantities of marine debris during coastal debris surveys and were similar to the quantities and types of debris found at nearby survey sites by CSIRO scientists (Figure 11).

Table 1. The number of transects and emu parades for marine debris completed by primary and secondary students and adults during the project and the level of training of the teachers supervising each activity. The subset of project transects made within 150 km of citizen scientist transects is also shown.

Survey method	Group	Training	N
Transect	Adults	1 day	33
		1 week	54
	Primary students	1 day	-
		1 week	8
	Secondary students	1 day	42
		1 week	19
Emu parade	Adults	1 day	2
		1 week	13
	Primary students	1 day	7
		1 week	6
	Secondary students	1 day	7
		1 week	7
Transects	Scientists	-	116

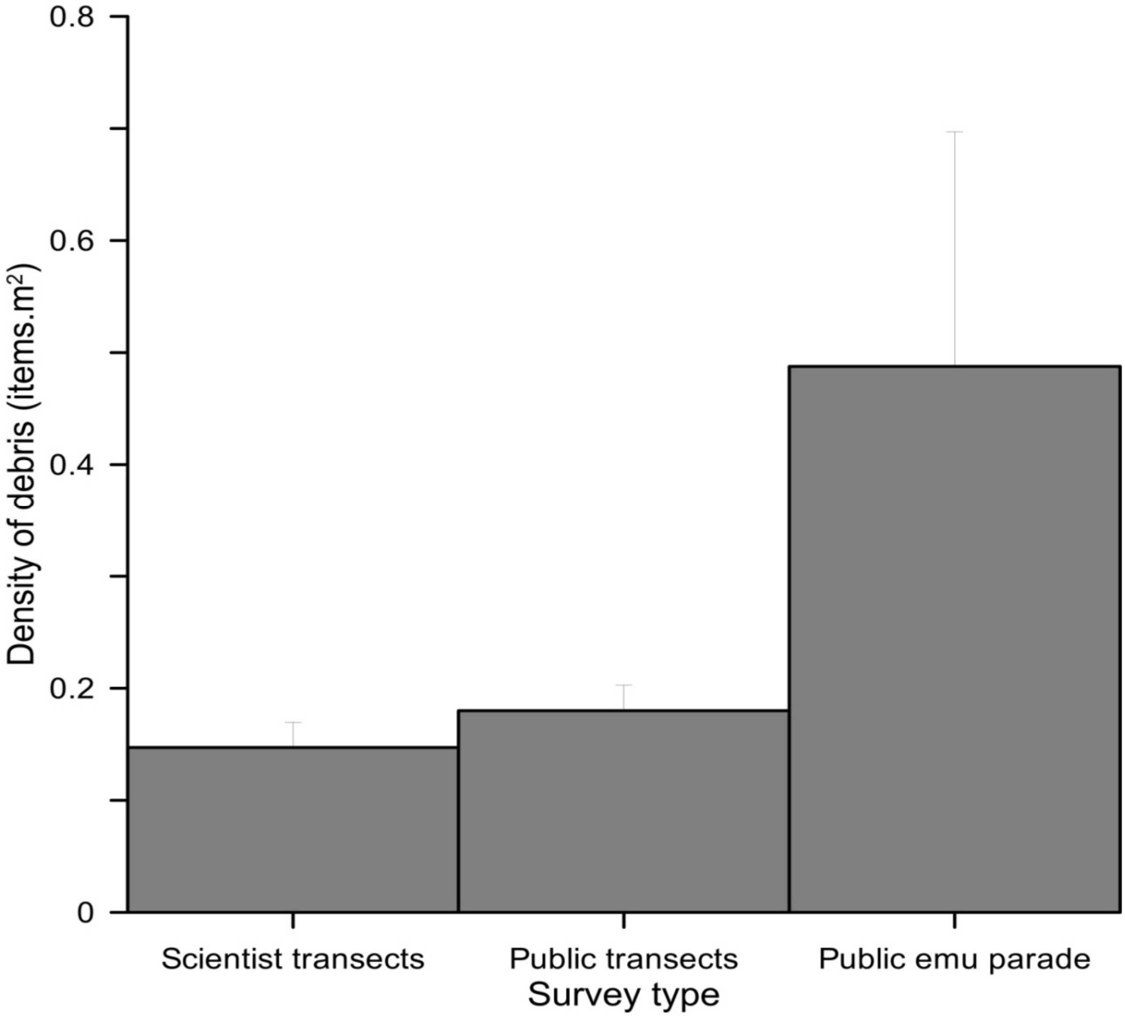

Figure 9. The mean density (items.m2 ± se) of marine debris found during citizen science transects and emu parades compared with nearby transects by project staff.

However, the density of marine debris collected during emu parades did differ among trained and untrained primary school students (Figure 12). Primary school students supervised by teachers who participated in the one-week training found significantly more marine debris than did other groups ($P<0.01$).

There was a significant difference in the relative abundance of marine debris collected by students who conducted emu parade surveys and those carried out by CSIRO staff scientists ($p<0.05$, Figure 13). The students detected a higher abundance of the smallest size class debris than project staff and students who carried out transect sampling.

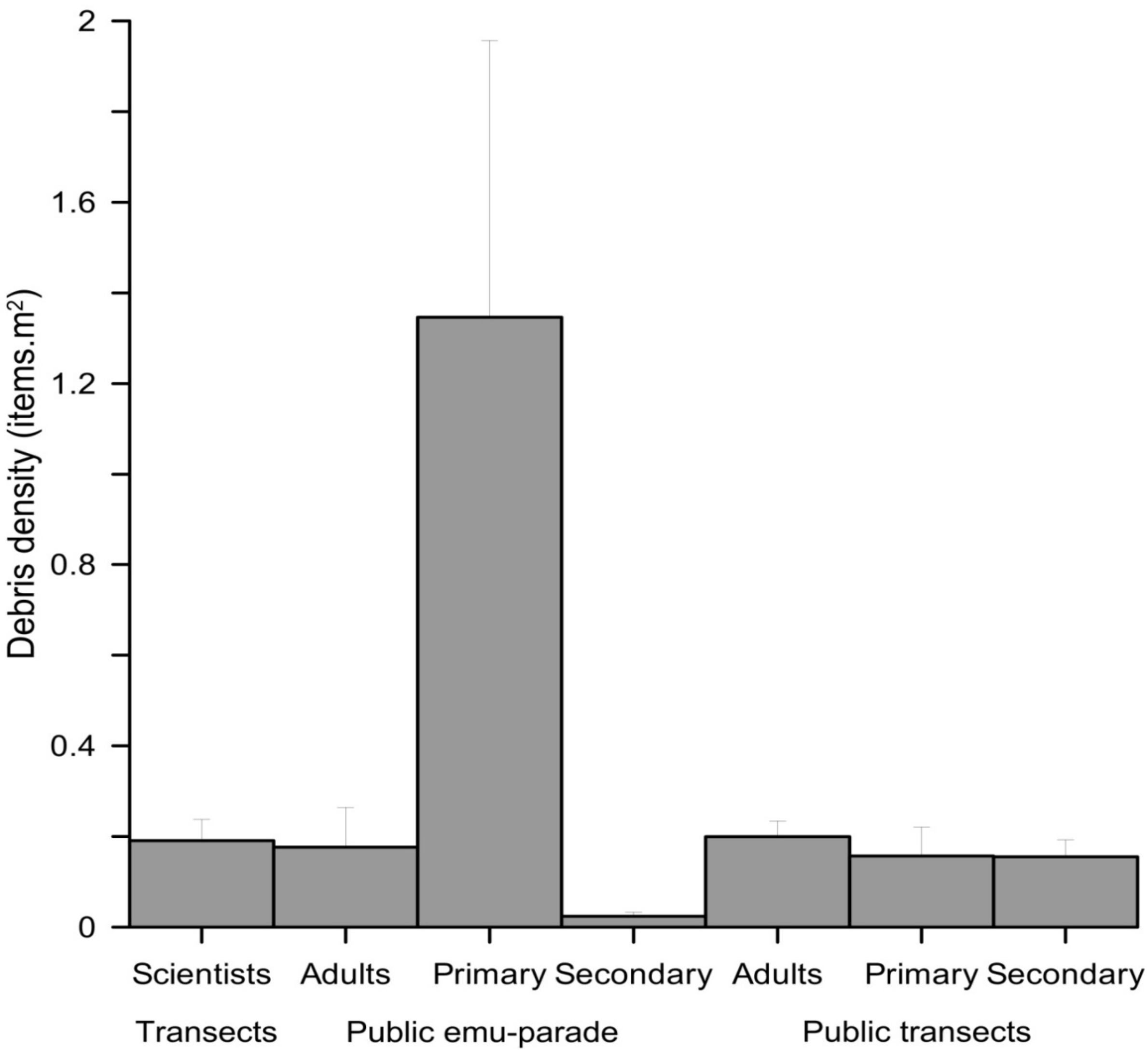

Figure 10. **The mean density (items.m2 ± se) of debris items found on transects and emu parades by adults, secondary and primary school students compared with nearby transects carried out by CSIRO staff.**

Sample sizes for all groups was low for emu parades (Table 1) so these results may be confounded by location as the mean density found by trained primary school students was 10 times that found by other groups.

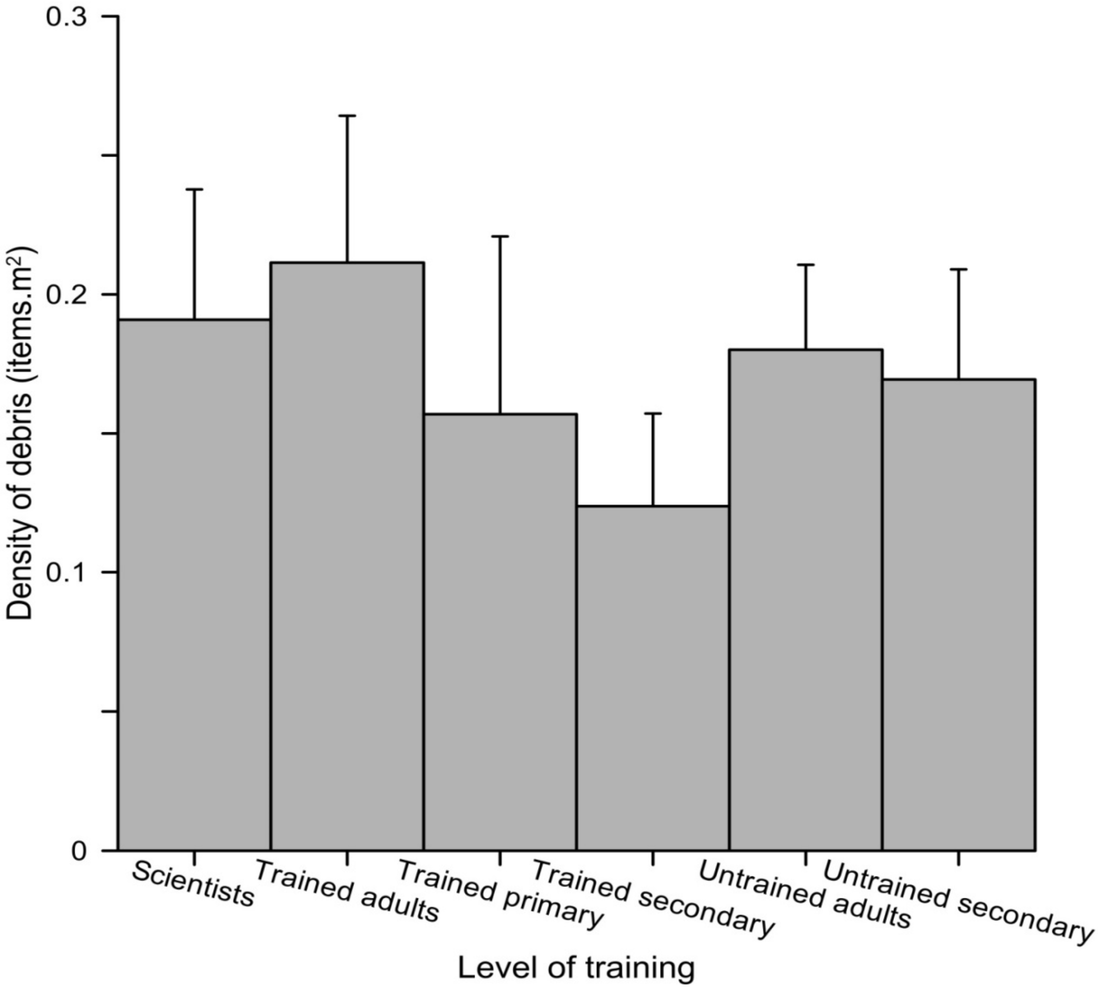

Figure 11. The mean density (items.m2 ± se) of marine debris found among transects made by trained and untrained adults, primary and secondary school students supervised by trained and untrained teachers compared with nearby transects by project staff.

Size composition of debris

The size composition of the marine debris found during transects and emu parades was similar (χ^2_{10} = 4.1; P>0.8). This suggests that the citizen scientist were detecting marine debris of a similar composition to that found by scientists.

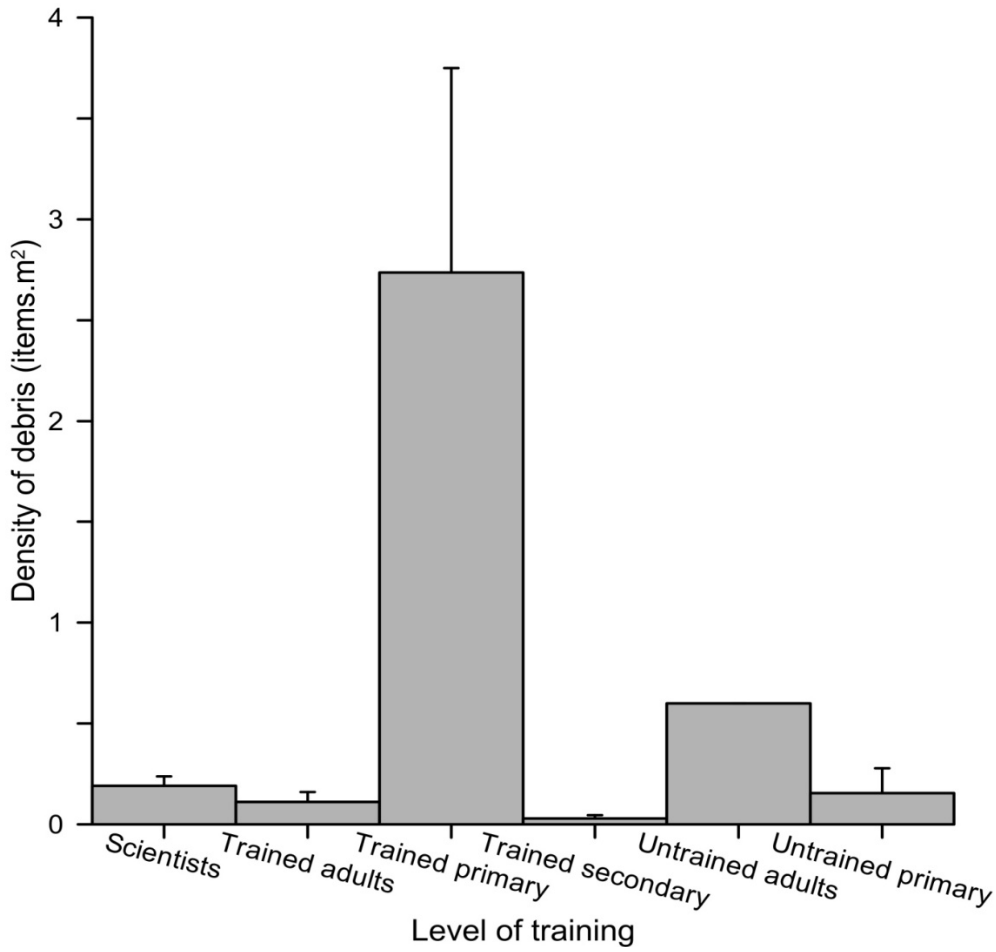

Figure 12. The mean density (items.m2 ± se) of marine debris found among emu parades made by trained and untrained adults, primary and secondary school students supervised by trained and untrained teachers compared with nearby transects by project staff.

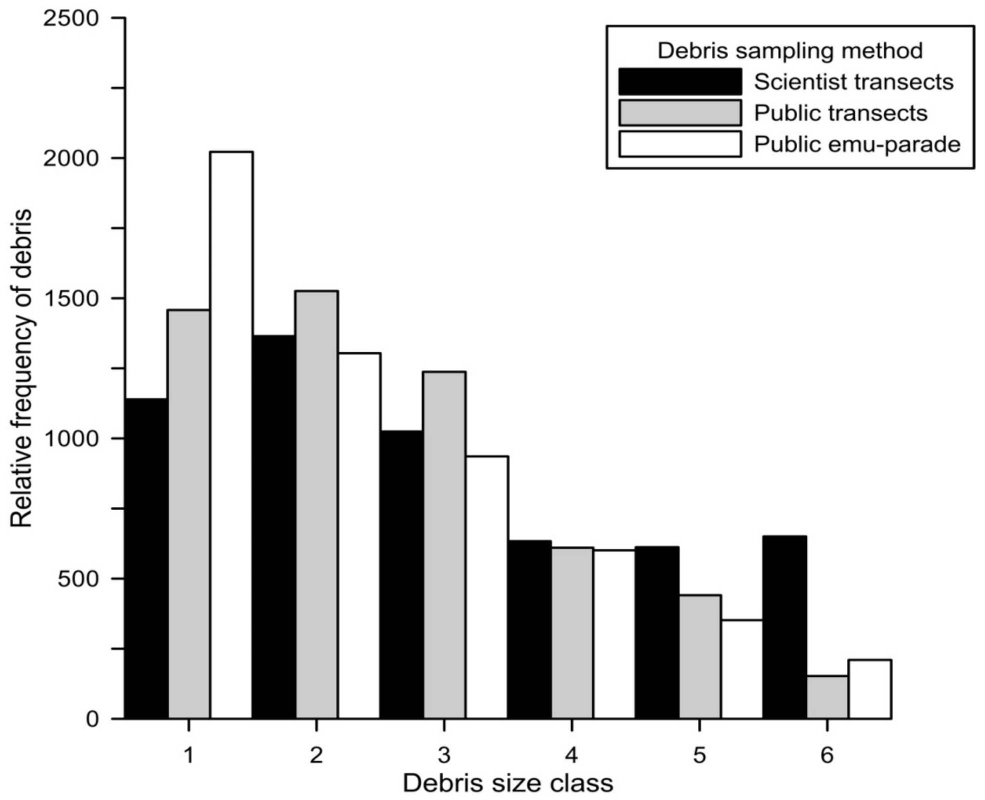

Figure 13. The relative abundance of marine debris of different size classes found during citizen science transects and emu parades compared with transects by project staff.

Survey cost analysis

The greatest training effort was undertaken on adult teachers, especially those who participated in week-long TeachWild expeditions. Participants in intensive expeditions carried out the greatest number of surveys and the conducted the highest mean daily number of surveys of the citizen science groups. The total time cost for the groups that participated in intensive excursions was much greater than that for the single day training. Scientists were the most efficient survey group (0.8.person-day^{-1}) followed by secondary school students (0.6 person-day^{-1}).

Discussion

The aim of citizen science project was to gather more data to strengthen the scientific outputs and also to raise awareness of a global issue. The volunteers performed four tasks successfully. Firstly they identified and mapped out relevant transect areas. Secondly they were able to find the marine debris. Thirdly they learned to recognised and accurately identify categories of marine debris within these transects. And finally they were able to provide accurate and reliable data that they could enter into the National Marine Debris database. These tasks enhanced their knowledge and raised awareness on the issue of marine debris. For this study it was imperative to keep the sampling methodology simple so that volunteers could easily follow instructions and that the tasks were achievable and realistic. Training was also instrumental in ensuring reliability and repeatability of this data. The results of our study suggest that scientists are more time efficient at surveying marine debris than citizen scientists, while primary and secondary school students appear to be of similar efficiency as adults. However, the results illustrated in Figures 9 and 10 highlight the significant differences between primary and secondary students in terms of debris detected, which may be thought of as accuracy.

For Emu parade surveys, secondary school students detected a significantly lower density of marine debris than all other groups (Figure 10), while primary schools students detected debris at nearly seven-times the rate of all other groups. Anecdotally we observed that teenage (secondary) students were sometimes less engaged in the survey process, subject to more peer distractions and more frequently required refocusing on the objectives and tasks at hand. These effects may have contributed to the lower density of marine debris detected by these age groups. In contrast, the higher density of marine debris detected by primary students on Emu parade surveys may be attributed to their general enthusiasm and positive response toward adult supervision (particularly by trained teachers, Figure 12), but also (in their enthusiasm) perhaps the tendency to bob-down and look more closely at the beach surface and in doing so potentially detect more debris items or even smaller size class of debris (Figure 13). Another influencing factor might be the choice of location where citizen scientists undertook surveys – perhaps influenced by the nature of the task to seek areas of known or higher levels of marine debris. Figure 13 illustrates that for size class 1, 2 and 3 items, scientists detected fewer items compared with public transects. It cannot be positively determined whether this is because public surveys were carried out in more populous areas where litter deposition may be higher, or whether citizen scientist surveyors may not have always remained in a normal standing position (i.e. bending over to see more and/or scratch through sand to find more small debris items).

It might be argued that survey tasks undertaken by citizen scientists need to be carefully matched to the appropriate age/skill set, or that some results be carefully assessed for their inclusion in broader datasets.

The five-fold increase in training costs to undertake the week-long events did not generate any detectable improvement in survey efficiency, precision of accuracy compared with surveys made by scientists nearby. Findings were similar to Tulloch (2013) who found that increasing the investment in a volunteer monitoring program did not necessarily lead to higher quality data and more publications. One aim of this marine debris project was to inspire a generation of young scientists and encourage critical thinking toward how they make their decisions as future leaders. This was done by immersing students in the global problem of marine debris and the issues that need to be addressed.

Conclusions

This was the first marine debris distribution study within Australia that tested and validated citizen science data against scientific data. The results of this study have proven that with the right protocols, methodology and training, volunteers are able to follow instructions and collect robust reliable data. It can be concluded that using citizen scientist is an effective approach to collecting data on a large scale.

Another important aspect of this study was to collaborate and engage with school groups to promote science education, improve scientific literacy and learning through a timely and relevant topic. It was an integral part of the national science curriculum, fitting in with maths, chemistry, physics, biology, oceanography and other parts of the national curriculum. On a national scale students now have an understanding of the issue and impact that marine debris has on wildlife. The inclusion of volunteers within the community also helps to build trust and leads to acceptance of scientific outcomes. This also helps to understand, accept and support recommendations and potential policy changes implemented by management at both local and national levels.

Part VIII Solutions

8. Overview

Marine debris is significant global problem that presents a serious threat to the health of the oceans and its ecosystems. It also degrades the aesthetic of the beaches and there is direct evidence that 'dirty beaches' result in to economic losses in millions of dollars of lost tourism revenue. This is but one potential motivation for keeping coastlines free of litter and in some areas it has motivated and increased public participation with clean-up campaigns and governmental involvement.

8.1 The effectiveness of Local Waste Management Policies and Activities

Most of the litter that ends up in our oceans is produced on land and enters the marine environment from land-based sources. Hence, waste management practices and litter prevention activities on land may affect the amounts and types of anthropogenic litter that enter the marine environment. Around Australia, there are a range of cleanup activities as well as waste management policies and practices. The effectiveness of various outreach and engagement activities and waste management practices and policies differ according to the state, the region and the councils. Considering this, our national coastal debris survey has carried out surveys around the nation to collect data on the types and the density of the anthropogenic litter found along Australia's coastline. Data from these coastal debris surveys have then been compared with local council waste management activities, practices and policies in an effort to begin to understand the effectiveness of various policies, practices and activities.

Although beyond the initial goals and aims of the project we have begun to collect information about the legislations, policies, plans and actions done to manage and recycle the waste in Australia in coastal regions around the country. Ultimately we aim to assess policy effectiveness at a range of: within the nation, between the states and territories, and the regions and with varying council practices. We have carried out surveys with participants from coastal councils in each state and territory, asking questions about the range of the policies and practices in the council regions where these sites were situated We asked questions regarding to waste management in general and more precisely in the coastal regions for various councils. This information was completed with the help of the council's websites. Ultimately, to understand how the policies, the legislations and the actions influence the density of the marine debris we will analyse the link between the different waste management practices with the geographic and demographic characteristics of the councils.

8.2 Container Deposit: an effective policy for reducing litter

CSIRO analysed a dataset on litter clean-ups provided by CleanUp Australia (CUA; www.cleanup.org.au) to evaluate whether there are any differences in the types of litter that are found among the states. Specifically, we asked whether sites in South Australia, which has a container deposit scheme, had fewer beverage containers in the waste stream. CleanUp Australia provided counts of the number of items in each of 94 categories across 750 sites in their 2012 clean-up (Table 1). Due to missing information from some records, we reduced the dataset down to 693 records. These records cover clean-ups from a wide range of sites, including parks, schools, beaches, waterways, etc. The CUA data does not include information on the total area covered by a clean-up, nor does it include detailed information on the effort, aside from the number of people involved. Given these limitations, we chose to look at the relative frequencies of beverage containers in the clean-ups as a metric of the effect of the container deposit scheme. Beverage containers were restricted to seven of the 94 categories and included PET drink containers, non-PET containers, alcoholic beverage bottles, soft drink bottles, fruit juice bottles, alcoholic beverage and soft drink containers. Drink cartons, milk cartons, bottle caps and straws were not included as beverage containers in this analysis.

Table 2. The number of sites cleaned up in each state or territory as part of the 2012 Clean Up Australia Day activities. For a full listing of the 94 categories of items, please refer to the CleanUp Australia website (www.cleanup.org.au).

Australian Capital Territory	7
New South Wales	235
Northern Territory	9
Queensland	168
South Australia	63
Tasmania	29
Victoria	127
Western Australia	55

We used regression analysis to compare the frequency of beverage containers with the frequency of other items in the clean-up data. We found that a model that included the state as an explanatory factor was significantly better than a model that assumed that the ratio of beverage containers to other items was constant nationwide based on Aikaike Information Criterion (AIC; constant everywhere: 61440, differ by state: 54624). We examined the differences between the various states using a multiple comparison test to evaluate whether pairs of regression coefficients for each state were different.

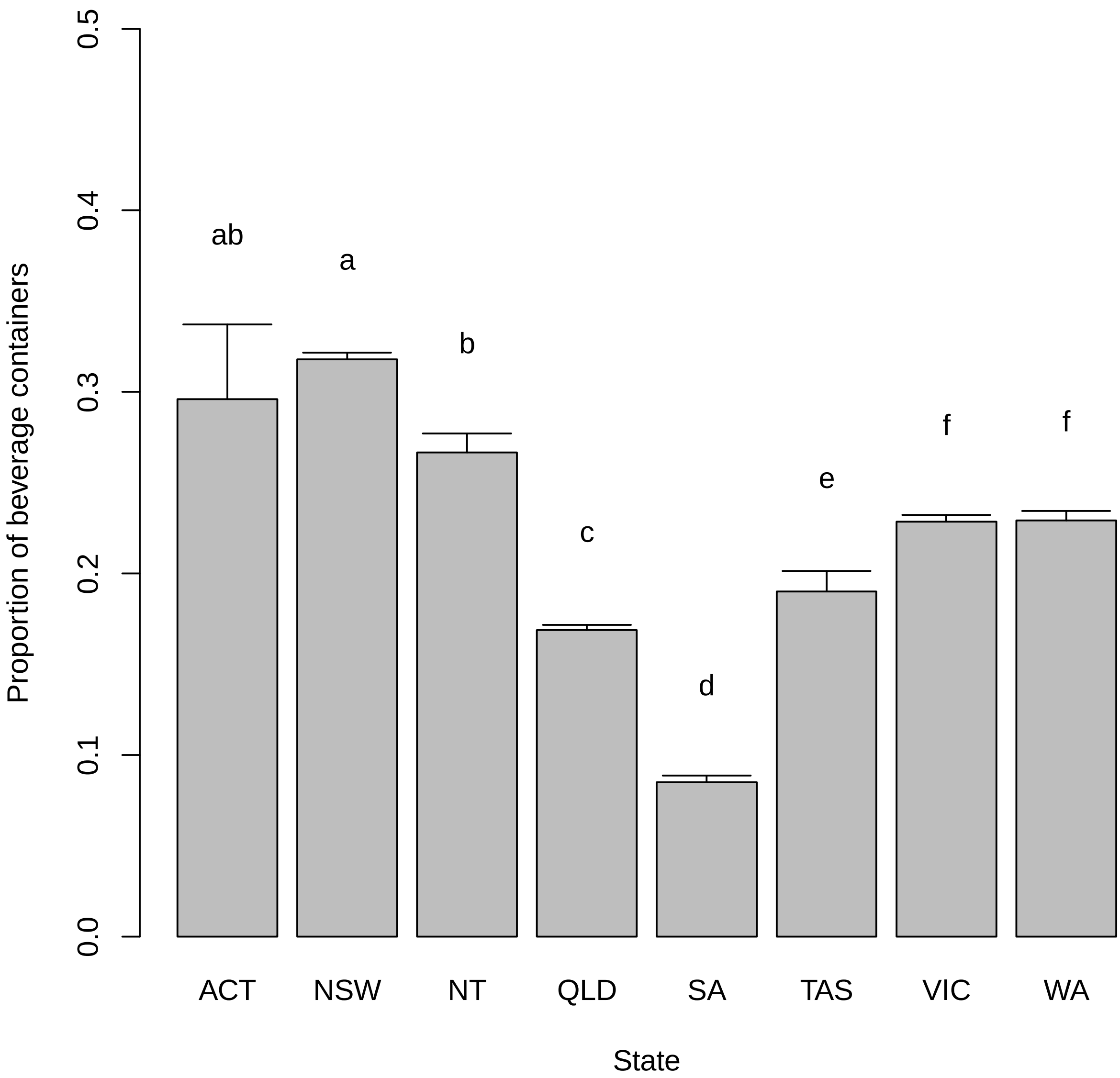

Figure 14. The proportion of beverage containers in materials recovered during clean-ups in Australia. Shaded bars depict the proportion of beverage containers in each state, error bars show the 95% confidence interval on these mean estimates. Bars which do not share a letter are significantly different in a pairwise comparison at the $p < 0.05$ level.

We found that beverage containers make up a significantly smaller fraction of litter in clean-ups from South Australia, in comparison with the other states. While it would be preferable to be able to compare these results before and after the implementation of a container deposit scheme to look at its impacts experimentally, termed a before-after-control-impact experimental design, we were not able to obtain information from prior to South Australia's implementation of its deposit scheme. Thus the results here are only correlative, not causal. However, they do provide very strong evidence that there are fewer beverage containers lost into the environment in South Australia than in other states, supporting the efficacy of a container deposit scheme (Figure 14). For instance, based on our analysis less than 1 in 10 items found in the environment is a beverage container in South Australia, by comparison with other states where the frequency is nearly 3 in 10.

It is reasonable to predict that the ratio of beverage container lids to beverage containers might provide additional information about the effectiveness of the container deposit scheme, as containers attract a refund while lids do not. Thus, if there are fewer containers in clean-up data in South Australia due to less consumption of beverages there or other drivers, that should be reflected in both containers and the lids. However, if the deposit is causing fewer beverage containers to be lost into the environment in South Australia, then one might expect clean-ups to find fewer beverage containers but similar numbers of lids in comparison with other states.

When we compared the ratio of beverage containers to beverage container lids across states in the clean-up data, South Australia came out with a much higher ratio of lids to containers in the clean-up data than any other state (Figure 15). This supports the inference that the container deposit scheme is causing beverage containers to be recycled, as the supply of containers and lids could be assumed to be equivalent, but only containers attract a deposit refund.

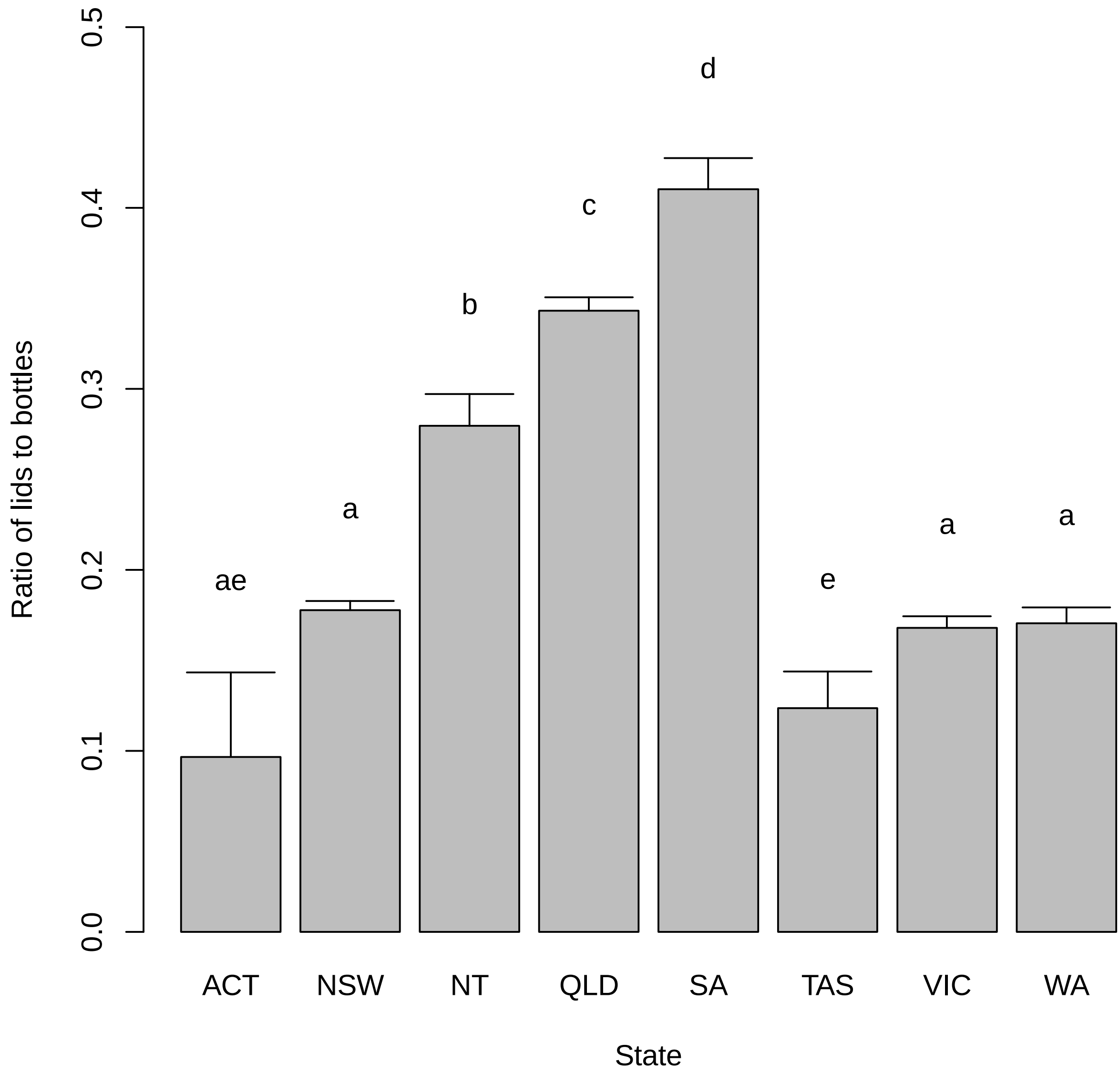

Figure 15. The ratio of beverage container lids to beverage containers found by Clean Up Australia volunteers in 2012 for each state and territory. The error bars give the 95% confidence interval around the estimates. Shared letters across bars denote values that are not significantly different at the $p < 0.05$ level.

8.3 CSIRO Policy input to the Threat Abatement Plan

CSIRO commenced a major research effort on marine debris, in particular focusing on understanding sources, evaluating risk to wildlife, and investigating the effectiveness of policy responses in 2009. This research has involved 4 major research efforts, a collaborative project on derelict fishing gear in collaboration with Ghostnets Australia, a relatively small scoping project funded by the Department of Environment (SEWPaC), a large project involving marine debris generally at the continental scale funded by Shell Australia in collaboration with Earthwatch Australia, and a collaborative working group of international experts funded by the National Center for Ecological Analysis and Synthesis in the United States. The summaries below are targeted to activities outlined in the Threat Abatement Plan for Marine Debris. However, they do not represent the full range of research on this topic. Many of the references cited below are available publically. For those not available contact the authors of this report. For each relevant activity outlined in the Threat Abatement Plan, the section from the plan is provided along with the response. CSIRO's research activity in this space will continue through 2014.

CSIRO research and activities relevant to Table 2.1 in the Threat Abatement Plan

1.7 Australian Government agencies in collaboration with state and territory governments to identify appropriate responses and responsibilities for recovery of hazardous debris at sea, notably large derelict fishing nets. Australian, state and territory governments 1–2 years.

CSIRO and Ghostnets Australia published a study which included modelled net pathways, validated against independent data for the Gulf of Carpentaria and surrounding regions (Wilcox et al. 2013). This study illustrated the vast majority of nets that are found in the Gulf and surrounding regions pass relatively close to the port of Weipa. This work points to a potential significant cost saving in recovery efforts, if nets can be identified at sea to the northwest of Weipa and then retrieved as they pass close to the port. Existing Customs surveillance flights pass through this region, and could provide the necessary reporting if targeted. This would reduce both the impacts and the cost of retrieval for nets, as they could be retrieved at sea prior to entering the Gulf and passing through areas with high densities of turtles and dugong. CSIRO and Ghostnets Australia collaborated to track several drifting nets in the Gulf using satellite tracking devices. Together with existing modelling work in the region (Wilcox et al. 2013) this information would allow identification of a most cost-effective surveillance location for identifying large drifting nets, and prediction of the timing of arrival of the drifting gear in the region around Weipa to allow the most cost-effective deployment of recovery vessels.

CSIRO, Ghostnets Australia, and ATSEA recently held a series of workshops with fishermen in both Australia and Indonesia, with the goal of identifying the sources of these nets. At the present time it appears that the majority of the nets come from Indonesian waters to the northwest of the gulf in the region (Gunn et al. unpublished data). Discussions with fisheries ministry and industry representatives suggest that there are a number of potential actions that could reduce the number of lost nets reaching Australia, including development of a voluntary logging program for lost net, financial incentives for net recovery, technical support for better identification of nets and recovery of lost gear, and increased training for fisheries workers.

1.10 DEWHA to support an analysis of financial incentives to encourage return of waste generated at sea to land for appropriate disposal, for example:

• fishing gear inventories by port and vessel supported by deposits and bounty initiatives

• introduction of regulations relevant to insurance of lost fishing or other gear and/ or insurance levies to support removal of derelict DEWHA 2–4 years

Preliminary results from workshops held in Indonesia with fishermen and fisheries ministry officials suggest that nets have an economic value and are worth recovering if possible. Technical support for aggregation of data on locations of lost nets was identified as a valuable contribution by Indonesian fishermen. This location information would assist in avoiding the hazard to vessels and gear posed by existing lost net, loss of future nets on at points identified as high risk for snagging, and would also facilitate the possibility of profitable salvage operations. Fishing gear labelling and inventory was also suggested by operators as being a potential solution, supporting a reporting system. Other possible incentives discussed included low interest loan programs for gear, conditional on return of damaged or worn gear. Given that large nets can cost between 5,000 and 30,000 dollars per net, low interest loan programs would provide significant leverage to implement net marking, reduce disposal of repairs at sea, and enhance recovery efforts for lost gear, without requiring extensive fisheries management regulation.

1.12 State, territory and local governments and other relevant bodies to consider providing increased funding for the introduction of improved solid pollutant (particularly litter) control strategies in waterways. State and territory governments and relevant bodies 2–4 years

Recent work by CSIRO examined the connection between State, regional, and local council infrastructure, policy and expenditure on waste management with the density of debris present in the near shore environment in the council area. Results suggest that council actions can have a significant influence on the amount of debris accumulating in the coastal areas of the council. The study results suggest that outreach programs had a much higher impact that the provision of infrastructure in terms of reducing waste washing up on council coastlines. In particular education programs and anti-illegal dumping campaigns appeared to have major benefits. Based on the results it would be possible to evaluate the cost-effectiveness of local, regional and state initiatives to design an effective and low-cost model policy that could be adopted by local and regional government. CSIRO also conducted a national survey of marine debris along the coast of the Australian continent.

Analysis of this survey data suggests that most marine debris in the Australian region is domestic. Furthermore, debris in the marine environment appears to increase with the local population, suggesting local sources outweigh input from the high seas. Analysis of the data also suggests that areas that have a high population in the region, but relatively isolated coast tend to have high amounts of debris, consistent with illegal dumping being a significant driver of plastic inputs to Australian waters.

1.13 State and territory governments to facilitate an analysis of the effectiveness of current litter public awareness and education campaigns to identify gaps and areas for improvement. State and territory governments 1–2 years

Analysis of local policies suggests that clean-up campaigns are not as effective as education campaigns, and in particular campaigns against illegal dumping. Given analysis suggesting the effectiveness of various measures, recently completed by CSIRO, a reasonable next step would be to evaluate the cost of various actions at the state, regional and council level to identify the most cost-effective responses to reduce inputs of litter to the marine environment.

1.14 State, territory and Australian governments, in collaboration with appropriate non- government organisations, to develop options for establishing a more consistent and long-term national approach to litter abatement education, particularly for marine-based activities. Australian, state and territory governments 1–2 years.

Analysis of coastal debris in the Australian marine zone suggests that most debris is from land-based activities, not marine activities. This is particularly true near populated centres. Targeting of education campaigns appeared to be one of the most important correlates of reduced debris densities in our analysis of coastal debris patterns.

1.15 DEWHA and relevant agencies to examine introducing awareness-raising and outreach programs aimed at relevant groups contributing to marine debris in the Asia-Pacific region DEWHA and relevant agencies 2–4 years. See comments for 1.7 and 1.10 above.

In addition to those general debris results, a significant portion of fishing related debris in the Gulf of Carpentaria and surrounding regions comes for overseas, in particular from the coastal and offshore regions of Indonesia that border Australia's northern EEZ boundary. During workshops with fishermen in the region, a number of potential outreach and education activities were identified that could assist in reducing lost gear in the region.

For non-fishing related debris, the majority of the material in Australia's marine region appears to be Australian in origin, and from land-based activities in particular. Exceptions to this pattern are areas that are particularly remote, and which have high levels of fishing effort, such as the west coast of Tasmania, where domestic fishing gear dominates the debris in the nearshore region.

1.16 DEWHA, in collaboration with DFAT, to identify opportunities for exchange visits between coastal (especially Indigenous) communities experiencing the impacts of marine debris and groups in other nations where large proportions of harmful marine debris originate. DEWHA and DFAT 1–2 years

Ghostnets Australia facilitated several exchanges as part of the program of workshops with Indonesian fisheries officials and fishermen. Environment (DEWHA) cofounded a number of these, via Travis Bover's team.

1.17 DEWHA, in collaboration with DFAT, to strengthen relations with regional neighbours on marine debris through relevant fora, and develop collaborative project proposals to address the sources and impacts of harmful marine debris. DEWHA and DFAT 2–4 years.

Ghostnets Australia is currently leading a collaborative project in cooperation with CSIRO and ATSEA to develop approaches for reducing lost gear in Indonesia. This project has reached the end of its major funding. There is some ongoing activity in developing outreach through ATSEA, which is currently funded by Environment (DEWHA).

2.1 DEWHA in collaboration with state and territory governments and other relevant stakeholders to support the development of nationally consistent, statistically rigorous data collection protocols and survey methods. DEWHA to support the development and management of national mapping of the spatial distribution and concentration of marine debris over time to assess the significance of marine debris and to reduce its occurrence. DEWHA 1–3 years

CSIRO developed a large project to quantify the amount and distribution of debris in Australia's coastal environment. The project included: 1) development of a statistically robust sampling design at the continental scale; 2) development of a simple, rapid, quantitative survey method; 3) implementation of surveys every 100km along the coastline following this design; 4) development of a database for housing and handling this information; and 5) development of robust statistical tools that could identify both terrestrial and marine sources of debris, and provide a standardized map of the distribution of debris at the national scale. This project is currently in its final year, with results available either post- or prepublication. The database developed for this project can accommodate both at sea and terrestrial sampling, along with volunteer clean up data. The survey methods are designed to be useable with a range of participants, including professional staff, primary and secondary schools, and volunteers. The survey methods have been optimized to deliver quantitative and repeatable data, along with all the supporting metadata, in a format that allows for rapid assessment (less than 2 hours per site). These materials are readily available over the web.

Development of a national approach to information collection and management 2.2 State, territory and Australian governments to provide support for community-based coastal and waterway clean-up and monitoring activities. Australian, state and territory governments 1–2 years.

The recent CSIRO marine debris project involved a significant amount of citizen scientist participation. For this process we developed a number of potentially useful materials, including several volunteer friendly survey protocols, and a database front end that was easy for volunteers to use. These volunteer oriented materials are designed to mesh directly with the full CSIRO marine debris database, which can incorporate both survey and cleanup data. The survey methods have been optimized to deliver quantitative and repeatable data, along with all the supporting metadata, in a format that allows for rapid assessment (less than 2 hours per site). These materials are readily available over the web.

2.3 DEWHA in collaboration with state and territory government to facilitate the establishment of a national network of a limited number of permanent marine debris monitoring sites (including within Commonwealth Marine Protected Areas) to promote consistent monitoring and information gathering and exchange, to enable understanding of long-term trends, and to inform adaptive and effective management responses. DEWHA 1–2 years

While there are a number of coastal sites that could be used as long term monitoring sites, some of which have existing historical data (Gulf ranger groups, SA NRM), a potentially more useful approach may be to combine direct monitoring at coastal sites with monitoring of seabirds as indicators for debris. There are existing programs in the EU for use of seabirds as monitors for marine debris, including environmental targets for reporting on debris densities and changes in the North Sea (van Franeker 2011). CSIRO has developed a non-invasive method for measuring the amount of plastic in a seabird, based on plastic breakdown products found in oil secreted from seabirds (Hardesty et al. in press).

The advantage of using seabirds is that particular species tend to forage in relatively consistent areas. Species like shearwaters tend to pick up relatively large amounts of debris, and thus could readily be used as bio monitors of debris in the ocean. This would be far less expensive than at-sea surveys from vessels, and likely less expensive than coastal surveys of debris. It also has the advantage of sampling relatively large areas, which depending on the species chosen could range from hundreds to thousands of square kilometres. Targeting 3 to 5 seabird colonies around Australia, and choosing one or two representative species to work with, could provide relatively low cost and effective monitoring of marine debris. Linking this monitoring to other Key Ecological Features, such as ocean productivity, or threatening processes such as organic and inorganic pollution levels, could provide a useful bio monitoring system for State of the Environment tracking and monitoring Commonwealth Marine Reserves. Using the existing CSIRO national survey and statistical methods it would be possible to identify a set of sites that would be useful for monitoring, in terms of providing a sensitive and cost-effective set of sites that will give a national picture of the distribution of debris at sea, and the change in land based inputs.

2.4 DEWHA to support a study on the wind and sea circulation patterns in the Asia-Pacific region as a basis for better understanding the pathways and potential sources and sinks of harmful marine debris of foreign origins in Australian waters. DEWHA 1–2 years

There are a number of analyses that have been done which can provide information on the sources of debris in Australia. CSIRO provided the Department with a report (Hardesty and Wilcox 2011; http://www.environment.gov.au/coasts/pollution/marine-debris/publications/pubs/marine-debrissources.pdf) detailing current modelling at sites distributed along Australia's EEZ. Findings from this report suggest that most debris in the Australian marine zone is of Australian origin. More recently, CSIRO and UWA have collaborated to collect data on debris densities every 100 nautical miles around the entire Australian continent. A subset of these results have recently been published (Reisser et al. 2014), with analysis of the likely sources for debris observed at sea. In general, the west coast and very north eastern tip of the continent appear to receive material from international sources, while the east coast of the continent appears to primarily receive materials from domestic sources. CSIRO has collaborated with Ghostnets Australia to evaluate the sources of derelict fishing gear along Australia's northern coast. Of the nearly 15,000 nets recovered to date, it appears that the majority come from neighbouring countries in the Arafura and Timor Seas, with a particular concentration along the international boundary and in the prawn trawling waters to the north of the Gulf (Wilcox et al. 2013, Wilcox et al. 2014, Gunn et al. Unpublished Data). CSIRO and Ghostnets Australia cooperated to put satellite tracking devices on several drifting nets in the Gulf, validating that nets circulate in the Gulf clockwise, completing a circuit of the gulf in less than a year.

2.5 Australian Government to facilitate a feasibility study on introducing marking of fishing gear so that it may be identified as originating from a specific fishery. The feasibility study will also consider the practical implications of marking fishing gear and the implications of derelict gear being traced back to fisheries operations. Australian Government 2–4 years

CSIRO has investigated the potential for marking of fishing gear using a number of technologies. Two of the most promising are microdots, which encode information on a small dot that is then incorporated into the gear itself, and chemical marking of the rope used in making the net. Chemical marking of plastics could be widely applicable, in essence providing a bar code that is incorporated into the material itself and thus readable even from small fragments. Both of these technological approaches are feasible, and exist widely in other applications, but have not been used for tracking marine debris.

3.1 State, territory and Australian governments to support expanded and consistent, long-term monitoring, investigation, recording and management of data on vertebrate marine life harmed and killed by the physical and chemical impacts of marine debris. This information will assist the impacts of different types of marine debris on vertebrates to be quantified and characterised. For example: • DEWHA to support monitoring of regurgitated marine debris at albatross and giant petrel breeding colonies (linked with the *Recovery plan for albatrosses and giant* Australian, state and territory governments 1–2 years

CSIRO research has focused on two different sets of impacts from marine debris, those resulting from entanglement and those resulting from ingestion. CSIRO entanglement research has been conducted primarily in collaboration with Ghostnets Australia, focusing on derelict fishing gear in Northern Australia. To date we have been able to identify areas of likely high risk to marine turtles in the Gulf of Carpentaria and surrounding regions, along with estimating the likely sources and paths of drifting nets (Wilcox et al. 2013). More recently we have analysed the characteristics of nets entangling animals to identify particular types of nets that are likely to entangle animals, identify the fisheries they come from, and estimate the total number of turtles killed (Wilcox et al. 2014). We have also worked with the ATSEA program to run workshops in Indonesia estimating the distribution of fishing effort by type of fishing, the relative number of vessels, and the frequency with which they lose gear to allow connection of impacts in Australia to fisheries operating across the border. We plan to revisit the analysis of net impacts, to improve the estimate of the number of animals killed. CSIRO has recently evaluated the impact of ingestion on seabirds, including conducting a global analysis of the literature on ingestion rates, and using forecast distributions of debris fields and statistical modelling of species to predict ingestion rates for 188 seabird species at the global scale (Wilcox et al. in prep.). These analyses identify two important patters: 1) the frequency of ingestion by seabirds is increasing significantly, at about 1.5% per year; 2) the discovery of new seabird species impacted by plastic ingestion is increasing at about 0.5% per year; and 3) there is global hotspot for ingestion rates at the boundary between the southern hemisphere temperate oceans and the southern ocean, with the highest expected impact globally in the region south of the Tasman Sea.

3.2 DEWHA to coordinate marine debris abatement strategies identified in existing marine wildlife recovery plans. For example: • DEWHA to support analysis of the impact of marine debris on the survival and behaviour of marine turtles (linked with DEWHA 1–2 years)

There are two relevant research projects involving CSIRO, one in collaboration with the University of Queensland investigating ingestion of plastics by marine turtles and a second in collaboration with Ghostnets Australia investigating entanglement in drifting gear.

The ingestion work has identified types of plastics ingested, evaluated the role of selection by turtles in ingestion, and identified characteristics of debris which lead to higher ingestion rates (Schuyler et al. 2012, Schuyler et al. 2013, Schuyler et al. 2014). Based on that work ingestion rates by turtles are relatively high, and increasing over time (Schuyler et al. 2013). Turtles are selective of materials, and tend to prefer items that are flexible, and different in colour from the background debris in the ocean. These results suggest that changing the design of consumer items, which constitute the largest portion of debris, might reduce the ingestion rates of turtles. Recent results on entanglement include a rough estimate of the catch rates of turtles by Ghostnets drifting ashore in northern Australia. The preliminary estimate for the number of turtles captured by these nets is between approximately 5,000 and 15,000 turtles (Wilcox et al. 2014). There are plans to refine this estimate over the next six months to increase the accuracy of the estimate.

Part IX Science Communication

9. Overview

There are a multitude of ways of reaching out to intended audiences. In addition to the more traditional ways scientists share their findings (though publications), interacting with the broader community and engaging with school children, Shell employees, and science educators has been a fundamental part of this project. Outreach and effective communication are incredibly important ways of educating the public and reaching a broader community. Local, regional, national and international interest in the project has exceeded the expectations of all three of the project partners, and as described in the previous section (8.3), CSIRO has provided input to the federal government on the marine debris topic. As part of the CSIRO commitment to excellence in communication, a number of informational leaflets have been developed during the project (Appendices N and O) and CSIRO scientists have written two news pieces published in *The Conversation* about their marine debris project. Staff scientists even carried a simple, informational flyer with them when carrying out coastal debris surveys because it quickly became apparent that members of the public they encountered during fieldwork were interested in learning more (Appendix P). The marine debris project was also highlighted as the CSIRO research project selected for the prime minister's science highlight (Appendix Q).

Interest has been widespread and included features in ABC's Catalyst, National Geographic, The Wall Street Journal and numerous other media outlets overseas (see an example in Appendix R, from CSIRO's invited participation at the African Marine Debris Summit in 2013). Here we provide a list of some the media interest generated in the final year of the marine debris project, as well as a list of the publications to date that have resulted from CSIRO's marine debris research.

9.1 Year 3 Media associated with the CSIRO national marine debris project

Year 3 (2013 – 14) of the Marine Debris project, has again been the interest of much media attention. The following is a summary list of electronic, television, print, and web-based media associated with the project:

- The Adelaide Advertiser - http://adelaideadvertiser.newspaperdirect.com/epaper/viewer.aspx
- Futurity. – top spot ☺ - http://www.futurity.org/top-stories/sea-turtles-gobble-plastic-at-record-pace/

- ABC local - http://www.abc.net.au/news/2013-08-09/green-sea-turtles-eat-more-plastic-than-ever2c-researchers-say/4877322
- Guardian - http://www.theguardian.com/environment/2013/aug/09/green-turtles-swallowing-plastic-study
- News.com.au - http://www.news.com.au/breaking-news/national/turtles-eating-record-amounts-of-plastic/story-e6frfku9-1226693992742
- MSN.com - http://now.msn.com/green-sea-turtles-eating-more-plastic-than-ever-research-says
- Straitstimes.com - http://www.straitstimes.com/breaking-news/technology/story/green-sea-turtles-eat-more-plastic-ever-study-20130809
- Softpedia.com - http://news.softpedia.com/news/Sea-Turtles-Eat-Twice-More-Plastic-Than-They-Used-To-Just-25-Years-Ago-374589.shtml
- Inhabitat.com - http://inhabitat.com/green-sea-turtles-are-ingesting-twice-as-much-plastic-as-they-did-25-years-ago/
- Zeenews.india.com - http://zeenews.india.com/news/eco-news/endangered-sea-turtles-eating-more-plastic-than-ever_867937.html
- Skynews.com.au - http://www.skynews.com.au/eco/article.aspx?id=894986
- The Conversation - http://theconversation.com/endangered-sea-turtles-eat-more-plastic-than-ever-16877
- Manoramaonline.com (Malayan)- http://english.manoramaonline.com/cgi-bin/MMOnline.dll/portal/ep/contentView.do?contentId=14730255&tabId=1&programId=11565556&channelId=-1073865025
- The Inquisitor - http://www.inquisitr.com/896702/endangered-green-sea-turtles-eating-more-plastic/
- Deccan Herald - http://www.deccanherald.com/content/350159/endangered-sea-turtles-eating-more.html
- Wallace J Nichols - http://www.wallacejnichols.org/234/555/new-study-endangered-sea-turtles-eat-more-plastic-than-ever.html
- Econews.com.au - http://econews.com.au/news-to-sustain-our-world/report-green-sea-turtles-eating-more-plastic/
- Brisbane Times.com.au - http://www.brisbanetimes.com.au/queensland/turtles-eating-record-amounts-of-plastic-20130809-2rlv0.html

- Inquirer News - http://newsinfo.inquirer.net/462047/green-sea-turtles-eat-more-plastic-than-ever-study
- University Herald - http://www.universityherald.com/articles/4171/20130809/endangered-turtles-eating-more-plastic-green-leatherback.htm
- Business Standard - http://www.business-standard.com/article/pti-stories/endangered-sea-turtles-eating-more-plastic-than-ever-113080900354_1.html
- Jagran Post (Hindi) - http://post.jagran.com/endangered-sea-turtles-eating-more-plastic-than-ever-study-1376049880
- Before Its News - http://beforeitsnews.com/environment/2013/08/more-plastic-bags-mean-bad-news-for-worlds-turtles-2477146.html
- Examiner.com (Tampa Bay)- http://www.examiner.com/article/endangered-sea-turtles-eating-more-plastic-than-ever
- ReptilesCanada.com - http://www.reptilescanada.com/showthread.php/69013-NY-Press-Endangered-Turtles-Eating-More-Plastic-than-Ever-Study
- CriEnglish (China) - http://english.cri.cn/6909/2013/08/09/2361s781070.htm
- Perthnow.com - http://www.perthnow.com.au/news/breaking-news/turtles-eating-record-amounts-of-plastic/story-fnhrvfuw-1226693992742
- Globalnews.ca - http://globalnews.ca/news/771031/sea-turtles-consuming-record-amounts-of-plastic-study-finds/
- Euronews.com - http://www.euronews.com/2013/08/09/ingestion-of-plastic-at-record-high-for-sea-turtles/
- WildSingapore.com - http://wildsingaporenews.blogspot.com.au/2013/08/green-turtles-swallowing-more-plastic.html#.Ugwe2OBqnAY
- Cairns post - http://www.cairns.com.au/article/2013/08/14/246700_local-news.html
- The Telegraph - http://www.dailytelegraph.com.au/news/breaking-news/turtles-eating-record-amounts-of-plastic/story-fni0xqi3-1226693992742
- News.co.me - http://www.newsco.me/content/go/story?news=133866
- Aidesante.net - http://aidesante.net/english/sea-turtles-eat-twice-more-plastic-than-they-used-to-just-25-years-ago/
- OneNewsPage - http://www.onenewspage.com/n/Science/74vzeg48k/Green-sea-turtles-eat-more-plastic-than-ever.htm
- NewsWhip - http://www.newswhip.com/MoreInfo/Green-sea-turtles-eat-more-plastic-now-t/65788850 (NZ Herald)

- Cowra Community News – central NSW - http://www.cowracommunitynews.com/viewnews.php?newsid=4370&id=15
- Plastics Industry news - http://www.industriesnews.net/story?sid=s216333971&cid=40
- Scoop.it - http://www.scoop.it/t/marine-conservation-by-prof-brendan-godley
- Space and Earth Sciences news - http://www.news-about-space.org/earth-sciences-news/cluster40913982/
- Asean business news - http://asean-business-news.com/singapore/industries/green-sea-turtles-eat-more-plastic-than-ever-study/
- Silobreaker - http://news.silobreaker.com/green-sea-turtles-eat-more-plastic-now-than-ever-study-5_2267019634815270913
- Anygator.com - http://uk.anygator.com/article/green-sea-turtles-eat-more-plastic-than-ever-study__731772
- News fiber – Phys.org, NZ Herald, Guardian - http://www.newsfiber.com/p/s/h?v=Ejx5xPKsBntQ%3D+LamiIZAPKKo%3D
- WorldLatest News - http://www.newslatestworld.com/?p=14307
- OceanSentry.org - http://www.oceansentry.org/en/7124-endangered-sea-turtles-eat-more-plastic-than-ever.html
- The Global Fool - http://theglobalfool.com/do-sea-turtles-eat-plastic-marine-debris-yes/
- Greenfudge.org - http://www.greenfudge.org/2013/08/12/more-plastic-bags-mean-bad-news-for-worlds-turtles/
- eWallstreeter - http://ewallstreeter.com/more-plastic-bags-mean-bad-news-for-world-s-turtles-5269/
- Democratic Underground.com - http://www.democraticunderground.com/112751313
- International Whale protection org - http://www.internationalwhaleprotection.org/forum/index.php?/topic/5966-green-turtles-swallowing-twice-as-much-plastic-as-20-years-ago/
- Ifood.tv - http://www.ifood.tv/blog/green-turtles-survive-on-plastic
- http://science.blogdig.net/archives/articles/August2013/12/Sea_turtles_swallow_plastic_at_accelerating_pace.html
- http://news.nationalgeographic.com/news/2014/04/140414-ocean-garbage-patch-plastic-pacific-debris/?utm_source=Twitter&utm_medium=Social&utm_content=link_tw20140414news-oceatra&utm_campaign=Content&sf2585522=1

- http://www.dailyexcelsior.com/web1/11dec15/inter.htm

In addition to the preceding, a University of Queensland press release was put out for a new global turtles and plastics paper led by PhD student Qamar Schuyler. Please see the University of Queensland website for more information and details:
http://www.uq.edu.au/news/?article=26558.

Media interest in the recent publication was not limited to the domestic audiences. A brief summary is provided below:

- AFP
- Brisbane Courier Mail
- ABC radio
- Plastics News magazine
- Canadian news organization – Globalnews.ca
- Sport Diver magazine
- ABC Pacific 1 Oct 2013.
- This work was internationally highlighted in The Borneo Post, Arab News, Khaleej Times, China News, The National (Emirates) – via http://www.pressdisplay.com/pressdisplay/viewer.aspx

9.2 Publications

Over the course of the three years of this project, several publications have been produced and a number of additional papers are in preparation. Below is a summary list (in alphabetical order).

1. Acampora, H, Q Schuyler, K Townsend and BD Hardesty 2013. Comparing plastic ingestion between juvenile and adult stranded Short-tailed Shearwaters (*Puffinus tenuirostris*) in Eastern Australia. Marine Pollution Bulletin. http://doi.org/10.1016/j.marpolbul.2013.11.009.

2. Acampora, H, BD Hardesty, K Townsend and K Erzini 2014. Plastic ingestion by short-tailed shearwaters (Puffinus tenuirostris) in northern Australia. Proceedings of the International workshop on fate and impacts of microplastics in marine ecosystems.

3. Hardesty BD, C Wilcox, J Butler, R Gunn. 2013. Exploring sources, impacts and methods for amelioration of ghost nets as a threat to marine species. A final report of the CSIRO and GhostNets Australia Partnership: 2009-2013.

4. Hardesty BD, D Holdsworth, A Revill and C Wilcox 2014. A biochemical approach for identifying plastics exposure in live wildlife. *Accepted,* Methods in Ecology and Evolution.

5. Hardesty BD, TJ Lawson, T van der Velde, M Lansdell, G Perkins and C Wilcox 2014. Estimating quantities and sources of marine debris at a continental scale. *In preparation* for Frontiers in Ecology and the Environment.

6. Hardesty, BD, J Reisser, R Sharples, C Wilcox. 2011. Understanding the types, sources and at-sea distribution of marine debris in Australian Waters. Proceedings of the 5th International Marine Debris Conference, Honolulu, HI, USA, 2011.

7. Hardesty BD and C Wilcox 31 Jan 2013. Ghostnets fish on: marine rubbish threatens northern Australian turtles. The Conversation http://theconversation.edu.au/ghostnets-fish-on-marine-rubbish-threatens-northern-australian-turtles-11585.

8. Hardesty BD and C Wilcox 2011. Marine debris: biodiversity impacts and potential solutions. The Conversation http://theconversation.edu.au/marine-debris-biodiversity-impacts-and-potential-solutions-2131.

9. Hardesty BD and C Wilcox. 2011. Understanding the types, sources and at-sea distribution of marine debris in Australian Waters. Final report to the Department of Sustainability, Environment, Water, Health, Population and Communities. http://www.environment.gov.au/coasts/pollution/marinedebris/publications/pubs/marine-debris-sources.pdf

10. Lawson, TJ, K Johns, R Kirkwood, C Wilcox and. BD Hardesty 2014. Net characteristics and entanglement in Australian Fur Seals. In preparation for Marine Pollution Bulletin.

11. Reisser J, J Shaw, G Hallegraeff, M Proietti, D Barnes, M Thums, C Wilcox, BD Hardesty and C Pattiaratchi 2014. Millimeter-sized marine plastics: a new pelagic habitat for microorganisms and invertebrates. PLoS ONE 9(6): e100289. doi:10.1371/journal.pone.0100289.

12. Reisser J, J Shaw, C Wilcox, BD Hardesty, M Proietti, M Thums and C Pattiaratchi 2013. Marine plastic pollution in waters around Australia: characteristics, concentrations and pathways. PLOS One. 8(11): e80466. doi:10.1371/journal.pone.0080466.

13. Schuyler, Q, K Townsend, C Wilcox, BD Hardesty and J Marshall 2014. Marine debris through a turtle-eyed view. BMC Ecology. http://www.biomedcentral.com/1472-6785/14/14.

14. Schuyler, Q, BD Hardesty, C. Wilcox and K Townsend 2013. A global analysis of anthropogenic debris ingestion by sea turtles. Conservation Biology. 28:129-139. DOI: 10.1111/cobi.12126.

15. Van der Velde, T., Milton, D.A., Lawson, T.J., Lansdell, M., Wilcox, C., Davis, G., Perkins, G., & Hardesty, B.D. 2014. Is citizen science data worth our investment? In preparation for Conservation Biology.

16. Vegter A, M Barletta, C Beck, J Borrero, H Burton, M Campbell, M Eriksen, C Eriksson, A Estrades, K Gilardi, BD Hardesty, J Assunção I do Sul, J Lavers, B Lazar, L Lebreton, WJ Nichols, E Ramirez Llodra, C Ribic, PG Ryan, Q Schuyler, SDA Smith, H Takada, K Townsend, C Wabnitz, C Wilcox, L Young and M Hamann 2014. Global research priorities for the management and mitigation of plastic pollution on marine wildlife. *In press* Endangered Species Research.

17. Wilcox C, G Heathcote, J Goldberg, R Gunn, D Peel and BD Hardesty 2014. Understanding the sources, drivers and impacts of abandoned, lost and discarded fishing gear in northern Australia. Conservation Biology. DOI: 10.1111/cobi.12355.

18. Wilcox, C and BD Hardesty. 2011. Cluster Analysis: a novel approach to identify types of derelict nets that comprise ghost nets. Final Report to GhostNets Australia and the Northern Gulf Resource Management Group.

19. Wilcox, C, BD Hardesty, R Sharples, DA Griffin, TJ Lawson and R Gunn 2013. Ghost net impacts on globally threatened turtles, a spatial risk analysis for northern Australia. Conservation Letters, DOI: 10.1111/conl.12001.

20. Wilcox, C, E vanSebille, BD Hardesty 2014. The threat of plastics to seabirds is global, pervasive and increasing. In preparation for Frontiers in Ecology and the Environment.

References

Acampora, H., Schuyler, Q., Townsend, K. & Hardesty, B.D. (2014). Comparing plastic ingestion between juvenile and adult stranded Short-tailed Shearwaters (*Puffinus tenuirostris*) in Eastern Australia. *Marine Pollution Bulletin* 78, 63-69.

Bengtson, J.L., Fowler, C.W., Kajimura, H., Merrick, R., Yoshidda, K., & Nomura, S. (1988) Fur seal entanglement studies: juvenile males and newly weaned pups, St Paul Island, Alaska. In: Kozloff, P. & Kajimura, H.S. (Eds) Fur seal investigations, Alaska, 1988. US Department of Commerce, 35-57.

Blakers, M., Davies, S. J. J. F. & Reilly, P. N. (1984). *The atlas of Australian birds*. Melbourne: Melbourne University Press.Cooper, C.B., Dickinson, J., Phillips T., Booney R., 2007. Citizen science as a tool for conservation in residential ecosystems. *Ecology and Society* 12 (2).

Couvet, D., Jiguet, F., Levrel, H., & Teyssedre, A., (2008). Enhancing citizen contributions to biodiversity science and public policy. *Interdisciplinary Science Reviews* 33, 95-103.

Cozar, A., Echevarria, F., Gonzalex-Gordillo, J. I., Irigoien, X., Ubeda, B., Hernandez-Leon, S., Palma, A.T., Navarro, S., Garcia de Lomas, J., Ruiz, A., Fernandez de Puelles, M.L., & Duarte, C.M. (2014). Plastic debris in the open ocean. *Proceedings of the National Academy of Sciences of the USA*. 111 (28): 10239-10244.

Croxall, J.P., Rodwell, S., & Boyd, I.L. (1990) Entanglement in man-made debris of Antarctic fur seals at Bird Island, South Georgia. *Marine Mammal Science* 6, 221-233.

Day, R. H., Wehle, D. H. S. & Coleman, F. C. in *Proceedings of the workshop on the fate and impact of marine debris, 26 - 29 November 1984, Honolulu, Hawaii.* Vol. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-54 (eds R.S. Shomura & H.O. Yoshida) (U.S. Department of Commerce, La Jolla, CA, USA, 1985).

Department of the Environment, W., Heritage and the Arts. 2009. Threat abatement plan for the impacts of marine debris on vertebrate marine life. Department of the Environment, Water, Heritage and the Arts, Canberra.

Department of the Environment, Key threatening Process – Marine Debris. http://www.environment.gov.au/system/files/resources/9195dcd0-52eb-45c4-8b3f-7796e530b4e2/files/marine-debris.pdf, accessed 05/02/2014.

Department of the Environment – Injury and fatality to vertebrate marine life caused by ingestion of, or entanglement in, harmful marine debris http://www.environment.gov.au/node/14589, accessed 05/02/2014.

Derraik, J.G.B. (2002). The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin* 44, 842–852.

Dickinson, J. L., Zuckerberg, B., & Bonter, D. N., (2010). Citizen Science as an Ecological Research Tool: Challenges and Benefits. *Annual Review of Ecology, Evolution, and Systematics* 149-172.

Greenwood, J.J.D., (2007). Citizens, science and bird conservation. *Journal of Ornithology* 148, S77-S124.

Feldkamp, S. (1985). The effects of net entanglement on the drag and power output of a Californian Sea Lion, *Zalophus californianus*. *Fisheries Bulletin* 83, 692 – 695.

Fowler, C.W. (1987) Marine debris and northern fur seals: a case study. *Marine Pollution Bulletin* 18, 326-335.

Fowler, C.W. (1988) A review of seal and sea lion entanglement in marine fishing debris. In: Alverston, D.L. & June, J.A. (Eds) Proceedings of the North Pacific Rim Fisherman's Conference on Marine Debris. Fisheries Management Foundation: Washington, 16-63.

Fowler, C.W., Merrick, R. & Baker, J.D. (1990) Studies of the population effects of entanglement on northern fur seals. In: Shomura, R.S. and Godfrey, M.L. (Eds) Proceedings of the Second International Conference on Marine Debris, 2 – 7 April 1989, Honolulu, Hawaii. US Department of Commerce, 453 – 474.

Galgani, F., Hanke. G., Werner. S. & De Vrees, L.D. (2013). Marine litter within the European Marine Strategy Framework Directive. *Ices Journal of Marine Science* 70, 1055-1064.

Good, T. P., June, J. A., Etnier, M., & Broadhurst, G. (2010) Derelict fishing nets in Puget Sound and the Northwest Straits: Patterns and threats to marine fauna. *Marine Pollution Bulletin* 60, 39-50.

Hardesty, B.D. & Wilcox, C. (2012). Understanding the effects of marine debris on wildlife: A progress report prepared for Earthwatch Australia by CSIRO.

Hardesty, B.D., D. Holdsworth, A. Revill & C. Wilcox (2014). A biochemical approach for identifying plastics exposure in live wildlife. *In press*, Methods in Ecology and Evolution.

Irwin, A. (2001). Constructing the scientific citizen: science and democracy in the biosciences. Public Understanding of Science 10, 1-18.

Jang, Y. C., S. Hong, J. Lee, M. J. Lee, & W. J. Shim. (2014). Estimation of lost tourism revenue in Geoje Island from the 2011 marine debris pollution event in South Korea. *Marine Pollution Bulletin* 81, 49-54.

Le, H.H., Carlson, E.M., Chua, J.P. & Belcher, S.M. (2008). Bisphenol A is released from polycarbonate drinking bottles and mimics the neurotoxic actions of estrogen in developing cerebellar neurons. *Toxicology Letters,* 176, 149-156.

Mouat, J., Lozano, R. L. & Bateson, H. (2010). Economic impacts of marine litter. Kommunenes Internasjonale Miljøorganisasjon, Lerwick, Shetland, UK.

Ofiara, D. D. & Brown, B. (1999). Assessment of economic losses to recreational activities from 1988 marine pollution events and assessment of economic losses from long-term contamination of fish within the New York Bight to New Jersey. *Marine Pollution Bulletin* 38, 990-1004.

Ocean Conservancy. (2014) International Coastal Cleanup - Top 10 Items Found. Available at: http://www.oceanconservancy.org/our-work/international-coastal-cleanup/2014-ocean-trash-index.html.

OSPAR. (2010). Guideline for Monitoring Marine Litter on the Beaches in the OSPAR. Maritime Area. OSPAR Commission, ISBN 90-3631-973.

Page, B., McKenzie, J., McIntosh, R., Baylis, A., Morrissey, A., Calvert, N., Haase, T., Berris, M., Dowie, D., Shaughnessy, P.D., & Goldsworthy, D.D. (2004) Entanglement of Australian sea lions and New Zealand fur seals in lost fishing gear and other marine debris before and after Government and industry attempts to reduce the problem. *Marine Pollution Bulletin* 49, 33-42.

Pemberton, D., Brothers, N.P. & Kirkwood, R. (1992) Entanglement of Australian Fur Seals in Man-made debris in Tasmanian Waters. *Wildlife Research* 19, 151-159.

Reisser J, Shaw, J., Hallegraeff, G., Proietti, M., Barnes, D., Thums, M., Wilcox, C., Hardesty, B.D. & Pattiaratchi, C. (2014). Millimeter-sized marine plastics: a new pelagic habitat for microorganisms and invertebrates. PLoS ONE 9(6): e100289. doi:10.1371/journal.pone.0100289.

Reisser J., Shaw, J., Wilcox, C., Hardesty, B.D., Proietti, M., Thums, M., & Pattiaratchi, C. (2013). Marine plastic pollution in waters around Australia: characteristics, concentrations and pathways. *PLoS One*. 8(11): http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0080466.

Rochman, C. M., Hoh, E., Kurobe, T., & Teh, S. J. (2013). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific Reports* 3:3263, DOI: 10.1038/sreo03263.

Rochman, C. M., Kurobe, T., Flores, I. & Teh, S. J. (2014). Early warning signs of endocrine disruption in adult fish from the ingestion of polyethylene with and without sorbed chemical pollutants from the marine environment. *Science of the Total Environment* DOI: 10.1016/ j.scitotenv.2014.06.051.

Ryan, P.G. (1990). The marine plastic debris problem off southern Africa: types of debris, their environmental effects, and control measures. In: Shomura, R.S., Godfrey, M.L., (Eds.), Proc. Second International Conference on Marine Debris. US Dept Commerce. NOAA Tech. Mem., NOAA-TM-NMFS-SWFSC- 154, pp. 85– 102.

Schulz, M., Neumann, D., Fleet, D. M. & Matthies, M. (2013). A multi-criteria evaluation system for marine litter pollution based on statistical analyses of OSPAR beach litter monitoring time series. *Marine Environmental Research* 92, 61-70.

Schuyler, Q, Hardesty, B.D., Wilcox, C. & Townsend, K. (2013). A global analysis of anthropogenic debris ingestion by sea turtles. *Conservation Biology* 28, 129-139.

Schuyler, Q, Townsend, K., Wilcox, C., Hardesty, B.D. & Marshall, J. (2014). Marine debris through a turtle-eyed view. *BMC Ecology* http://www.biomedcentral.com/1472-6785/14/14.

Schuyler, Q, K Townsend, BD Hardesty & C Wilcox. 2012. To eat or not to eat: debris selectivity by marine turtles. PLOS One 7(7): e40884. DOI:10.1371/journal.pone.0040884.

Shaughnessy, P.D. (1980) Entanglement of cape fur seals with man-made objects. *Marine Pollution Bulletin* 11, 332-336.

Shaughnessy, P.D., Troy, S.K., Kirkwood, R. & Nicholls, and A.O. (2000) Australian fur seals at Seal Rocks, Victoria: pup abundance by mark-recapture estimation shows continued increase. *Wildlife research* 27, 629-633.

Sheavly, S. B. (2007). *National Marine Debris Monitoring Program: Final Program Report, Data Analysis and Summary.*, United States Environmental Protection Agency, Washington, D.C.

Sheavly, S. B. (2010) National Marine Debris Monitoring Program Lessons Learned. Virginia Beach, VA.

Silvertown, J. (2009). A new dawn for citizen science. *Trends in Ecology & Evolution* 24, 467-471.

Talsness, C. E., Andrade, A. J. M., Kuriyama, S. N., Taylor, J. A. & vom Saal, F. S. (2009). Components of plastic: experimental studies in animals and relevance for human health. *Philosophical Transactions of the Royal Society B-Biological Sciences* 364, 2079-2096, doi:10.1098/rstb.2008.0281.

Tanaka, K. Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M., & Watanuki, Y. (2013). Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. *Marine Pollution Bulletin* 69, 219-222.

Teuten, E. L. Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Bjorn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Pham, H.V., Tana, T.S., Prudente, M., Boonyatumanond, R., Zakaria, M.P., Akkhavong, K., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagino, Y., Imamura, A., Saha, M., Takada, H. (2009). Transport and release of chemicals from plastics to the environment and to wildlife. *Philosophical Transactions of the Royal Society B-Biological Sciences* 364, 2027-2045, doi:10.1098/ rstb.2008.0284.

Thompson, R.C., La Belle, G.E., Bouwman, H. & Neretin, L. (2011). STAP (2011). Marine Debris as a Global Environmental Problem: Introducing a solutions based framework focused on plastic. A STAP Information Document. Global Environment Facility, Washington, DC.

van Franeker , J. A., Blaize, C., Danielsen, J., Fairclough, K., Gollan, J., Guse, N., Hansen, P., Heubeck, M., Jensen, J., Guillou, G. L., Olsen, B., Olsen, K., Pedersen, W.W.M., & Turner, D. M. (2011). Monitoring plastic ingestion by the northern fulmar *Fulmarus glacialis* in the North Sea. *Environmental Pollution* 159, 2609-2615.

Tulloch, A.I.T., Possingham, H.P., Joseph, L.N., Szabo, J., & Martin, T.G. (2013). Realizing the full potential of citizen science monitoring programs. *Biological Conservation* 165, 128-138.

Vegter, A., Barletta, M., Beck, C., Borrero, L., Burton, H., Campbell, M., Eriksen, M., Eriksson, C., Estrades, A., Gilardi, K., Hardesty, B.D., Assunção I do Sul, J., Lavers, J., Lazar, B., Lebreton, L., Nichols, W.J., Ramirez Llodra, E., Ribic, C., Ryan, P.G., Schuyler, Q., Smith, S.D.A., Takada, H., Townsend, K., Wabnitz, C., Wilcox, C., Young, L., & Hamann, M. (2014). Global research priorities for the management and mitigation of plastic pollution on marine wildlife. *In press Endangered Species Research*.

Vadja, A.M., Barber, L.B., Gray, J.L., Lopez, E.M., Woodline, J.D., & Norris, D.O. (2008). Reproductive disruption in fish downstream from an estrogenic wastewater effluent. *Environmental Science and Technology*, 42, 3407-3414.

Wilcox, C., Hardesty, B.D., Sharples, R., Griffin D.A., Lawson, T.J. & Gunn, R. (2013). Ghost net impacts on globally threatened turtles, a spatial risk analysis for northern Australia. *Conservation Letters* DOI:10.1111/conl.12001.

Wilcox, C., Heathcote, G., Goldberg, L., Gunn, R., Peel, D. & Hardesty, B.D. (2014). Understanding the sources, drivers and impacts of abandoned, lost and discarded fishing gear in northern Australia. *Conservation Biology* DOI: 10.1111/cobi.12355.

Wood, S. (2008). R Package 'mgcv'. Mixed GAM computational vehicle with GCV/AIC/REML smoothness estimation. cran.r-project.org/web/packages/mgcv/mgcv.pdf.

LETTER

Ghostnet impacts on globally threatened turtles, a spatial risk analysis for northern Australia

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Abstract

As human population growth continues, so too does our waste, often with unintended consequences for wildlife. The estimated 640,000 tons of fishing gear lost, abandoned, or discarded annually exerts a large but uncertain impact on marine species. These "ghostnets" drift in the ocean and can fish unattended for decades (ghost fishing), killing huge numbers of commercially valuable or threatened species. We developed an integrated analysis combining physical models of oceanic drift with ecological data on marine turtle species distribution and vulnerability to make quantitative predictions of threat. Using data from beach cleanups and fisheries in northern Australia, we assessed this biodiversity threat in an area where high densities of ghostnets encounter globally threatened turtles. Entanglement risk is well-predicted by our model, as verified by independent strandings data. We identified a number of previously unknown high-risk areas. We are also able to recommend efficient locations for surveillance and interception of abandoned fishing gear. Our work points the way forward for understanding the global threat from marine debris and making predictions that can guide regulation, enforcement, and conservation action.

Introduction

Human activities impact nearly all ecosystems (Glover & Smith 2003; Halpern *et al.* 2007, 2008), with the exponentially increasing flood of human debris and rubbish being one of the major threats to marine ecosystems (Ryan & Moloney 1993; Derraik 2002; Thompson *et al.* 2004). Annually, an estimated 640,000 tons of fishing gear is lost, abandoned, or discarded (Macfayden *et al.* 2009) exerting a large but uncertain impact on marine wildlife. This waste can "ghost fish" unattended for years or even decades, killing huge numbers of commercially valuable or threatened species (Laist 1987, 1997) resulting in loss of food resources and decreased biodiversity. Although we know there are tremendous quantities of rubbish in our oceans (Thompson *et al.* 2004), far less is known about where the debris occurs, what species it interacts with and what the direct impacts are of those interactions (Derraik 2002; Mrosovsky *et al.* 2009).

Much available information on marine debris comes from coastal cleanups. Data on the distribution of debris at sea are scarce, largely due to the expense of collecting these data, which requires use of aircraft or vessels (e.g., Thompson *et al.* 2004; Barnes & Milner 2005; Pichel *et al.* 2007). Progress has been made in predicting the distribution of marine debris at sea (Maximenko *et al.* 2012), although predictions have only recently incorporated any aspects of debris sources as driving variables (Lebreton *et al.* 2012). Critically, to date none of these efforts at modeling the distribution and fate of debris has taken the next step and analyzed the ecological effects of the debris.

Our work extends existing analyses beyond a description of where debris occurs, to estimating its impact on biodiversity. We accomplish this by adding two fundamental innovations to existing analyses of marine debris. First, we use empirical data from coastal surveys as a driving variable in a model of oceanic drift to estimate the density of marine debris across a large geographic region.

Previously, debris density has been estimated based on equilibrium assumptions without empirical data on debris sources (e.g., Maximenko *et al.* 2012), meaning that density estimates are only equilibrium estimates and are not useful for estimating ecological impact of debris. Second, we use a risk analysis approach to model impacts of debris on species affected by ghostnets. We identify species impacted using coastal survey data, and then model the encounter rate for these species using the spatial overlap in the predicted density of debris and the vulnerable species.

We focus on ghostnets for three reasons. First, ghostnets are expected to exert a disproportionate impact on marine species. Composing only 20% of marine debris, the 640,000 tons of fishing gear lost annually by commercial fisheries (Derraik 2002) is designed to capture wildlife—often killing unintended species. For example, up to 40,000 fur seals were killed each year by unintentional entanglement which resulted in an annual population decline estimated at 4–6% (Weisskopf 1988; Derraik 2002). Second, ghostnets are a global problem. They are even found on remote islands such as Midway Atoll, thousands of kilometers from commercial ports or local net-based fishing operations (Hardesty 1998, personal observation). Therefore, developing tools to understand their impacts and to suggest potential solutions has broad applications. Third, ghostnets are a particular issue along the northern coast of Australia, with concentrations of derelict nets washing onshore in the Gulf of Carpentaria (GOC) of up to 3 tons/km in some areas, as high as or higher than any other area in Oceana and southeast Asia (Kiessling 2002). Derelict gear in this region has been observed to entangle invertebrates, teleost fish, sharks, turtles, crocodiles, and dugongs (Gunn *et al.* 2010). Addressing this issue requires understanding the sources of these nets. To date, it has been possible to identify the country of manufacture or flag state of the vessels for ca. 55% of the nets, which include trawl, gillnet, and longline gear originating from fisheries in Taiwan, Indonesia, Korea, Australia, Japan, and Thailand (Gunn *et al.* 2010). However, it is unclear where this fishing gear was lost due to the high volume of illegal and unreported fishing in the region.

Our integrated analysis successfully utilizes disparate data types in a novel way: we combine physical models of oceanic drift and beach cleanup data to estimate the distribution of ghostnet fishing in the Gulf. We combine these estimates with ecological data on species distribution and vulnerability to make quantitative predictions of threat. Finally, we test our predictions of threat using independent data on entanglements, to ensure that our model accurately captures the system dynamics. Our analysis integrates existing information and tools in a novel manner, pointing a way forward in understanding the global marine debris threat by making predictions that can guide regulation, enforcement, and conservation action.

Methods

The 5,491 ghostnets used in our analyses were collected from beaches around the GOC as part of a large-scale coastal cleanup (2005–2009). Each cleanup site was exhaustively searched and nets were removed or destroyed onsite. Based on comparison with net observations from a systematic aerial survey, the cleanup data were representative of the spatial distribution of nets in the GOC region. For each net in the cleanup data, net size and any animals caught were recorded. Because >80% of animals recorded in nets were marine turtles, we concentrated on evaluating the expected interactions between nets and turtles. Turtles identified in nets and used in analyses included 53 Olive Ridley, 35 Hawksbill, 14 Green, and 3 Flatback turtles.

We created potential paths of drifting nets by simulating nets lost at sea in the region and following their tracks over time. Because the actual sources of the nets are unknown, simulated drifting nets were released on a regular grid spanning 115–152°E and 16–10°S on a daily basis (1996–2007). Each release was at a random location within a 4° × 4° grid cell. Simulated nets were tracked for 2 years, or until they drifted outside 110–156° longitude or 8–20° latitude (Figure 1A). Paths were estimated using a Runge–Kutta fourth order integration of daily velocity estimates based on velocity fields generated by the Bluelink Ocean Data Assimilation System for the relevant period for each net (Oke *et al.* 2008).

We recorded the track of any drifting net that came within 25 km of an observed net from beach cleanup data. We used this proximity approach because available oceanographic models are unlikely to be accurate enough near shore to use exact point locations of nets (Wolanski & Ridd 1990; Burford *et al.* 2009). We determined whether we had an adequate sample of simulated drifting nets by examining the change in the distribution predicted for nets from a site as nets were added to the data set of potential net tracks. When the number of new grid cells did not increase as additional potential tracks were added, we assumed all likely pathways for nets to arrive at a site had been sampled and were included in the data set. We evaluated the sample size of our simulated nets applied to four locations around the GOC, including sites with high and low net densities. We used 48,148 tracks in total: with this number the spatial distribution of nets from our four evaluation sites had stabilized.

Data are sparse for at-sea distribution of marine turtles in the GOC. Although most nesting sites are known

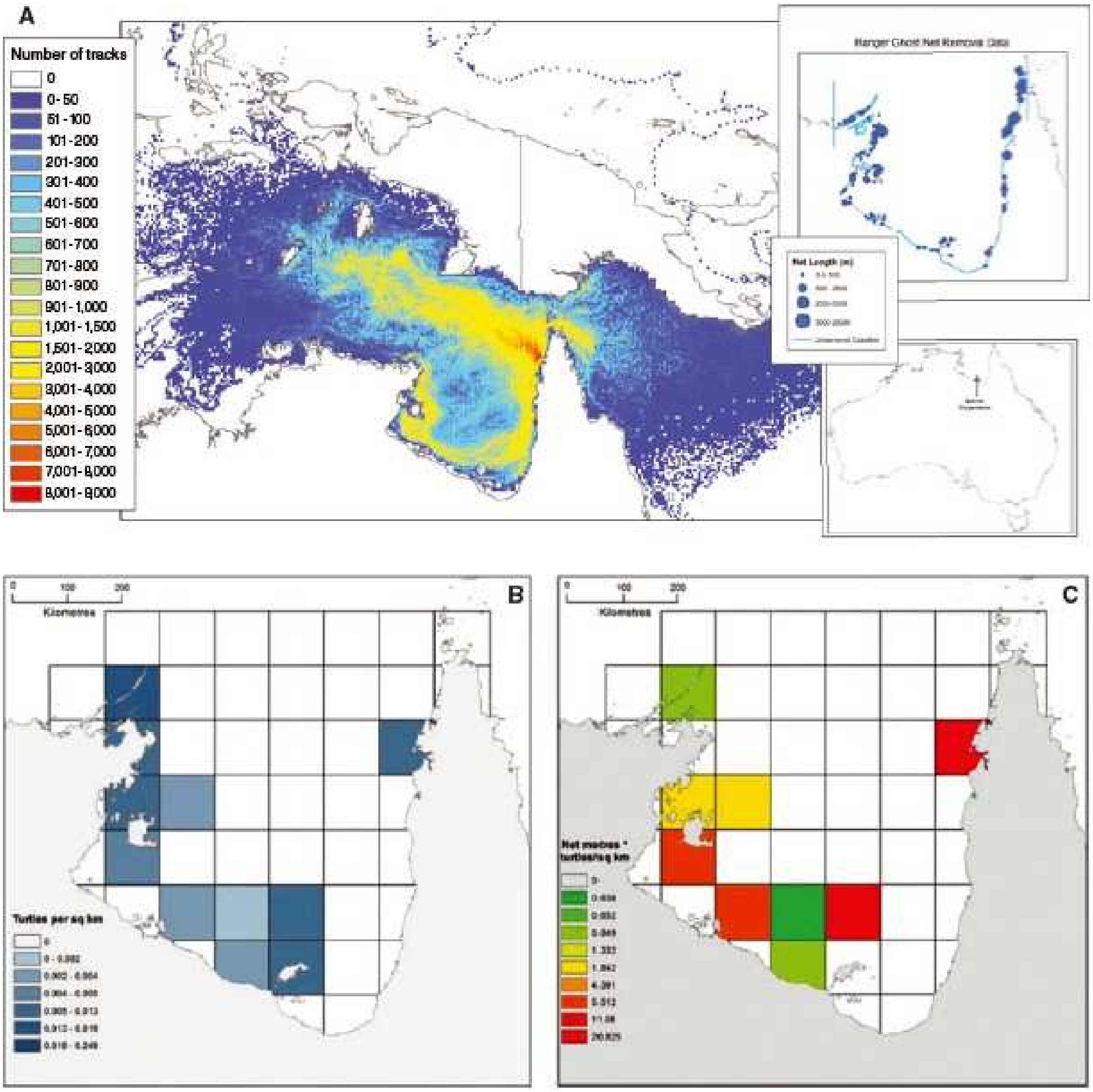

Figure 1 Components of a risk model for ghostnet impacts to turtles. (A) Potential ghostnet tracks based on daily particles releases (1996–2008) and (inset) total length of net found at sites along the GOC coastline. (B) Estimated at-sea distribution of marine turtles in the GOC based on catch per unit of effort by research and commercial trawl vessels. (C) Predicted threat to turtles from ghostnets in the GOC. Threat is based on the probability of encounter, where encounter is predicted as the product of relative turtle density (measured as turtles caught per unit of trawl effort) and ghost fishing effort (expected value of the number of meters of abandoned fishing net passing through each cell). Final units are expected relative rate of turtle-net encounters.

and there are data on the number of individuals nesting at each location (see http://www.environment.gov.au/coasts/species/turtles/), the distribution of nesting sites is not representative of the at-sea distribution of turtles. The best information on turtle densities at-sea in the GOC are bycatch records from trawl data taken as part of the prawn trawl fishery operating in the region. We used these data to estimate the spatial distribution of marine turtles, calculating the relative density in 51 5° latitude × 5° longitude cells covering the region. The data set contained 178,056 trawl records (1990–2009) with start location, net size, trawl duration, and number of turtles caught. Turtles caught included 105 Flatback, 52 Olive Ridley, 12 Loggerhead, 10 Green, 6 Hawksbill, and 66 unidentified turtles. We aggregated species and ignored time of year when estimating the spatial distribution of turtles, as there were no significant differences based on the data. The area swept (km^2) was calculated based on net size and trawl duration as a measure of sampling effort. Relative densities were based on the catch of turtles per unit of fishing effort calculated by number of turtles caught/area swept.

We validated the risk model by comparing model predictions to observations collected by ranger groups of the turtles in nets that washed up on beaches. We did this using the following logic: to be observed once caught in a high-risk area, a turtle had to remain in the net until it reached a location near the coast, and once in that area it had to wash onshore.

We identified a buffer along the coastline extending 25 km seaward from the coast dividing this buffer into 1 km × 1 km cells (Figures 2A and B). We then assembled all drift trajectories that left any of the 5° cells identified as having both high turtle density and high ghostnet fishing effort and subsequently crossed the boundary of the 25 km coastal buffer. For each track, we identified each contiguous period during which it was in one of the 1 km × 1 km cells in the coastal buffer. We used this sample of tracks to estimate the relative frequency of turtles washing up entangled in nets along the GOC coast.

Considering a single drifting track and event j as the continuous presence of a net (i.e., the drifting net) in a single cell in the coastal buffer for some period of time, $\mathrm{pr}\{T_j\}$, the probability of the net washing onshore with a turtle in it as the net passes through the coastal cell is

$$\mathrm{pr}\{T_j\} = 1 - \prod_{t_j=t'_j}^{t_j=t''_j} (1 - ((1 - \mathrm{pr}\{loss\})^{t'_j-1} \times (1 - \mathrm{pr}\{loss\})^{t_j-t'_j}\, \mathrm{pr}\{strand\})), \qquad (1)$$

where t'_j is the first time (i.e., day) in event j, t''_j is the last time for event j, i.e., the final time the track is in the cell during event j. Here, $\mathrm{pr}\{loss\}$ is the chance that a turtle caught in a net is lost from that net in a day, and $\mathrm{pr}\{strand\}$ is the chance a net within 25 km of the coast washes onshore in a given day. We also account for $\mathrm{pr}\{F_j\}$, the probability that the net did not wash ashore from a different coastal cell, prior to the time the drifting track entered the cell of interest. This is

$$\mathrm{pr}\{F_j\} = \prod_{t=1}^{t=t'_j} ((1 - \mathrm{Pr}\{strand\})^{\Theta(t)}),$$

where $\Theta(t)$ is an indicator function, taking the value of 1 if the net is in any coastal cell on day t and 0 if it is not. We combine the two equations above to get $\mathrm{pr}\{O_j\}$, the probability of observing a turtle during event j as

$$\mathrm{pr}\{O_j\} = \left(1 - \prod_{t_j=t'_j}^{t_j=t''_j} (1 - ((1 - \mathrm{pr}\{loss\})^{t'_j-1} (1 - \mathrm{pr}\{loss\})^{t_j} \times \mathrm{pr}\{strand\}))\right) \prod_{t=1}^{t=t'_j} ((1 - \mathrm{Pr}\{strand\})^{\Theta(t)}). \qquad (2)$$

To calculate the expected number of turtles stranding in nets from each cell, we search for any event j for each cell in the coastal buffer from our data set of tracks that entered the buffer. We sum (2) for each of those events for a given cell, yielding the expected number of turtles stranding in nets from that cell in the coastal buffer. We assume that strandings from a cell in the buffer occur at the nearest point on the coastline to that cell. Summing all coastal cells we then get the relative density of nets strandings with turtles. This is a relative density, as the daily probabilities of loss from net or stranding are unknown. However, based on a sensitivity analysis with $\mathrm{pr}\{loss\}$ and $\mathrm{pr}\{strand\}$ taking a range of values between 0.01 and 0.2, these probabilities rescale the predicted relative density of strandings, but do not affect the spatial pattern across sites.

Results

We took a risk-based approach to understanding the biodiversity impacts of ghostnets, focusing on estimating the rate and spatial distribution of encounters with turtles. Accordingly, we estimated likely tracks of ghostnets using an ocean current model, given final locations of actual nets observed onshore in the GOC (Figure 1A). Net tracks are concentrated along the shore of the GOC and northwest into the Arafura Sea (Figure 1A). Accounting for net size (Figure 1A, inset), we find that these are areas of concentrated fishing effort by ghostnets. Taking into account the distribution of turtles in the GOC (Figure 1B), we find that entanglement risk is concentrated in one area along the eastern margin of the GOC, and in a wide section in the southwest extending up the west coast (Figure 1C).

There is good concordance between the distribution of turtles predicted to strand on beaches based on our model and the actual frequencies of turtles found in ghostnets, with all observations falling in areas that are predicted to be likely to have entangled animals, and vice versa (Figures 2A and B). Removing one outlying observation of 81 turtles in the northeast section of the GOC with an artificially high number of turtles due to more intensive

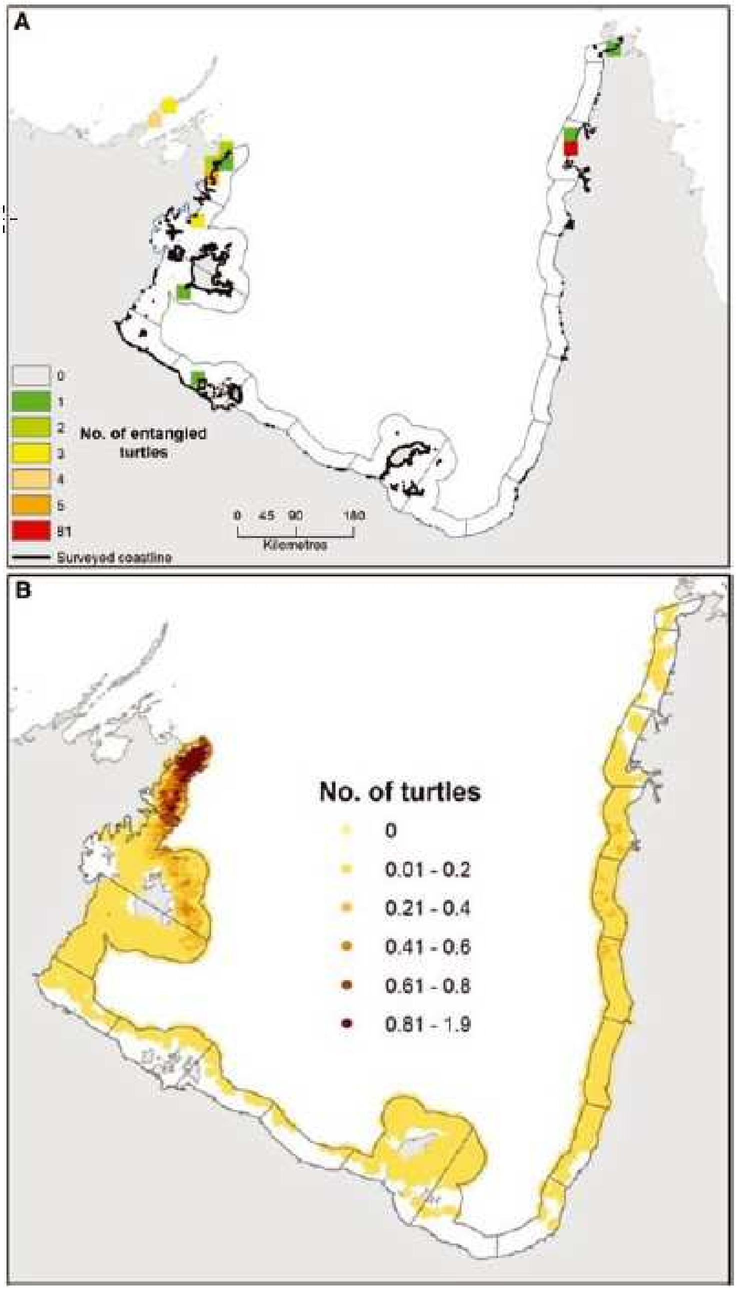

Figure 2 Validation of the risk model. Predictions were aggregated into 100-km sections along the coastline for analysis, shown by polygons. (A) Distribution of turtles entangled in ghostnets removed from beaches by ranger teams. Black outlines along the coast show areas searched, blue delineates areas that were not searched. (B) Distribution of the predicted number of turtles stranding on beaches based on the risk model.

sampling at that site, a linear regression of observed density of strandings on predicted density, weighted by proportion of the coastline searched, was highly significant ($R^2 = 0.88$, $P = 1.84e\text{-}08$), giving further confidence in the appropriateness of the model.

Discussion

We focused on risk to marine turtles because they comprise >80% of the observed animals entangled, entanglement is among the most common known sources of their

Figure 3 An example of the drifting pattern of a tracked net (with geolocator) in the GOC. The net (green dots show track locations) validates our model, showing the pattern we predicted and highlighting the lack of ghostnets arriving in the southern Gulf.

mortality in Australia and the primary one reported in the Gulf region, and Australia has 6 of the 7 threatened marine turtle species, including large portions of the remaining global populations for several species (Limpus & Fien 2009; Biddle & Limpus 2011). Mapping predicted encounters, we found that risk is high not only where entangled turtles have been observed, but also in the southwestern GOC in an area that was not identified from the strandings data: a prediction that could not be made in the absence of our integrated analysis. Furthermore, testing our approach in a geographic region where there are good data are critical for assessing its utility in other regions.

The match between our model predictions and observed entanglements was very close ($R^2 = 0.88$), indicating that net entanglement occurs in areas with high ghostnet density and high turtle density, and that we have accurately represented these distributions. This suggests that encounters can be used as a reasonable measure of risk (Figure 1C) and provides an excellent example of the utility of applying this approach to other marine and coastal systems. A map of an actual net tracked in the GOC provides illustration of our model as it follows the pattern predicted, sweeping clockwise through the Gulf (Figure 3).

The fit between our predictions and the observed entanglements also suggests that entanglement is driven by the frequency with which turtles encounter debris rather than based on foraging behavior of turtles. Ideally, we would have tested for species differences in entanglement rates directly by comparing relative densities of each turtle species in an area with the observed entanglement rate in that area. However, a direct test was not possible due to the limited number of turtle strandings observed and a lack of detectable differences between species distributions.

Our approach is readily expandable to the national or even global scale for a wide range of taxa. Over 200 species are known to be affected by marine debris, including seabirds, marine mammals, and sea turtles (Laist 1997). Recently, other researchers have developed predicted global densities of oceanic marine debris (Lebreton *et al.* 2012). Combining models such as these with species distribution data, even at coarse scales, would provide estimates of relative encounter rates of debris across species and is an important next step. This analysis could identify global hotspots for impact, which might differ from the highest concentrations of debris alone, and can assist in identifying species to further investigate as those potentially heavily impacted. The end result of such a global analysis could be a list of species and their relative level of debris encounter, which might form the basis for prioritizing actions to mitigate this impact. This is critical because data from breeding sites alone underestimates the number of animals killed at sea (Good *et al.* 2010). Australia has identified exactly this information requirement as a component of the national marine debris policy (actions 2.1 and 2.4, Anonymous 2009).

Our results also suggest several direct actions for addressing ghostnet issues. It appears that most nets enter the Gulf from the northwest and move along its northeastern shore, following a clockwise path. Hence, it would be possible to effectively monitor nets arriving here, via aerial or satellite surveys, focusing on a relatively small area north of the GOC. Coastal surveillance programs might provide an opportunity for incorporating this area in their overflights. Also, tracks suggest that intercepting nets along the northeast of the Gulf would prevent much of their impact, as they sweep through the GOC and encounter most of the high-density turtle areas along the south and east margins. It would be relatively efficient to intercept ghostnets in this region as there is a major port along the northeastern GOC that could provide an operations center.

Management that incentivizes gear return or provides waste disposal sites locally may also reduce gear loss. In South Korea, a buyback program helps to reduce the 23,900 tons of fishing gear abandoned each year by recovering up to 20% of the gear by weight (Cho 2009). However, management costs money—the Korean program yields 1.2 kg of gear/U.S.$. Cleanup data and preliminary surveys with fishers indicate that most of the drifting nets in the Arafura and Timor Seas north of Australia are from Illegal fishing vessels or from legal Indonesian vessels, with a minor component from Australian vessels (Kiessling 2002). However, causes of gear loss/abandonment are complex and involve overcapacity leading to crowding and gear conflicts (R. Gunn, unpublished data). Thus, incentive programs like the Korean one may work in the Arafura/Timor Sea, but must be carefully designed keeping the drivers specific to this system in mind.

Prioritizing investment to tackle this global problem requires understanding the sources, locations, and species affected, pointing to a critical need for global analyses of ghost fishing and other marine debris impacts. Applying our model at a global scale and incorporating those species most likely to be impacted will allow us to focus resources appropriately to best mitigate the impacts of ghostnets and other marine debris.

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References

Anonymous. (2009). Threat abatement plan for the impacts of marine debris on vertebrate marine life. *Australian Government Department of the Environment, Water, Heritage and the Arts*. Canberra Australia. 16 pp. Available from: http://www.environment.gov.au/biodiversity/threatened/publications/tap/marine-debris.html. Accessed 15 June 2012.

Barnes, D.K.A. & Milner, P. (2005). Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. *Mar. Biol.*, **146**, 815-825.

Biddle, T.M. & Limpus, C.J. (2011). Marine wildlife stranding and mortality database annual reports 2005–2010. Marine Turtles. *Conservation Technical and Data Report*, **2010**(1), 1-124.

Burford, M.A., Rothlisberg, P.C. & Revill, A.T. (2009). Sources of nutrients driving production in the Gulf of Carpentaria, Australia: a shallow tropical shelf system. *Mar. Freshwater Res.*, **60**, 1044-1053.

Cho, D.-O. (2009). The incentive program for fishermen to collect marine debris in Korea. *Mar. Pollut. Bull.*, **58**, 415-417.

Derraik, J.G.B. (2002). The pollution of the marine environment by plastic debris: a review. *Mar. Pollut. Bull.*, **44**, 842-852.

Glover, A.G. & Smith, C.R. (2003). The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. *Environ. Conserv.*, **30**, 219-241.

Good, T.P., June, J.A., Etnier, M.A. & Broadhurst, G. (2010). Derelict fishing nets in Puget Sound and the northwest straits: patterns and threats to marine fauna. *Mar. Pollut. Bull.*, **60**, 39-50.

Gunn, R., Hardesty, B.D. & Butler, J. (2010). Tackling "ghost nets": local solutions to a global issue in northern Australia. *Ecol. Manage. Restor.*, **11**, 88-98.

Halpern, B.S., Selkoe, K.A., Micheli, F. & Kappel, C.V. (2007). Evaluating and ranking the vulnerability of marine ecosystems to anthropogenic threats. *Conserv. Biol.*, **21**, 1301-1315.

Halpern, B.S., Walbridge, S., Selkoe, K.A. *et al.* (2008). A global map of human impact on marine ecosystems. *Science*, **319**, 948-952.

Kiessling, I. (2002). Finding solutions: derelict fishing gear and other marine debris in N. Australia. *Key Ctr for Trop. Wild. Mgmt*.

Laist, D.W. (1987). Overview of the biological effects of lost and discarded plastic debris in the marine environment. *Mar. Pollut. Bull.* **18**, 319-326.

Laist, D.W. (1997). Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In J.M. Coe & D.B. Rogers, editors. *Marine debris—sources, impacts and solutions*. Springer-Verlag, New York.

Lebreton, L.C.-M., Greer, S.D. & Borrero, J.C. (2012). Numerical modelling of floating debris in the world's oceans. *Mar. Pollut. Bull.*, **64**, 653-661.

Limpus, C. & Fien, L. (2009). *A biological review of Australian marine turtles*. Queensland Government, Environmental Protection Agency, Brisbane. 96 pp.

Macfayden, G., Huntington, T. & Cappell, R. (2009). Abandoned, lost or otherwise discarded fishing gear. UNEP Regional Seas Reports and Studies, No. 185; FAO Fisheries and Aquaculture Technical Paper, No. 523. Rome, UNEP/FAO. 115 pp.

Maximenko, N., Hafner, N. & Niiler, P. (2012). Pathways of marine debris derived from trajectories of Lagrangian drifters. *Mar. Pollut. Bull.*, **65**, 51-62.

Mrosovsky, N., Ryan, G.D. & James, M.C. (2009). Leatherback turtles: the menace of plastic. *Mar. Pollut. Bull.*, **58**, 287-289.

Oke, P. R., Brassington, G.B., Griffin, D.A. & Schiller, A. (2008). The Bluelink ocean data assimilation system (BODAS). *Ocean Model.*, **21**, 46-70.

Pichel, W.G., Churnside, J.H., Veenstra, T.S. *et al.* (2007). Marine debris collects within the North Pacific subtropical convergence zone. *Mar. Pollut. Bull.*, **54**, 1207-1211.

Ryan, P.G. & Moloney, C.L. (1993). Marine litter keeps increasing. *Nature*, **361**, 23.

Thompson, R.C., Olsen, Y., Mitchell, R.P. *et al.* (2004). Lost at sea: Where is all the plastic? *Science*, **304**, 838.

Weisskopf, M. (1988). Plastic reaps a grim harvest in the oceans of the world (plastic trash kills and maims marine life). *Smithsonian*, **18**, 58.

Wolanski, E. & Ridd, P. (1990). Mixing and trapping in Australian coastal waters. Pages 165-183 in R.T. Cheng, editor. *Coastal and estuarine studies*, Vol. **38**. Springer-Verlag, New York.

Conservation Biology

Contributed Paper

Understanding the Sources and Effects of Abandoned, Lost, and Discarded Fishing Gear on Marine Turtles in Northern Australia

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Abstract: *Globally, 6.4 million tons of fishing gear are lost in the oceans annually. This gear (i.e., ghost nets), whether accidently lost, abandoned, or deliberately discarded, threatens marine wildlife as it drifts with prevailing currents and continues to entangle marine organisms indiscriminately. Northern Australia has some of the highest densities of ghost nets in the world, with up to 3 tons washing ashore per kilometer of shoreline annually. This region supports globally significant populations of internationally threatened marine fauna, including 6 of the 7 extant marine turtles. We examined the threat ghost nets pose to marine turtles and assessed whether nets associated with particular fisheries are linked with turtle entanglement by analyzing the capture rates of turtles and potential source fisheries from nearly 9000 nets found on Australia's northern coast. Nets with relatively larger mesh and smaller twine sizes (e.g., pelagic drift nets) had the highest probability of entanglement for marine turtles. Net size was important; larger nets appeared to attract turtles, which further increased their catch rates. Our results point to issues with trawl and drift-net fisheries, the former due to the large number of nets and fragments found and the latter due to the very high catch rates resulting from the net design. Catch rates for fine-mesh gill nets can reach as high as 4 turtles/100 m of net length. We estimated that the total number of turtles caught by the 8690 ghost nets we sampled was between 4866 and 14,600, assuming nets drift for 1 year. Ghost nets continue to accumulate on Australia's northern shore due to both legal and illegal fishing; over 13,000 nets have been removed since 2005. This is an important and ongoing transboundary threat to biodiversity in the region that requires attention from the countries surrounding the Arafura and Timor Seas.*

Keywords: bycatch, cryptic mortality, derelict nets, gill net, illegal fishing, IUU, trawl

Entender las Fuentes y Efectos de Equipo de Pesca Abandonado, Perdido y Desechado sobre las Tortugas Marinas del Atlántico Norte

Resumen: *A nivel global, 6.4 millones de toneladas de equipo de pesca se pierden anualmente en los océanos. Este equipo (p. ej.: redes fantasmas), ya sea perdido accidentalmente, abandonado o desechado deliberadamente, es una amenaza para la vida marina mientras se encuentre flotando con las corrientes dominantes y siga enredando organismos marinos indiscriminadamente. El norte de Australia tiene una de las densidades más altas de redes fantasmas en el mundo, con hasta tres toneladas llegando a la orilla por kilómetro de línea costera al año. Esta región es útil para poblaciones significativas a nivel global de fauna marina amenazada internacionalmente, incluyendo a seis de las siete tortugas marinas existentes. Examinamos la amenaza que las redes fantasmas presentan para las tortugas marinas y evaluamos si las redes asociadas con ciertas pesquerías están vinculadas con el enredamiento de tortugas al analizar las tasas de captura de tortugas y pesqueras potenciales de origen de casi 9,000 redes halladas en la costa norte de Australia. Las redes con mallas relativamente más grandes y un menor tamaño de cordel en nuestra muestra (p. ej.: redes de flote pelágico) tuvieron la probabilidad más alta de enredamiento para tortugas. El tamaño de la red fue importante; pareciera que las redes más grandes atraen a las tortugas, lo que incrementa su*

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tasa de captura. Nuestros resultados señalan a problemas con las pesqueras que usan redes de arrastre y de flotación, la anterior debido a un gran número de redes y la última debido a tasas altas de captura resultantes del diseño de la red. Las tasas de captura para redes de malla fina pueden alcanzar hasta 4 tortugas/100 m de largo de la red. Estimamos que el número total de tortugas capturadas por las 8,690 redes fantasmas que muestreamos se encontró entre 4,866 y 14, 600, asumiendo el uso de redes para un año. Las redes fantasmas siguen acumulándose en la costa norte de Australia debido a la pesca legal e ilegal; más de 13, 000 redes han sido removidas desde 2005. Esta es una importante amenaza continua y transfronteriza para la biodiversidad en la región que requiere de atención de los países que rodean los mares Arafura y Timor.

Palabras Clave: captura accesoria, IUU, mortalidad críptica, pesca ilegal, red de arrastre, red de malla, redes descuidadas

Introduction

Introduction of plastic debris into the marine environment is of increasing concern and has been identified as an emerging global issue under the Convention on Biological Diversity (Sutherland et al. 2010; Thompson et al. 2012). Derelict fishing gear in particular is of major concern because, although it makes up <10% of marine debris, it can have very damaging effects on marine fauna (Macfayden et al. 2009). It is estimated that 6.4 million tons of fishing gear are lost in the oceans annually (Macfayden et al. 2009). Whether they are abandoned, lost accidently, or deliberately discarded, the number of these so-called ghost nets in the world's oceans is increasing (Kiessling 2003; Macfayden et al. 2009). In areas where nets accumulate due to oceanic currents, densities can be high. For instance, Gilardi et al. (2010) report that more than 52 tons of derelict fishing gear accumulates annually in the northwest Hawaiian Islands.

Derelict gear from fisheries has been recognized as a threat to marine wildlife since the 1980s (Laist 1987; Macfayden et al. 2009). Once lost, derelict gear drifts and can continue to entangle wildlife indiscriminately for periods from days to multiple decades (Matsuoka et al. 2005; Gilardi et al. 2010). Entanglement can lead to drowning, inflict severe lacerations, increase drag while swimming and foraging, prevent diving and feeding, and increase exposure to predators (Ceccarelli 2009; Macfayden et al. 2009; Gilardi et al. 2010). The advent of synthetic materials made nets cheaper, more durable, lighter weight, and stronger (Laist 1987). These properties, while beneficial for fishing, also make them more buoyant, longer lasting, and more difficult for trapped animals to break free from, substantially increasing the damage associated with lost gear (Laist 1987; Derraik 2002; Gilardi et al. 2010).

A recent review documented that 663 species are affected by marine debris: a large fraction of those effects are due to entanglement (Thompson et al. 2012). Entanglement in marine debris, and derelict fishing gear specifically, is a source of mortality in a wide range of species including pinnipeds, cetaceans, marine turtles, seabirds, cephalopods, fish, crustaceans, corals, and sponges (Macfayden et al. 2009; Gilardi et al. 2010; Gilman et al. 2010). Turtles, in particular, are affected by ghost nets due to their tendency to use floating objects for shelter and as foraging stations (Kiessling 2003; White 2006).

The northern Australia coastline has one of the highest densities of derelict gear that washes ashore globally: up to 3 t · km^{-1} · $year^{-1}$ (Gunn et al. 2010; Wilcox et al. 2013). Based on oceanographic modeling, these nets likely originate from fisheries operating in the Arafura and Timor Seas, to the north of Australia (Gunn et al. 2010; Wilcox et al. 2013). Fisheries in the region target prawns, tropical snappers, sharks, squid, and tuna with a mix of gears including trawl nets, gill nets, purse seine, longline, and traps (Northridge 1991; Morgan & Staples 2006; Wagey et al. 2009; Alongi et al. 2011; Stacey et al. 2011). Additionally, there is considerable illegal, unreported, and unregulated (IUU) fishing activity occurring in the region (Resosudarmo et al. 2009; Wagey et al. 2009).

This is cause for concern because the waters of the gulf support important foraging, breeding, and nesting grounds for 6 of the world's 7 marine turtle species (Department of Environment, Water, Heritage and the Arts 2008), most of which are affected by derelict fishing gear globally (Donohue et al. 2001). Limpus (2008) stated that "turtle mortality in the Gulf of Carpentaria's 'ghost net' fishery is unquantified but appears to be hundreds, if not thousands of turtles annually."

We examined the threat ghost nets pose to marine turtles in a tropical environment. We analyzed stranding data to determine which net characteristics are associated with capture rates of marine turtles; classified the types of nets according to their characteristics to allow identification of the fisheries losing gear in the region; and linked the estimates of capture rates with the net classifications to provide predictions of damage by fishery and gear type.

Methods

Study Region and Surveys

We focused on the northern Australian coastline from east of the Gulf of Carpentaria (the gulf) across the northern Australian coastline to the northwestern coast of

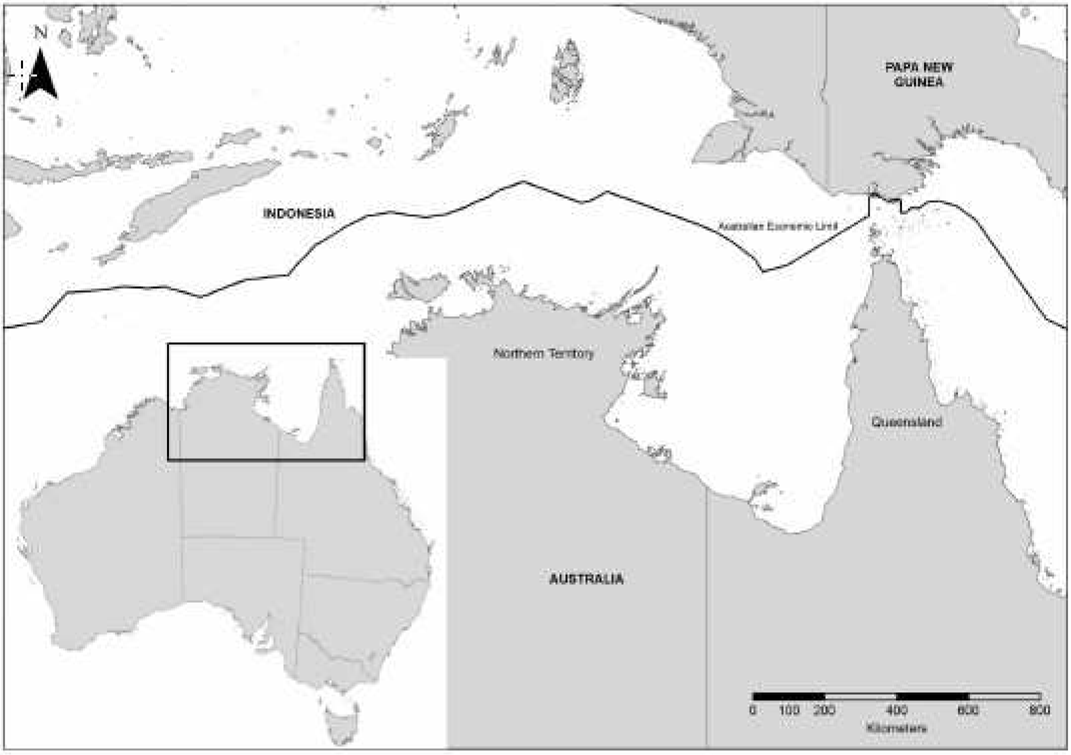

Figure 1. Study area in relation to economic exclusion zone and neighboring countries.

Western Australia (Fig. 1). Coastal debris in this region is driven by oceanic currents that circulate in a clockwise gyre. Materials are transported into the gulf by south-easterly trade winds. These winds become northwesterly during the monsoon season (Wilcox et al. 2013).

Data on stranded nets and entangled animals were collected between 2005 and 2012 by local indigenous rangers. Commercial fishers, government agencies (Australian Fisheries Management Agency, Great Barrier Reef Marine Park Authority), community groups, volunteers (Conservation Volunteers Australia), and individuals provided additional data. Data recorded included GPS position, survey date, and net information such as length, width, and height of net bundle; color; presence of attached items (lead lines, floats, wood, squid jigs, etc.); twine composition (monofilament or multistrand); twine structure (braided or twisted and single or double strands); number of strands; mesh size; twine size; and mesh knotting (presence or absence). Samples were frequently collected prior to disposal of the net. Animals associated with nets were recorded and identified to species where possible.

Data Analyses

There were 11,867 independent net records with 442 entangled animals, 76% of which were turtles. Sharks, rays, dugong, a variety of fish, and some invertebrates were also found entangled. These animals were not included in analysis due to inconsistent reporting. We anticipated data recording and entry errors, due to the limited literacy and numeracy skills of some observers. After quality control and exclusion of records with incomplete data, we retained 8690 net records, of which 137 had turtles caught in them.

We used logistic regression to investigate the effect of net size on the probability that a net contained a turtle. We were limited to using the longest dimension as a proxy for area, due to low reporting rates. There is a theoretical expectation that a larger net is more likely to catch a turtle because it samples a larger area, and thus, this effect should be included in all analyses if it is established. We evaluated both first- and second-order linear models to allow for some flexibility in the relationship between net size and probability of capture. After evaluating the effect of net size, we explored possible additional covariates in the logistic regression model with a stepwise model building approach based on Akaike's information criterion (AIC), allowing both forward and backward steps, implemented in the R statistical language (Venables & Ripley 1994; R Development Core Team 2011). We aggregated whether the net was made from monofilament or multistrand twine, and if it was multistrand, we included the number of strands (range = 1–13).

We used regression trees implemented in a conditional inference framework to explore the relationship between the catch per unit effort, expressed as turtles per meter of net length, and the various net characteristics recorded (Party package in R; Hothorn et al. 2006). This approach was a complement to our linear regression analysis, primarily to ensure that we captured the main explanatory variables and higher order interactions.

We classified the nets based on their characteristics (described above), on the assertion that the resulting groupings would correspond to different types of fishing operations. For instance, larger mesh sizes should correspond to fisheries targeting larger species (Gabriel et al. 2008). Similarly, monofilament nets and light twine might correspond to gill nets, while heavier multistrand twine could be more indicative of trawl nets (Gabriel et al. 2008). We applied a mixture-model-based cluster analysis that allowed for both continuously distributed and discrete characteristics (McLachan & Peel 2000). Parameters in the cluster analysis were estimated using the EM algorithm (sensu Dempster et al. 1977). We estimated the most parsimonious number of clusters following the established method of starting at a model with 1 cluster and adding additional clusters until the AIC reached a local minima (McLachlan & Peel 2000). We then evaluated which of these inferred types of nets (i.e., clusters) was the most environmentally harmful in terms of catch of turtles, as inferred from our logistic regression and regression tree analyses.

We calculated the total expected catch across all nets and net fragments with the fitted regression model. Due to missing data, we excluded some of the 8690 net records from these predictions: we included only the nets that had the relevant characteristics recorded. We then expanded these estimates by multiplying the sum of the expected catches across the nets we included from each net type by the ratio between the total number of nets of that type and the number included in the regression predictions. This allowed us to expand our predictions to include all 8690 nets. We assumed that nets with missing data were a random subset of the nets with all available data within each net type.

Results

Turtles found in nets on the gulf coast included flatback (*Natator depressus*, 9.9%), green (*Chelonia mydas*, 13.8%), hawksbill (*Eretmochelys imbricate*, 32.6%), loggerhead (*Caretta caretta*, 1.1%), and olive Ridleys turtles (*Lepidochelys olivacea*, 42.5%); approximately 24% of turtles were unidentified. Due to inconsistent identification, we considered all turtles together.

There was a strong effect of the length of the net on the probability that it contained turtles: longer nets caught more turtles. This effect appeared to be nonlinear because the second-order model including length and its square had a lower AIC score (1082.1) than a first-order model with length alone (1101.5). Both the length and the square of the length had highly significant coefficients (Supporting Information). The positive first-order and negative second-order terms indicated that although longer nets caught more turtles, the effect of a unit increase in length on the probability of capture decreased as the length of nets increased (Supporting Information).

Table 1. Regression coefficients for a logistic regression predicting whether a ghost net is found with a turtle in it or not based on stepwise model selection with the Akaike information criterion.

*Covariate**	*Estimate*	*SE*	*z*	*Pr(>|z|)*
Intercept	−1.90E+01	5.51E + 02	−0.035	0.97242
Length	2.48E−02	8.63E−03	2.871	0.00409
Length^2	−8.07E−05	4.57E−05	−1.766	0.07746
Multi/mono (multi)	−2.17E + 00	1.08E + 00	−2.011	0.04435
No. of strands	1.19E + 00	1.14E−01	10.388	<2e−16
Double/single (single)	1.55E + 01	5.51E + 02	0.028	0.97751
Mesh size	8.54E−04	4.30E−04	1.985	0.04714
Twine size	−1.09E + 00	1.24E−01	−8.756	<2e−16

**For factors, the code in parentheses gives the relevant level of the factor for the coefficients. For instance, in the case of Multi mono, the coefficient applies to the multi level, and the mono level has a coefficient of 0. See Supporting Information for details on net characteristics.*

The best fitting model for predicting the capture of turtles in nets included the number of strands, whether the net was double- or single-strand twine, and the size of the twine (Supporting Information, Table 1). Monofilament nets were more likely to contain turtles. For nonmonofilament nets, twines with larger numbers of strands, but smaller diameters, were more likely to contain turtles. Capture rates also increased with mesh size. The term describing whether the net has single or double twine construction was included based on the decrease in AIC; however, this parameter was not significant at the $P < 0.05$ level. Results of the regression tree analysis were consistent with these patterns: nets with twine thickness of 1–2 mm and with 3 or more strands had higher catch rates. The regression tree did not identify any complex interactions that were not included in the linear regression.

Based on AIC scores, there was statistical support for a total of 14 types of net among the nets recovered from beaches (Fig. 2). Because we were not concerned with the length of the nets, but only their characteristics, we were able to include several thousand records that had been excluded from the regression analysis, which increased the sample size to 8690 nets. Mean mesh size for the net types ranged from 50 to >900 mm; mean twine sizes also varied widely (from 1 to >6 mm (Fig. 3). Some net types, such as those in cluster 3, were relatively homogenous, in this case consisting largely of fine mesh

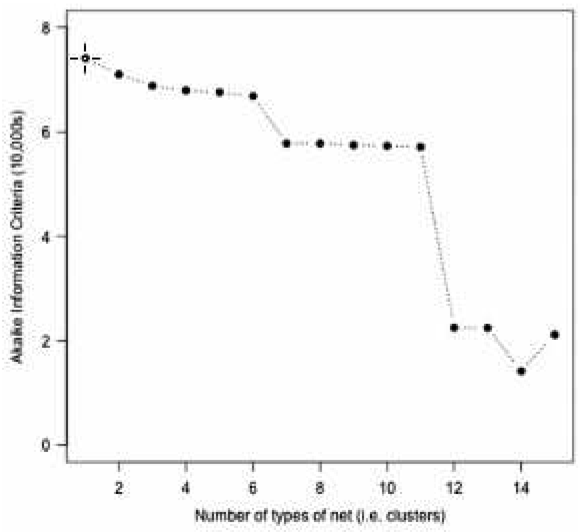

Figure 2. Statistical support for the number of types of net washing ashore in northern Australia. Net types are identified through cluster analysis, and model selection is via Akaike information criterion.

gill nets (Fig. 3). Other net types, such as those in cluster 13, included a wider range of mesh sizes and twine thickness. In this case, the range of mesh sizes was a result of the group being composed of trawl net fragments, which increase in mesh size moving out from the central section of the net.

Net types varied widely in their predicted catch rates (Fig. 4). Nets in cluster 3 had by far the highest catch rate; the expected value was just over 4 turtles/100 m of net. Net type 9 had the 2nd highest predicted catch rate. It had an expected value of approximately 3 turtles/100 m of net. It is possible that both of these nets were gill nets. Type 3 was a fine mesh gill net (e.g., for small fish) and type 9 was a larger gill net for demersal or pelagic shark. Net type 2 also fell in this group; it was likely a relatively fine mesh gill net, although with slightly heavier construction than type 3. Two of the heavy twine nets, types 5 and 14, had intermediate catch rates; expected values were approximately 1 turtle/100 m of net. In the case of type 14, this was due to the very large mesh, which increased the expected catch rate. For type 5, the increased catch rate could be due to a slightly different construction in the twisted 4 strand single twine nets because both the heavy twine and small mesh would otherwise predict low catch rates for nets with these characteristics (R.G., unpublished data). Most of the remaining net types had relatively heavy twine and medium to fine mesh, both of which were expected to have low catch rates.

We predicted that 202 turtles would be captured across all nets in each of the 14 net types based on our fitted regression model (Table 2). These predictions scaled fairly closely with the observed captures (Table 2). Nets differed widely in their abundances. Types 2, 3, 7, and 10 composed most of the nets found and thus contributed most of the expected catch. Net type 2, a smaller mesh and twine trawl net, was by far the most common. Types 2 and 10, which were slightly heavier trawl nets, also occurred in the largest fragments. Although less common, net type 3 had a relatively high expected catch, owing to a combination of net characteristics that lead to high catch rates. Net type 9, which was composed of large mesh and fine twine, had the second highest catch rate of all the net types, but it had a relatively low expected total catch due to its relative rarity (Fig. 4, Table 2).

Discussion

Ghost Nets with the Largest Effect

As mesh size increased, nets were more likely to ensnare marine turtles. This result was similar to those from southern Brazil (Lopez-Barrera et al. 2012) and the U.S. mid-Atlantic (Murray 2009). According to Gilman et al. (2010), gill net fisheries that target marine turtles often use nets with a relatively large mesh size (from 20 to 60 cm). Nets with small twine sizes, from 1.1 to 2 mm, had the highest probability of catching marine turtles of those in our sample. Few studies have related twine size and turtle entanglements in fishing nets, although the sizes recorded for nets with high bycatch in other studies were mostly smaller than 2.5 mm (Trent et al. 1997; Romero 2008; Solarin et al. 2008; Alfaro-Shigueto et al. 2010).

Based on net design principles, larger mesh size and finer twine would be expected to increase the level of ensnarement for turtles coming in contact with nets (Gabriel et al. 2008). In a study of catch rates of turtles, Lopez-Barrera et al. (2012) found this to be the case, a result that suggests finer twine causes a more thorough entrapment. Macfayden et al. (2009) argue that the relatively thicker twine diameter of trawl netting makes it more visible and increases the encrusting community on the net, both of which decrease its effectiveness in ensnaring turtles.

The size of nets and net fragments also had a major effect on the probability that a net contained turtles as it washed ashore. This was likely due to a combination of 2 mechanisms. First, a larger net will sweep through more water volume as it moves; thus, one would expect the probability of capture to increase with net size. Second, floating objects that provide habitat heterogeneity are well known to have aggregations of marine life around them (Castro et al. 2001). This is the reason for the use of fish aggregating devices (FADs) (i.e., to increase fish density and thus rates of commercial harvest in an area) (Castro et al. 2001; Dagorn et al. 2013). FADs are frequently constructed with discarded fishing net or other net designed for the purpose (Castro et al. 2001). There

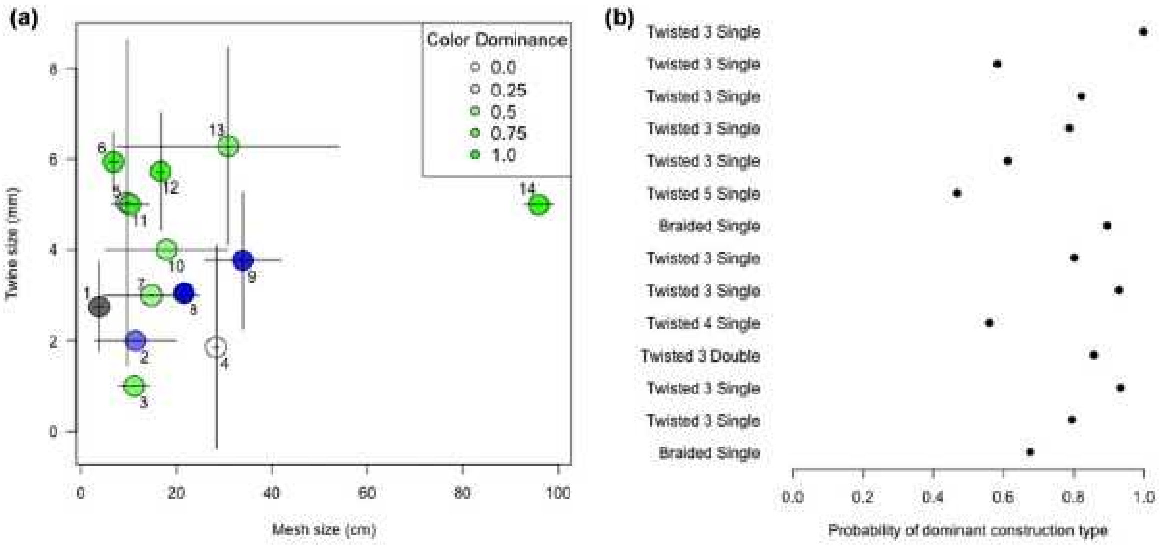

Figure 3. Characteristics of ghost nets in each of the 14 net types identified with a cluster analysis: (a) mean mesh and twine sizes and dominant color for each cluster (lines, SD of the distribution for mesh and twine size distributions; colors, dominant color of the nets in the cluster; intensity of the color, relative dominance of that color in comparison with all other colors in that cluster; numbers next to markers, cluster numbers) and (b) probability of the most common construction for each type of net from net cluster 1 just above the origin to cluster 14 at the top.

Table 2. Sizes of ghost nets, total number of fragments, and captures of turtles across all 8690 nets.

		Net size[b] (m)					Captures	
Net type[a]	Number of nets	min	median	mean	max	Proportion of nets with data	predicted	observed
1	80	0	3	4.5	42	0.57	0.27	0
2	3459	0	5	9.6	375	0.61	89.69	73
3	1403	0	4	7.7	150	0.64	65.53	70
4	14	1	7.5	9.8	23	0.86	0.0000002	0
5	48	1	5	9.6	78	0.81	0.54	0
6	56	1	5	7.3	29	0.61	0.01	0
7	2081	0	5	9.2	300	0.64	31.88	18
8	19	0	2	6.3	29	0.79	0.00000005	0
9	38	1	3.5	4.3	20	0.47	2.89	0
10	1009	0	5	9.7	555	0.66	9.98	13
11	345	0	4	8.8	300	0.61	0.61	2
12	24	1	6	12.1	31	0.67	0.01	0
13	97	0	2	3.7	33	0.51	0.89	3
14	17	1	8	8.4	25	0.53	0.08	0

[a] *Net types are the net categories identified in the cluster analysis.*
[b] *Net sizes are rounded to the nearest 0.5 m for presentation.*

is suggestive evidence that turtles aggregate near these FADs based on catch rates by purse seiners from the Indian Ocean (Dagorn et al. 2013).

Sources of Ghost Nets

Despite the dominance of trawl fishing in the region, the most frequently found ghost net in northern Australian waters was gill nets with a mesh size of 11.5–12.4 cm and twine size of 7 mm (cluster type 3). These nets composed 611 out of the 8690 nets in our data (7%). The combination of large mesh sizes and small twine diameters is characteristic of gear that is light, fine, and buoyant and is therefore ideal for use in targeting large pelagic species, such as tuna, shark, and mackerel, near the surface of the water (R.G. et al., unpublished data).

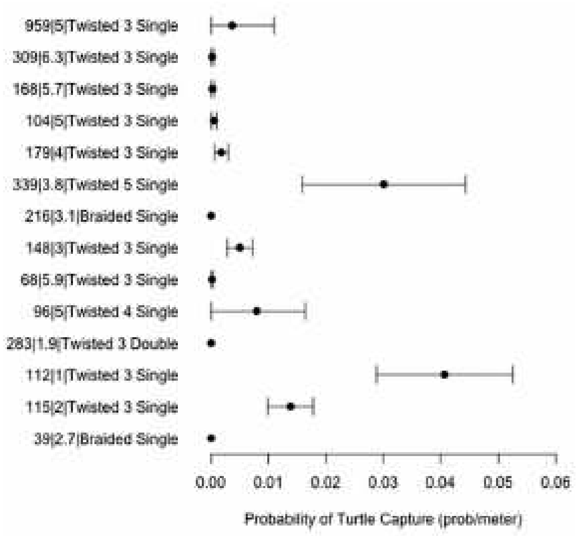

Figure 4. Turtle capture probability for each type of net identified with a cluster analysis. Net types are ordered from net cluster 1 just above the origin to cluster 14 at the top. Numbers to the left of the net types are (from left to right) mesh size (mm), twine size (mm), and net construction type. Error bars show 95% CIs around the estimated probability.

This suggests that drift nets, a type of floating gill net set at the surface that targets pelagic species, may have a disproportionate effect on marine turtles in the Gulf of Carpentaria region.

Fisheries in the region known to use drift nets similar to the cluster 3 nets include the Javanese tuna fisheries (Northridge 1991) and a Thai shark drift net fishery (R.G. et al., unpublished). Gillnetting accounts for 3% of the licensed fisheries in the Arafura Sea (Wagey et al. 2009). However, approximately 6000 gill net fishers operate from Timor L'Este to the west (Stacey et al. 2011). In addition, the presence of a large number of IUU vessels in the region makes it difficult to accurately assess the composition of nets being used (Wagey et al. 2009). In some areas north of the Arafura and Timor Seas, IUU catch is estimated at up to 1.5 times the legal catch (Varkey et al. 2010) and licensed fishers operating in the region suggest that some of these vessels use drift nets (R.G., unpublished data).

The World Wildlife Fund developed an identification key for nets that were washing up in northern Australia, which we had hoped to use in this analysis (Hamilton et al. 2002). However, the identification key had 3 characteristics that required us to develop our net classification system. First, variation in measurements led to nets being incorrectly assigned, sometimes to entirely different categories such as trawl to gill net because the key did not include variation in measurements around its values. Second, there was ambiguity in the net origin information; manufacturer, country of use, and fishery were used interchangeably as the source. Third, the key is not dynamic and thus requires updating as net designs change to incorporate new technologies, fishing approaches, and target species. Our statistical method groups nets based on size and construction, on the argument that nets used for similar target species in a similar mode of operation will generally be constructed in a similar way. Thus, while our clustering approach could not identify specific fisheries, it provided a means to link derelict gear to general types of fishing in an unambiguous way. In our view, this approach accommodated issues with measurement error and changing numbers of categories, either due to new fisheries emerging or an increasing sample of abandoned nets.

Size of the Effect on Marine Turtles

The 8690 nets we analyzed were predicted to capture 202 turtles, based on turtles observed in the nets when they washed onshore. This estimate was driven by net characteristics, net size, and the frequency with which they occurred. There was heterogeneity among nets within a given net type, both in size and design; thus, the predicted catch was not equivalent to simply multiplying the number of nets of a type times their expected catch rate. However, the expected catch rates for the net types (Fig. 4) can be taken as a general guide.

In predicting total catches by each net type, we also had to multiply up our estimates for nets in each type that had incomplete data, which precluded direct prediction based on the regression model. If nets with incomplete data are a random sample from the overall population of nets in a type, this approach should lead to accurate estimates. However, there is always the possibility that characteristics such as net size, presence of turtles, or other characteristics could lead to variation in the thoroughness of data recording. In this case, estimates would be biased, but in a potentially unknown and undetectable manner.

Transforming the estimate of the number of turtles caught in nets washing onshore into an estimate of the number of turtles captured by the nets at sea requires knowing the rate of loss of turtles from the net, either to decay or disentanglement after death. Based on a recent review by Cooper (2012), there is currently very little published information on decay rates of marine turtles. The one study providing experimental results for marine species estimated the postmortem interval (death to complete disarticulation) for hawksbill turtles in the Seychelles at 10–15 d (Meyer 1991). Our preliminary experimental results suggest a similar pattern, with a postmortem interval in subtropical or tropical marine environments of 5–14 d, depending on water temperatures, tidal currents, and other factors (H. Jones et al., unpublished data).

If we assume the nets drift for a year and that turtles are evenly distributed across the region where nets drift, then the portion of the turtles caught that would be available to be seen would be 0.0137/year (5 d/365 d) if turtles last 5 d and 0.041/year if turtles last 15 d. Given that 200 turtles were recorded, we estimate that 14,600 to 4866 turtles are killed by ghost nets in the year before the nets are stranded. Simulated net drift paths of nets entering the gulf had residence times ranging from 1 to 476 d; thus, we expect that calculating annual catch rates is not unreasonable (Wilcox et al. 2013; C.W., unpublished data). An important caveat in this estimate is that the 8690 nets in the data set were the accumulation of nets over some unknown period. Thus, the estimate of 4,866–14,600 turtles killed should be considered a cumulative estimate over this unknown period.

The estimate is most reasonably considered an approximate lower bound on the number killed, not as a point estimate of the value for several reasons. Nets are expected to decrease in catch efficiency with time, and because our data were based on the very end of a ghost net's path, the net may have been much more effective closer to the time when it ceased being actively used in a fishery (Matsuoka et al. 2005). In addition, nets continue to wash ashore in northern Australia. The current count is just over 13,000 nets removed from the gulf coast (R.G., unpublished data). Evidence from Flinders beach, on the northeast coast of the gulf, suggests that the number of nets washing ashore may even be increasing. There were 2213 nets removed from this beach between 2004 and 2012, but a large number of those arrived in the most recent years (2010: 419 nets, 2011: 526 nets, 2012: 163 nets). Thus, our estimate of turtle mortality based on the 8690 nets in our data set likely underestimates the total cumulative mortality to date.

Our estimates of catch rates suggest that management interventions should be targeted at reducing the number of large drift nets. Previous work (Wilcox et al. 2013) suggests that ghost nets drift into the gulf along a fairly narrow path that passes an industrial port just after entering the gulf, making detection by customs surveillance planes and interception near the port feasible and relatively inexpensive. Early interception before nets are caught in the gyre circulating in the gulf would likely substantially reduce their damage and would cost significantly less than the existing ad hoc removal program. Reductions in the loss of nets, particularly large drift gill nets, are also an important management priority. Anecdotal evidence suggests that many of these nets come from illegal vessels operating along the international boundary between Indonesia and Australia; thus, continued and enhanced interception and prosecution of these operators is critical in reducing the input of drift nets into the marine environment. Finally, targeted monitoring of ghost net effects on turtles and other species should be a priority, particularly given the scale of our predictions. There is currently little data available when nets are intercepted at sea, and improving this situation would cost little while allowing quantitative estimates of effects to be included in population assessments for turtles, sharks, dugongs, and other protected species thought to be affected in the region.

Acknowledgments

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Supporting Information

Parameter estimates for the logistic regression of the probability a turtle is found in a beached net on the size of the net (Appendix S1) and the net characteristics recorded by ranger groups during beach cleanup efforts (Appendix S2) are available on-line. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Appendix S1. Parameter estimates for the logistic regression of the probability a turtle is found in a beached net on the size of the net.

Appendix S2. Net characteristics recorded by ranger groups during beach cleanup efforts.

Literature Cited

Alfaro-Shigueto, J., J. C. Mangel, M. Pajuelo, P. H. Dutton, J. A. Seminoff, and B. J. Godley. 2010. Where small can have a large impact: structure and characterization of small-scale fisheries in Peru. Fisheries Research 106:8–17.

Alongi, D. M., K. Edyvane, M. O. do Ceu Guterres, W. S. Pranowo, S. Wiransantosa, and R. Wasson. 2011. Biophysical profile of the Arafura and Timor Seas. Arafura and Timor Seas Ecosystem Action Program. Jakarta, Indonesia.

Castro, J. J., J. A. Santiago, and A. T. Santana-Ortega. 2001. A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis. Reviews in Fish Biology and Fisheries 11:255–277.

Ceccarelli, D. M. 2009. Impacts of plastic debris on Australian marine wildlife. Department of the Environment, Water, Heritage and the Arts, Canberra, Australia.

Cooper, J. E. 2012. The estimation of post-mortem interval (PMI) in reptiles and amphibians: current knowledge and needs. Herpetological Journal 22:91–96.

Dagorn, L., K. N. Holland, V. Restrepo, and G. Moreno. 2013. Is it good or bad to fish with FADs? What are the real impacts of the use

of drifting FADs on pelagic marine ecosystems? Fish and Fisheries **14**:391–415.
Dempster, A. P., N. M. Laird, and D. B. Rubin. 1977. Maximum likelihood from incomplete data via the EM algorithm. Journal of the Royal Statistical Society. Series B (Methodological) **39**:1–38.
Department of Environment, Water, Heritage, and the Arts. 2008. The north marine bioregional plan bioregional profile. Department of Environment, Water, Heritage, and the Arts, Canberra.
Derraik, J. G. B. 2002. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin **44**:842–852.
Donohue, M. J., R. C. Boland, C. M. Sramek, and G. A. Antonelis. 2001. Derelict fishing gear in the Northwestern Hawaiian Islands: diving surveys and debris removal confirm threat to coral reef ecosystems. Marine Pollution Bulletin **42**:1301–1312.
Gabriel, O., K. Lange, E. Dahm, and T. Wendt, editors. 2008. Fish catching methods of the world. Blackwell, Oxford, United Kingdom.
Gilardi, K. V. K., D. Carlson-Bremer, J. A. June, K. Antonelis, G. Broadhurst, and T. Cowan. 2010. Marine species mortality in derelict fishing nets in Puget Sound, WA and the cost/benefits of derelict net removal. Marine Pollution Bulletin **60**:376–382.
Gilman, E., et al. 2010. Mitigating sea turtle by-catch in coastal passive net fisheries. Fish and Fisheries **11**:57–88.
Gunn, R., B. D. Hardesty, and J. Butler. 2010. Tackling 'ghost nets': local solutions to a global issue in northern Australia. Ecological Management and Restoration **11**:88–98.
Hamilton, C., K. Cook, and D. White. 2002. The net kit: a net identification guide to northern Australia. WWF Australia, Sydney.
Hothorn, T., K. Hornik, and A. Zeileis. 2006. Unbiased recursive partitioning: a conditional inference framework. Journal of Computational and Graphical Statistics **15**:651–674.
Kiessling, I. 2003. Finding solutions: derelict fishing gear and other marine debris in northern Australia. Department of Environment, Canberra.
Laist, D. 1987. Overview of the biological effects of lost and discarded plastic debris in the marine environment. Marine Pollution Bulletin **18**:319–326.
Limpus, C. 2008. A biological review of Australian marine turtle species. 4. Olive ridley turtle *lepidochelys olivacea* (Eschscholtz). Queensland Environment Protection Agency, Brisbane.
Lopez-Barrera, E. A., G. O. Longo, and E. L. A. Monteiro-Filho. 2012. Incidental capture of green turtle (Chelonia mydas) in gillnets of small-scale fisheries in the Paranaguá Bay, Southern Brazil. Ocean and Coastal Management **60**:11–18.
Macfayden, G., T. Huntington, and R. Cappell. 2009. Abandoned, lost or otherwise discarded fishing gear. UNEP Regional Seas Reports and Studies 185, FAO Fisheries and Aquaculture Technical Paper 523, United Nations Environment Programme, Food and Agriculture Organisation of the United Nations, Rome.
Matsuoka, T., T. Nakashima, and N. Nagasawa. 2005. A review of ghost fishing: scientific approaches to evaluation and solutions. Fisheries Science **71**:691–702.
McLachlan, G., and D. Peel. 2000. Finite mixture models. 2000. John Wiley and Sons, New York.
Meyer, C. A. 1991. Burial experiments with marine turtle carcasses and their paleoecological significance. Palaios **6**:89–96.
Morgan, G. R., and D. J. Staples. 2006. The history of industrial marine fisheries in southeast Asia. Regional Office for Asia and the Pacific Publication 2006/12. Food and Agriculture Organisation of the United Nations. Bangkok.
Murray, K. T. 2009. Characteristics and magnitude of sea turtle bycatch in US mid-Atlantic gillnet gear. Endangered Species Research **8**:211–224.
Northridge, S. P. 1991. Driftnet fisheries and their impacts on non-target species: a worldwide review. FAO Fisheries Technical Paper, No. 320, Food and Agriculture Organisation of the United Nations. Rome.
R Development Core Team. 2011. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.
Resosudarmo, B. P., L. Napitupulu, and D. Campbell. 2009. Illegal Fishing in the Arafura Sea. In B. P. Resosudarmo and F. Jotza, editors. Working with nature against poverty: development, resources and the environment in Eastern Indonesia. Institute of Southeast Asian Studies, Singapore.
Romero, J. S. L. 2008. Gillnet by catch in the southern part of "Bahia de Ulloa," Baja California Sur. In: Project GloBAL. 2009. Workshop Proceedings: Tackling Fisheries By catch: Managing and reducing sea turtle by catch in gillnets. Project GloBAL Technical Memorandum No. 1. Duke University. Durham, North Carolina.
Solarin, B. B., et al. 2008. An overview of sea turtle by catch in small-scale gillnet fisheries in Nigeria. In: Project GloBAL. 2009. Workshop Proceedings: Tackling Fisheries By catch: Managing and reducing sea turtle by catch in gillnets. Project GloBAL Technical memorandum 1. Duke University, Durham, North Carolina.
Stacey, N., S. Nurhakim, D. Nugroho, H. Soselisa, B. Resosudarmo, O. Kalis, J. Monteiro, J. Prescott, J. Martin, and J. Karim. 2011. Socio-economic profile of the Arafura and Timor Seas. Report of the Transboundary Diagnostic Component of the Arafura Timor Seas Ecosystem Action Program. Jarkarta.
Sutherland, W. J., et al. 2010. A horizon scan of global conservation issues for 2010. Trends in Ecology & Evolution **25**: 1–7.
Thompson, R. C., S. C. Gall, and D. Bury. 2012. Impacts of marine debris on biodiversity: current status and potential solutions. Technical series Vol. 67. Convention on Biological Diversity. Montreal.
Trent, L., D. E. Parshley, and J. K. Carlson. 1997. Catch and by catch in the shark drift gillnet fishery off Georgia and East Florida. Marine Fisheries Review **59**:19–28.
Varkey, D. A., C. H. Ainsworth, T. J. Pitcher, Y. Goram, and R. Sumaila. 2010. Illegal, unreported and unregulated fisheries catch in Raja Ampat Regency, Eastern Indonesia. Marine Policy **34**:228–236.
Venables, W. N., and B. D. Ripley. 1994. Modern applied statistics with S-PLUS. Springer-Verlag. New York.
Wagey, G. A., S. Nurhakim, V. P. H. Nikijuluw Badrudin, and T. J. Pitcher. 2009. A study of illegal, unreported, and unregulated (IUU) fishing in the Arafura Sea, Indonesia. Report to the Research Center for Capture Fisheries, Agency for Marine and Fisheries Research, Ministry of Marine Affairs and Fisheries.
White, D. 2006. Marine Debris in Northern Territory Waters 2004. WWF report. WWF, Sydney, Australia.
Wilcox, C., B. D. Hardesty, R. Sharples, D. A. Griffin, T. J. Lawson, and R. Gunn. 2013. Ghostnet impacts on globally threatened turtles, a spatial risk analysis for northern Australia. Conservation Letters **6**:247–254.

Appendix C. Understanding the effects of marine debris on wildlife Year One progress report to Earthwatch Australia 2012

WEALTH FROM OCEANS FLAGSHIP
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Understanding the effects of marine debris on wildlife: A

progress report to Earthwatch Australia

Britta Denise Hardesty and Chris Wilcox

30 July 2012

Prepared for Earthwatch Australia
Andy Donnelly, Science Director

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Important disclaimer

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1 Introduction

Marine debris poses a global threat to biodiversity of immense proportion. For instance, more than six million tons of fishing gear alone is lost in the ocean each year (Derraik 2002). Despite this staggering amount of marine waste, fishing gear forms only a small percentage of the total volume of debris in the ocean, not even making the list of the top 10 most common items found during coastal cleanup operations (Ocean Conservancy 2010). The impacts of this threat on biodiversity are both broad and deep. Marine debris have been reported to have direct impacts on invertebrates, fish, amphibians, birds, reptiles, and mammals (Good et al. 2010). These impacts are known to be a significant threat to the persistence of several threatened or endangered marine species, and likely to be affecting many others. For example, up to 40,000 fur seals are killed each year by entanglement in debris (Derraik 2002) and entanglement and ingestion are major causes of population decline for some marine mammals. Finally, the impacts from debris in the marine environment are rapidly intensifying, as the volume of refuse humans release into marine systems is growing at an exponential rate.

The goal of our work is to develop a national risk assessment for wildlife species that are affected by marine debris, addressing a topic (marine debris) that has been identified as a 'key threatening process' to wildlife in Australia. The project integrates field, modelling, genetic and biochemical marker approaches to understand the impact of marine debris on fauna at the national scale. One of the critical aspects of this work is that we collaborate and engage heavily with school groups to promote science education and learning through a timely and relevant topic that is part of the national science curriculum – and fits in which maths, chemistry, physics, biology, oceanography and other parts of the national curriculum.

This project seeks to answer four fundamental questions:

1) What are the sources, distribution, and ultimate fate of marine debris?
2) What is the exposure of marine wildlife to debris?
3) When wildlife are exposed to debris, what factors determine whether animals ingest or are entangled by debris?
4) What is the effect of ingestion or entanglement on marine wildlife populations?

In 2011, a three year partnership was entered into by Shell, Earthwatch Australia and CSIRO with an aim of addressing the four fundamental questions listed above.

Our overall aims are to:

- Carry out a risk analysis completed for focal species across multiple taxa across the country
- See increased science learning and uptake for individuals, schools, communities and industry across the country
- Inform policy decisions based upon sound science
- Develop a priority list of 'at risk' species based upon distribution, encounter and impact of debris

- Have increased engagement with industries contributing to the marine debris issue (with potential solution-based approaches to resolving the issue)

- Contribute to a change in behaviour resulting in decreased marine debris deposition across the country due to science learning at local scales

2 Key milestones identified for Year 1

Several key milestones were identified for the first year of the project. These milestones included 1) develop curriculum that fit into the national science curriculum; 2) develop a web based resource for public profile and community engagement; 3) identify potential schools with which to engage in the Teachwild program, particularly focusing on schools in important Shell-identified focal areas; 4) initiate data collection and input; 5) carry out 1 Day Scientist for a day excursions with schools; 6) carry out 7 day research expeditions with teachers and, if possible, 7) carry out sea-based research expeditions with teachers.

2.1 Curriculum development

Content was developed that fits into the national science curriculum with specific lesson plans developed for each of years 5-10. CSIRO scientists provided key input to the content, activities, and evaluation for the Teachwild science curriculum. Exercises and activities have been trialled with successful outcomes. See appendix for curriculum detail.

2.2 Web-based resource

CSIRO developed a collaborative relationship with the Atlas of Living Australia (ALA) and they agreed to and have established our national marine debris portal. The ALA is the Australian node of the Global Biodiversity Information Facility (GBIF). This information system aggregates data on Australian flora and fauna and provides an exceptional geospatial capability as well. It is here that the national marine debris database is available to volunteers, students, teachers, and citizen scientists, and where data on beach surveys, incidental sightings and other site location information is collated. The host address for the site is www.teachwild.ala.org.au. Individuals and groups are able to input data and see summaries of information from across the country.

Also, in February 2012, to further promote the project, ALA posted on their website focal information about the project including the aims, the importance of marine debris, the project scope, distribution maps for species and marine debris, marine debris exposure, key facts about entanglement and ingestion, partner organizations and activities, and key contact personnel at Earthwatch and CSIRO for various components of the project (see http://www.ala.org.au/blogs-news/fielddata-software-citizen-science-training-course/).

Teachers and schools participating in the program (see 2.5 and 2.6) have been entering their data into the online national marine debris data portal. To date, nearly 500 records have been logged, including records from at least nine teachers who have participated in the weeklong field expeditions (described in 2.6).

In addition, we have developed a secure community space where schools, teachers and community members can collaborate, use expertise, share data, information and generate intelligence. This is a community space platform developed by the Australian Biosecurity Intelligence Network (ABIN) using leading edge tools and technologies that ABIN makes available through their secure online workspace. www.abin.org.au is the host site. Within this platform, we have a secure Teachwild community space where web information, protocols, data sheets, photographs, videos, articles and other key resources are made available. Teachers can meet and interact with one another here, schools can compare data and information with one another from across the country, and a wealth of information is made available to participants in this shared community space. One of the fantastic attributes of the space is that videoconferencing can take place amongst multiple groups based at geographically disparate sites – and that this web conferencing capability has high functionality in areas where there is low bandwidth. This is particularly important and relevant for participants in remote or rural areas of the country, some of the relevant groups with whom we want to engage.

Through this community space and/or through use of skype, schools can also have live links to CSIRO scientists for regular question and answer sessions. Also in this space, videos of interviews with scientists and teachers can be made available to other Teachwild participants.

2.3 Identify potential schools

To identify potential schools, CSIRO education made contact with prospective teachers through the national Scientists in Schools (SiS) program to promote the new Teachwild partnership. As of 2011, Scientists in Schools has more than 2,000 partnerships between scientists and schools around the country and has been engaged with more than 1,300 primary and secondary schools. This represented a fantastic opportunity to reach the broader science education community about the work we are doing and how we are looking to engage with schools in coastal regions nationwide. Opportunities to increase the science communication and network profile of the project persist, with Double Helix, Scientrifix and other science publications available to share the marine debris Teachwild work, should the organizations opt to do so.

To date, we have worked with teachers and schools from Queensland, New South Wales Victoria, and Western Australia on the 1 Day Scientist for a Day program. Additional schools from the Northern Territory and South Australia have also shown interest and we will be running the scientist for a day program in those areas, as well as in the greater Melbourne area, Exmouth and Broome in the coming months.

2.4 Data collection

Coastal surveys

Data on the density of debris along coastal margins will be analysed using a statistical model to infer how local conditions, such as coastal aspect, slope, and prevailing wind direction, affect the density of debris. We will explore explanatory variables, such as distance from surrounding cities to understand factors affecting debris distributions. The end result of this analysis will be a standardized measure of the density of debris along the Australian coastline, which will allow comparison of the input across regions.

We will also explore the likely sources and at sea distribution of debris by using an oceanographic model to infer the starting location and pathway for debris observed on shore, which is the presumed sink for marine debris. Summing across all the paths of debris predicted to go through each location in the ocean, we will produce an estimate of the relative density of debris in that location. This will be compared to the densities of debris observed at sea from citizen science programs and Southern Surveyor transit voyages to validate predictions. The final result of the analysis will be a predicted distribution of debris at sea.

Furthermore, by predicting the distribution of debris at sea in the opposing direction, we will work forward in time from potential sources. We will posit several working hypotheses, such as debris is all released domestically from terrestrial sources and releases are proportional to population size. These source hypotheses will be implemented using the oceanographic model to predict the fate of debris originating at these sources, and the predicted fates compared to the distribution of debris observed at sea and along the coast. Based on the relative fit to the data, we will evaluate whether debris appears to come from domestic versus foreign sources and the relative proportion of terrestrial versus marine input. Again, the outcome of this analysis will be a prediction of the at-sea distribution of debris, but this prediction will be independent of the reverse prediction made above using data from the sinks.

At the projects inception, the initial plan was to survey disjunct areas of coastline at multiple sites around the country (shown in Figure 1). In order to have a better, more exhaustive dataset that encompasses more of the country's coastline, we have revised the original survey area to include a more comprehensive picture of marine debris along our coastal areas (Figure 2). From the project's inception through the end of June 2012, CSIRO staff have surveyed the coastline from just north of Cairns down the south coast past Brisbane and Sydney, along the south coast from Melbourne and Adelaide and westward to Perth.

Figure 1. Initial map of proposed coastal debris survey areas

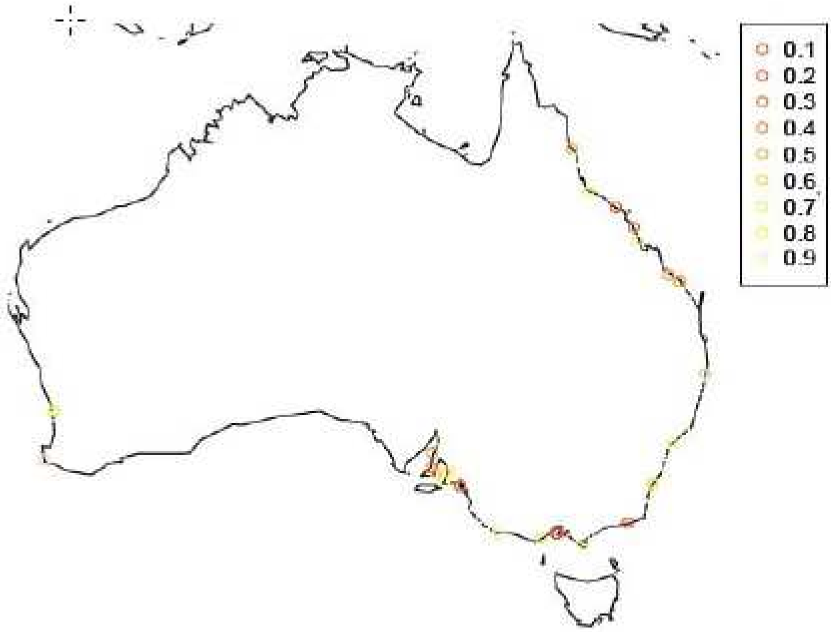
Figure 2 Revised map of proposed and completed coastal debris survey areas

The first important step prior to carrying out the coastal surveys, was to develop a field methodology that is robust, will adequately represent the debris found on beaches around the country, can be conducted in a reasonable amount of time, is as consistent as possible with other survey data that has been collected, and is suitable and appropriate for citizen scientist volunteers to carry out with a modicum of training. A great deal of time and energy therefore went into developing the working methodology and it is as consistent as possible with data collection approaches already in place by volunteer groups carrying out beach clean ups both in Australia and internationally. Because school groups with younger students may find the detail challenging, we also developed a methodology suitable for younger students. See Appendix for datasheets and data protocols for both data collection approaches. All information is available in the shared community space and on the www.teachwild.ala.org.au website and data portal.

Preliminary analyses from the coastal survey work has been underway, with analyses based upon surveys carried out in Queensland, New South Wales, Victoria and parts of South Australia and Western and Australia. Thus far, it appears that high debris density does not only occur near cities, but is also prevalent in some areas of low population density (see further description in Figures 3 and 4).

Figure 3. The log density of debris on beaches (count/area). It is worth noting that there is a single outlier, one debris amount was much higher than all the others. You can see the effects of urban areas, which indicates that there is a significant domestic source. Furthermore, the survey site near Melbourne stands out. However, there are also areas with high debris density in areas that are not particularly urban (such as western Victoria). This may be the result of the effects of prevailing currents and wind.

Figure 4. The ratio of glass/(glass + hard plastic) at beaches along the Queensland, New South Wales and parts of South Australia coast. It provides a measure, at least indirect, of how ocean influenced is the debris at a beach. This is based on the assumption that both hard plastic and glass come with people as beverage containers, but only hard plastic can float in from the ocean. Note that the more intense the red the colour at a particular beach, the lower the ratio. Thus the more plastic (and presumably the more ocean input). This could be still high near local population centres, because there is more debris floating around areas of higher population density.



At-sea surveys

In the first year we have carried out high seas and coastal marine debris surveys on board the Southern Surveyor and one of the AIMS research vessels. This work has been carried out by CSIRO project scientist Chris Wilcox, a PhD student from UWA (Julia Reisser), a PhD student from UQ (Qamar Schuyler) and a masters student from Ghent University (Heidi Acampora). Surveyed areas have included 1) New Zealand to Tasmania; 2) inside the Great Barrier Reef; 3) from Fiji to Hobart; and 4) from Adelaide to Perth.

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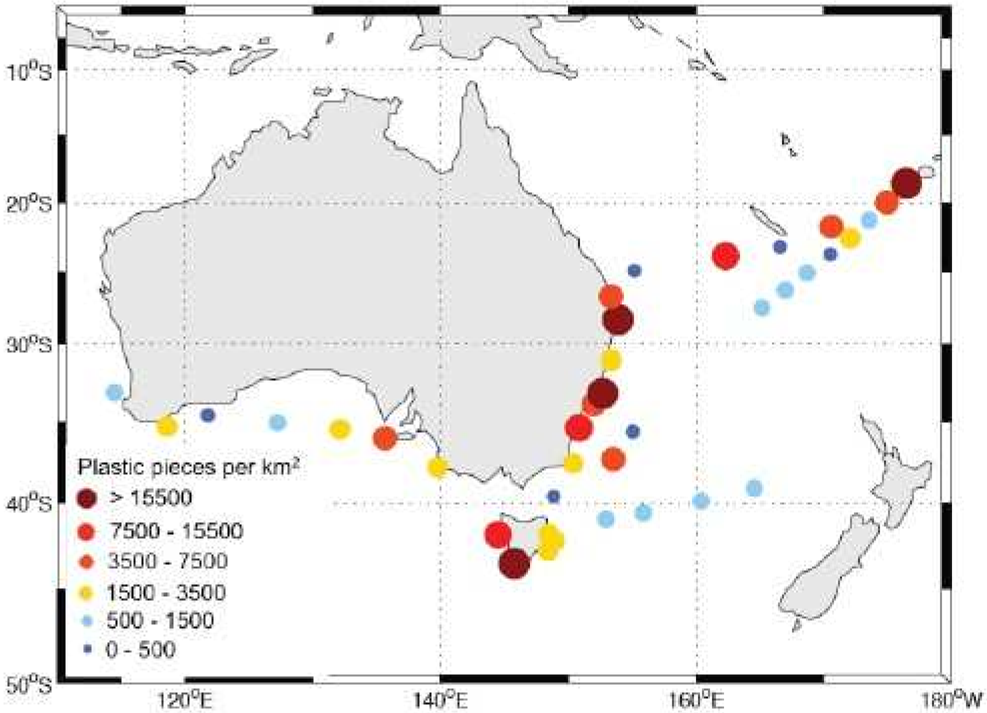
See map (below, courtesy of J. Reisser) of plastic debris densities (plastic pieces per km^2) based upon transit voyages on the Southern Surveyor bluewater research vessel.



2.5 Scientist for a Day

The successful Scientist for a Day program has resulted in engagement with more than 700 students to date. With Earthwatch staff, scientists from CSIRO have worked with teachers and schools from Queensland, New South Wales Victoria, and Western Australia on the 1 Day Scientist for a Day program. Schools from the Northern Territory and South Australia have also shown interest and we will be running the scientist for a day program in those areas, as well as in the greater Melbourne area, Exmouth and Broome in the coming months. The excitement and enthusiasm from schools around the country has been impressive. Schools have developed their own videos based upon their learning experiences and the program has led to engagement in state and national kids teaching kids participation from schools in two states using their learnings in the Scientist for a Day program to teach other students about the Teachwild program and the marine debris issue. Teachers and students have together developed waste reduction programs at their schools and have developed innovative practices to change school, community and home practices, particularly around plastic waste.

2.6 Teachwild 7 Day Research Teams

The 7 day Teachwild excursions have been tremendously successful. To date, we have completed two of these weeklong programs. Teachers from Queensland, Victoria, Tasmania, New South Wales and Western Australia have participated. The feedback from teachers has been overwhelmingly positive with several teachers remarking that this has been the best professional development opportunity of their careers.

Teachers have made real contributions to the science whilst learning new skills. Importantly, while doing so they have been able to skype or blog back to their classrooms, communicating with students in words, photos and in live video feeds about their experiences in the Teachwild program. Teachers have not only carried out coastal debris surveys, but have also helped to perform trawl surveys to look for plastics and other anthropogenic debris, they have assisted in necropsies for turtles and seabirds and they have learned to use spectrophotometers to record spectral characteristics for debris. They have also used other scientific equipment to collect and record data, whilst engaging with numerous scientists to aid in their studies and contribute significantly to important research of national and international relevance.

Teachers collecting data on coastal debris surveys

➢ Teachers helping to collect data on trawl samples to look for anthropogenic debris in the marine environment near North Stradbroke Island.

Teachers and researchers sorting debris found in trawl nets

Teachers using microscopes to identify anthropogenic debris

Teachers in the week long expeditions also helped to carry out necropsies on wildlife washed up on beaches. The data collected contributed to a student's masters thesis quantifying marine debris found in muttonbirds.

A happy group of teachers, scientists and Earthwatch staff at the Moreton Bay Reserach Station on North Stradbroke Island.

3 Communications and media

Importantly, a communications strategy yearly plan was developed and has been implemented between the three partner organizations. The official project launch for the Teachwild program took place on 8 March 2012 in Perth, with representatives from the three partner organizations, Earthwatch, CSIRO and Shell. The successful event also had representation from the Chief Scientist of WA (Professor Lyn Beazley) and during the launch we carried out a beach clean-up with the South Fremantle Senior High School year 8 class. The launch media promotion resulted in articles in 13 newspaper articles, one magazine write up (in the Australian Teachers magazine) and five radio interviews.

The CSIRO facebook page, with a readership of more than 15,000 has also posted photos, stories and other information about the project. This extends the Teachwild profile in both breadth and depth, reaching the broader Australian and international community. CSIRO twitter feeds have furthered the social networking communications of the project, and press releases from CSIRO about the research have highlighted this important partnership between Shell, Earthwatch Australia and CSIRO.

Additionally, because we encounter so many interested members of the public in the course of carrying out fieldwork, in consultation with the communications teams from partner organizations, CSIRO developed a brief handout to share some information about the Teachwild program (see Appendix). There has been a strong positive response from the general community and it seemed a simple and opportune way to share information about the project.

Media interest in the project has exceeded expectations and has resulted in not only a local and regional impact, but in a national and international profile as well. Some of the media highlights in the first year of the project have been a newspaper article in The Age (http://www.theage.com.au/environment/csiro-hits-the-beach-in-littermapping-study-20120219-1th92.html), featuring on the national television program The

Project (formerly the 7pm Project), and national radio coverage on ABC (as well as several state and regional radio interviews). The work has also been featured in Cosmos Magazine, the Herald Sun, the Courier Mail, www.news.com.au, the 730 report in Tasmania, Landmark Magazine, the Australian Marine Science Bulletin, Fishing Today and numerous other news outlets.

Additional project airings on national television include an upcoming feature scheduled on the children's science program Scope (to air in August), and an interview for Catalyst (to air early September).

A more exhaustive list of CSIRO interviews and media from project beginning through 30 June 2012 is provided:

- Researchers monitor beaches. Esperance Express. 25 May 2012.
- Tackling Marine Debris with CSIRO. http://ausmepa.blogspot.com.au/2012/04/tackling-marine-debris-with-csiro.html 28 April 2012.
- Australian Marine Science Bulletin 187, p 28. CSIRO hits the beach in litter-mapping study. Issue 1, 2012.
- Ocean Whispers. Tackling Marine Debris with CSIRO. AUSMEPA marine education. http://ausmepa .blogspot.com.au/2012_04_01_archive.html. 28 April 2012.
- Fishing Today. Tasmanian Seafood Industry News, Volume 25, No. 2, p 13. April/May 2012.
- Channel 7 News Adelaide. Marine Debris Project interview in South Australia. 17 April 2012.
- There's science in the flow of rubbish. Landmark Magazine. Issue 43, p. 14, April 2012.
- Wildlife Bytes 5/4/12 Marine Rubbish. http://wildlifebytes.blogspot.com.au/2012/04/wildlife-bytes-5412.html. 4 April 2012.
- Teachers 'go wild' to help marine life. The Redland Times. http://www.baysidebulletin.com.au/news /local/news/general/teachers-go-wild-to-help-marine-life/2501183.aspx 26 March 2012.
- Schools to help in marine debris. Noosa News. http://www.noosanews.com.au/story/2012/03/08/ schools-help-marine-debris/. 8 March 2012.
- Schools to help in marine debris. Warwick Daily News. http://www.warwickdailynews.com.au /story/2012/03/08/schools-help-marine-debris/. 8 March 2012.
- Schools to help in marine debris. North Queensland Herald. http://www.mysuburbannews. com.au/2012/03/08/marine-debris-initiative-launched-20208002.html 8 March 2012.

- Schools to help in marine debris. Whitsunday Times. http://www.whitsundaytimes.com.au/story/2012/03/08/schools-help-marine-debris/. 8 March 2012.

- Schools to help in marine debris. North Rivers Echo. http://www.echonews.com.au/story/2012/03/08/schools-help-marine-debris/. 8 March 2012.

- Schools to help in marine debris. Fraser Coast Chronicle. http://www.frasercoastchronicle.com.au/story/2012/03/08/schools-help-marine-debris/ 8 March 2012.

- Schools to help in marine debris. The Coffs Coast Advocate. http://www.coffscoastadvocate.com.au/ story/2012/03/08/schools-help-marine-debris/ 8 March 2012.

- Surf coast times. Finding the source of rubbish. http://www.surfcoasttimes.com.au/. 6 March 2012.

- The 7pm project. Television interview on http://theprojecttv.com.au/video.htm?movideo_p=39696&movideo_m=167510 5 March 2012.

- Atlas of Living Australia website 28 February 2012. http://www.ala.org.au/blogs-news/fielddata-software-citizen-science-training-course/

- Geelong Independent Newspaper. Beach 'debris' survey. 27 February 2012. http://www.starnewsgroup.com.au/indy/geelong/268/story/149237.html

- BEN waste. CSIRO undertaking marine litter survey. http://www.ben-global.com/Waste/News/CSIRO_undertaking_marine_litter_survey_9685.aspx 26 February 2012.

- Herald Sun. Eye in sky filming our rubbish shame. http://www.heraldsun.com.au/technology/eye-in-sky-filming-our-rubbish-shame/story-fn7celvh-1226280052411 24 February 2012.

- News.com.au. Eye in sky filming our rubbish shame. http://www.suasnews.com/2012/02/12305/eye-in-sky-filming-our-rubbish-shame/ 24 February 2012.

- Courier Mail. Eye in sky filming our rubbish shame. http://www.couriermail.com.au/news/technology /eye-in-sky-filming-our-rubbish-shame/story-fn7cejkh-1226280052411 24 February 2012.

- Silobreaker. Eye in sky filming our rubbish shame. http://www.adelaidenow.com.au/eye-in-sky-filming-our-rubbish-shame/story-e6frea6u-1226279926181 24 February 2012.

- SciStarter invited writer/participant for international citizen scientist website and blog. 22 February 2012.

- ABC AM radio. Statewide WA. Interview on Marine Debris project (pre-recorded). 26 February 2012.

- ABC AM radio. Victoria/South Australia. Interview on Marine Debris project 24 February 2012.

- ABC AM radio Cairns. Interview with Gen Perkins on Marine Debris project. 22 February, 2012.

- ABC AM radio Newcastle. Interview with Chris Wilcox on Marine Debris project. 22 February 2012.

- The Age Newspaper. CSIRO hits the beach in litter mapping study. http://www.theage.com.au/environment/csiro-hits-the-beach-in-littermapping-study-20120219-1th92.html. 20 February 2012.

- The Sydney Morning Herald. CSIRO hits the beach in litter mapping study. http://www.smh.com.au/ environment/csiro-hits-the-beach-in-littermapping-study-20120219-1th92.html 20 February 2012.

- Spatial Source. CSIRO researchers map beach rubbish. http://www.spatialsource.com.au/2012/01/30/article/CSIRO-researchers-map-beach-rubbish/VYWNYMHTXX.html 30 January 2012.

- ABC PM radio Queensland. Interview on Marine Debris Project, http://blogs.abc.net.au/queensland/ 18 January 2012.

- Manly Daily Newspaper, Swimming in Rubbish: CSIRO research map marine debris. http://origin.manly-daily.whereilive.com.au/news/story/swimming-in-rubbish-csiro-researchers-map-marine-rubbish/ 6 January 2012.

- ABC 774 Melbourne. Breakfast show interview on Marine Debris project. 15 December 2011.

- http://cpsu-csiro.org.au/2011/12/14/scientists-comb-beaches-for-rubbish-clues-featuring-staff-association-member-denise-hardesty/

- ABC PM Radio Sydney. Interview on Marine Debris Project. 13 December 2011. http://www.abc.net.au/pm/content/2011/s3390231.htm

- http://www.abc.net.au/news/2011-12-13/scientists-comb-beaches-for-rubbish-clues/3729460?section=nsw

- The 7.30 Report Tasmania. Television interview on Marine Debris project. 9 December 2011.

- http://www.abc.net.au/news/2011-12-12/marine-rubbish/3725946?section=tas

- Sea Change. Cosmos Magazine, Issue 39, July 2011. http://www.cosmosmagazine.com/features/print/4692/sea-change?page=0%2C0

- Port Macquarie News. Town Beach is king of the rubbish heap. 9 December 2011.

4 Accomplishments and learnings from Year 1

Some of our key science goals in the first year of the project have been to collect observations on the distribution of various types of debris from four sources: a) coastal debris cleanups, b) data collected by citizen scientist programs with schools, recreational boaters, ships of opportunity, and other platforms that allow for data collection, c) research surveys of debris and wildlife along the coastline, and d) research surveys organized during transit voyages on the Southern Surveyor or AIMS research vessels.

We have achieved each of these goals, and we developed an appropriate methodology for conducting coastal surveys at the national scale. We have collected data along more than 60% of the coastline to date. We have successfully worked with numerous schools and we have also been engaging with recreational boaters who are collecting data from multiple sites along the east coast of Queensland from Port Douglas down to Brisbane. There has also been a groundswell of interest from members of the public outside the education sector. The interest in the project from school and community groups as well as high media interest in the project from around the country has resulted in the opportunity to engage with a broader section of the Australian population than anticipated in the project's first year. This has also resulted in the need for increased effort by project staff to consistently respond to and engage with interested parties in a timely fashion.

In addition to the coastal surveys we have developed, trialled and begun carrying out the focal species work for a number of marine taxa. Two PhD students supported by CSIRO top-up scholarships have theses that are contributing to the project goals. Each of them focuses their research on marine debris impacts on sea turtles. Furthermore, survey approaches for detecting anthropogenic debris in and around seabird colonies has been successfully carried out at breeding populations on Lord Howe Island and in the Flinders Island group. Other suitable sites have been identified and we have developed collaborations with researchers from Phillip Island, Rottnest Island and other important seabird breeding areas.

Importantly, the first international journal publication relating to this project has recently been published by PLOS One (Schuyler et al. 2012). The paper focuses on debris selectivity in marine turtles, one of the key taxa we are targeting. Within the first month of publication, the paper has had a readership in excess of 1,700. Interest from the lay community has been noted through social media which has particularly been interested in the occurrence of rubber balloons as ingested material in marine turtles. In addition, a masters student's thesis (Acampora 2012) has been completed based upon her work in association with this project, and in the coming year we expect to have a paper published in an international journal based upon this research to which teachers on weeklong Teachwild expeditions contributed.

Overall, the first year has been tremendously successful with excellent school engagement, a fantastic and motivated group of teachers and students from around the country, and we have achieved and exceeded project expectations.

5 Looking forward

Over the next two years we will be developing coarse distribution maps for a number of species, along with distribution maps for marine debris. These maps will be based on a variety of data sources, incorporating multiple sources and analytical approaches where possible. We now have a memorandum of understanding in place with the department of the environment and they have provided species distribution information to CSIRO for a number of marine species. We will be developing the risk analysis on exposure and impact from marine debris, at both the individual and population level, for several marine vertebrate species. This information will be integrated to develop the main output of the project, an evaluation of the risk marine debris poses to Australian wildlife at the national scale.

In September, we will be carrying out a research expedition with four teachers and CSIRO scientists aboard the Southern Surveyor national research vessel. The excursion will take place from Broome to Darwin, providing an exciting and unique opportunity for teachers to assist researchers in collecting important data in the high seas environment.

In September and October additional week long science excursions are planned for North Stradbroke Island and for Phillip Island. For the first time since the project began, teachers and Shell employees will work alongside one another to participate in a variety of activities and assist scientists in critical data collection to contribute information needed for the national risk assessment.

By the end of 2012, we anticipate we will have completed all of the coastal debris surveys. Furthermore, we aim to have completed analyses from this component of the research, with the second year of the project focusing on individual taxa surveys in addition to school engagement at more remote and rural sites across the country.

References

Acampora H (2012) Assessing the impacts of plastic ingestion in Short-tailed shearwaters in northern Australia. Master of Science in Marine Biodiversity and Conservation with the Erasmus Mundus Masters Programme EMBC, Ghent University.

Derraik JGB (2002) The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin* 44:842-852.

Good TP, June JA, Etnier MA, Broadhurst G (2010) Derelict fishing nets in Puget Sound and the Northwest Straits: Patterns and threats to marine fauna. *Marine Pollution Bulletin* 60:39-50.

Schuyler Q, Townsend K, Hardesty BD, Wilcox C (2012). To eat or not to eat: debris selectivity by marine turtles. PLOS One 7(7): e40884. DOI:10.1371/journal.pone.0040884.

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TEACH WILD
A journey of discovery

Mapping marine debris around Australia

Scientists from CSIRO are surveying beaches and birdlife around Australia to better understand the sources and distribution of marine debris and the threat it poses to Australian wildlife.

The marine debris survey began near Cairns in late 2011 and is stopping every 100 kilometres around the coastline. Debris is recorded along three to five survey lines at each beach or rocky shore.

Data collected during the survey will contribute to a national marine debris database designed to assist the formulation of waste management policies and practices intended to protect marine ecosystems.

The marine debris survey is part of TeachWild, a national three-year marine debris research and education program developed by Earthwatch Australia together with CSIRO and Founding Partner Shell.

Volunteers can get involved in and collect data to contribute to this national project

TeachWild offers you the opportunity to join the national marine debris survey.

Interested?

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EARTHWATCH INSTITUTE

CSIRO

TEACH WILD
A journey of discovery

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Volunteers can get involved in and collect data to contribute to this national project

TeachWild offers students and teachers the opportunity to join the national marine debris survey.

School groups from Year 6–10 can take part in an excursion (to local beaches or waterways) that meets key learning areas of the Australian Curriculum.

Science teachers can apply to take part in a funded week-long land and sea based expedition with the science team.

Interested?

. . . teachwild.org.au

EARTHWATCH INSTITUTE

CSIRO

(Official use only)	Beach number (unique identity code):	Survey Area (A, B, C, D, E, F, G): ....

SURVEY AREA CODE: A = Cape Tribulation – Bris; B = Bris – Melb; C = Melbourne – Streaky Bay; D = Streaky Bay – Perth; E = Perth – Broome; F = Broome – Darwin; G = Around Tasmania

MARINE DEBRIS BEACH SURVEY

Survey Guidelines:

- Complete one Beach survey form per site and one transect data form for each transect at the site. Record all coordinates in WGS84 datum only.
- Minimum of three transects and minimum of six per site.
  - Minimum of one transect located within each major habitat type (transects proportional to habitat type).
  - Transects located at least 50 m from beach access point (ideally not located both sides of access points, unless different habitat types).
  - Transects located at least 25 meters apart (ideally 50 meters).
  - Transect to include two meters into continuing backshore terrestrial vegetation.

SURVEYOR DETAILS		
Organisation:		*Organisation responsible for survey.*
Surveyor name:		*Name of chief surveyor.*
Contact number:		*Contact number for surveyor.*
Access point location:	Latitude: .... Longitude:	*Latitude and longitude of access point where you enter the beach (dd.dddd).*
GPS accuracy:		*Accuracy (meters) of GPS at time of reading.*

SITE DETAILS		
State / Territory:		*State or territory in Australia beach is located.*
Beach name:		*Unique name of beach , if known.*
Survey date:		*Date survey undertaken (dd/mm/yyyy).*
Current weather:	Clear Rain/Storm Overcast Drizzle	*Circle best option to describe the weather.*
Wind speed:	0 1 2 3 4 5	*Circle Speed estimate:* *0: calm (flat ocean)* *1: light breeze (wavelets, <10km/h , <6 knots)* *2: moderate breeze (small waves braking crests, 10-25km/h, 6-20 knots)* *3: strong breeze (waves and many white caps, 25-49km/h, 21- 26 knots)* *4: high wind (white caps and airborne spray, 50-65 km/h , 27-35 knots)* *5: gale (high waves, foam and spray present, 65-85 km/h, 35-45 knots)*
Wind direction: *(compass)*	N NE E SE S SW W NW N/A	*Direction from which wind is coming measured by the compass. N/A if no wind.*
Wind direction: *(relative to shore)*	onshore offshore sideshore side-on side-off	*Onshore: wind blowing towards shore* *Offshore: wind blowing towards sea* *Sideshore: wind blowing parallel to shore* *Side-onshore: wind blowing sideways and towards shore* *Side-offshore: wind blowing sideways and towards sea*
Date of last clean up:		*If known.*
Number of humans:	Time of day (00:00): .... Visible distance (m): .... No. of people:	*Number of people counted in the visible area measured by instantaneous count. Visible distance is length of shore with a clear and unobstructed view.*
Comments:		*For example: entangled fauna, recent storms, shipwrecks, boat ramp in close proximity, coastal erosion or other conditions that may affect the survey.*

Marine Debris Size Chart

Guidelines:

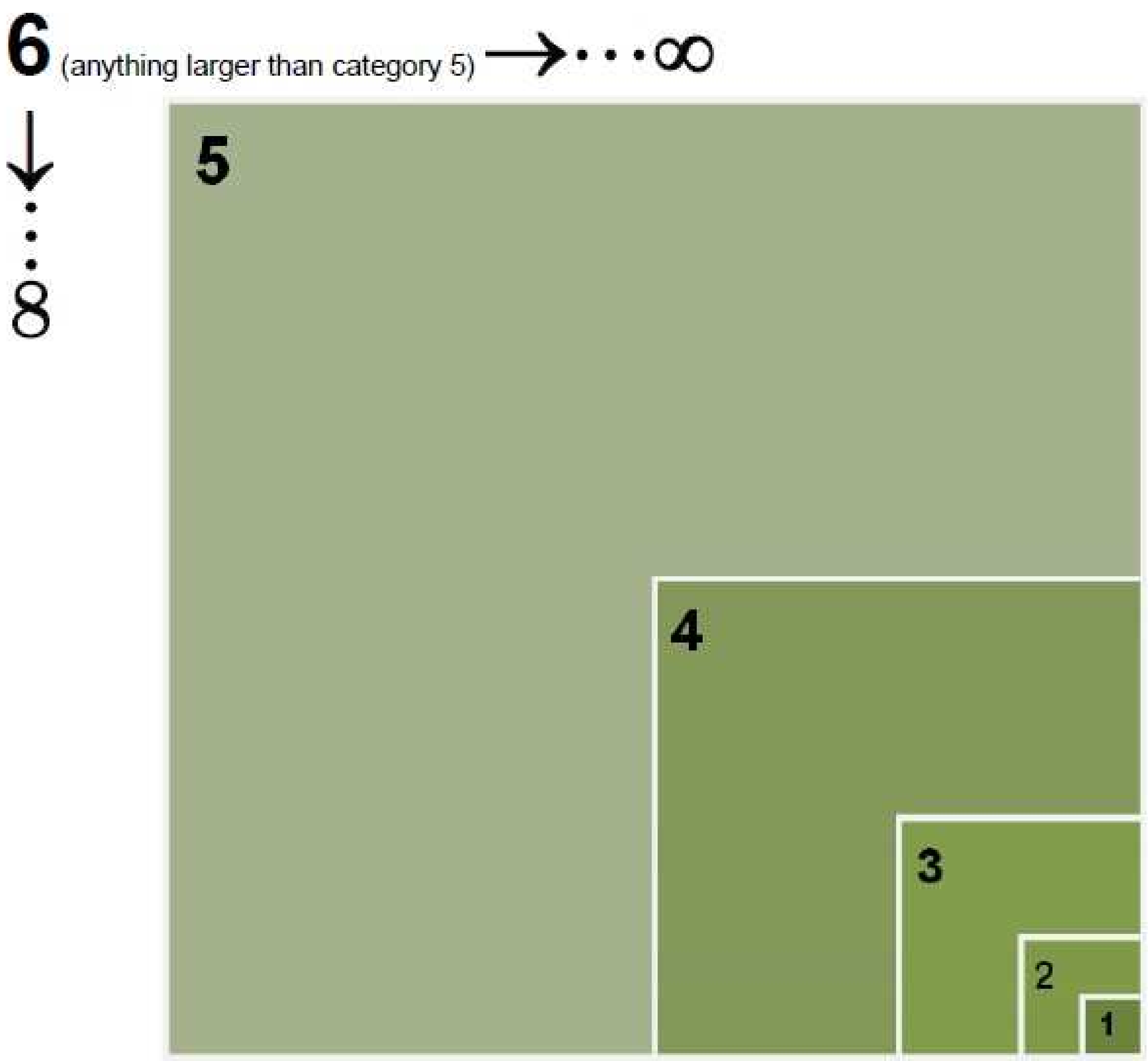
* This chart should be used as a guide to help estimate the size of marine debris during each beach transect (see transect sheet)

* The squares below represent different size classes

1 = 0–1 cm^2 ; 2 = 1–2 cm^2 ; 3 = 2–4 cm^2 ; 4 = 4–8 cm^2 ; 5 = 8–16 cm^2 ; 6 = >16 cm^2

* To estimate area, determine which square the object will fit into.

* Note. It may be helpful to fold objects that are long and thin in order to picture the total areas, e.g. plastic straws.



Transect Data

Beach Name:		Name of surveyor(s):	
Transect Number:		No. of surveyor(s):	
Transect width (m):			

Transect start:	Latitude: .... Longitude: .... GPS Accuracy: .... Start Time (00:00):	*Latitude and longitude recorded in decimal degrees (dd.dddd).* *Accuracy (in meters) of the GPS at time of reading.* *Record Start Time of Transect*
Transect end:	Latitude: .... Longitude: .... GPS Accuracy: .... End Time (00:00):	*Latitude and longitude recorded in decimal degrees (dd.dddd).* *Accuracy (in meters) of the GPS at time of reading.* *Record End Time of Transect*
Photo numbers:	Start of Transect: .... End of Transect:	*Number of photo, taken from transect start and end point.*
Transect length (m):		*From waters edge to two meters into continual terrestrial vegetation (meters).*
Distance to dominant debris line (m):		*Distance from water edge to major debris line (in meters) at time of survey. Example 23 meters. If no obvious debris line use NA.*
Beach gradient:	1 2 3 4 5	*Difference in elevation from start to end of transect.* *1 = < 1 m (less than hip height)* *2 = 1-2 m (hip to head height)* *3 = 2-4 m (1-2 body length)* *4 = 4-8 m (2-4 body lengths)* *5 = > 8 m (more than 4 body lengths)*
Substrate type:	Mud Sand Pebble / Gravel Boulders Rock slab Mangrove	*Major substrate type.*
Substrate colour:	White / cream Yellow Orange Brown Black Grey Red	*Predominant colour of substrate.*
Backshore type:	Cliff Seawall Urban building Forest / Tree (> 3m) Shrub (< 3m) Dune Grass - tussock Grass - pasture Mangrove	*Physical structure of backshore, where beach meets terrestrial vegetation.*
Beach exposure or shape:	Concave (cove) Straight Convex (headland)	*Shape of beach where survey is conducted. Based on 25m each side of transect.*
Aspect:	N NE E SE S SW W NW	*Direction when you are facing the water.*
Comments:		*For example: transect-related comments such as backshore flora, crossing paths, photo information, etc.*

Transect debris (type and colour): Record one mark (e.g. IIII) for each piece of rubbish larger than 1 cm^2 in size, within 1 metre each side of the transect line. If you find items other than those listed, add details to bottom of table.

	Rubbish Type	Colour of debris									
		Clear / translucent	White	Red/ pink	Orange	Yellow	Green	Blue / purple	Brown	Black	Grey / silver
Plastic	Hard plastic										
	Plastic bags										
	Film-like plastics (glad wrap and chip bags)										
	Other soft plastics										
	Plastic packing straps										
	Net (estimate size)										
	Fishing line										
	Plastic (string, twine, rope)										
Cloth	Non-plastic (string, twine, rope)										
Glass	Glass										
Metal	Fish hook										
	Metal (hard)										
	Metal (soft, tinfoil)										
Rubber	Balloon										
	Other rubber items										
Foam	Polystyrene (foam, from esky's buoys etc.)										
	Other foam										
Timber	Wood (posts, beams, ship hulls)										
Paper	Cigarette butts										
	Paper										
Other											

Size classes: Sample debris type and size class at ten intervals along each transect.

Sampling Interval	Distance from water (m)	Size Class	Type / colour
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

1. Divide the total transect length by 10 to determine sampling interval, e.g. if transect is 35 m, interval = 3.5 m.

2. At each interval record the type and size of the first piece of rubbish encountered. If no rubbish is detected within the interval draw a line through the box and continue to next interval, e.g. if no rubbish is found within the second interval (3.5–7m), but six pieces were detected in the third interval (7–10.5m) mark a line in the box for sample 2, and record the size and type for only the first item detected in sample 3.

Beach Litter Survey Methodology

You will need:
GPS (optional for volunteer surveyors)
Tape measure (50m if possible)
Compass
Pen/pencil
Data sheets (beach and transect data sheets – atleast 3 transect sheets)
Two markers (such as stakes you can stick in the ground)
Camera (optional)
Debris identification guide (optional)
Binoculars (optional – for observing wildlife for possible entanglements)

Before starting transects please note:

- Complete one Beach survey form per site (beach) and one transect data form for each transect at the site.
- Minimum of three and maximum of six transects per site (beach).
- Minimum of one transect located within each major habitat type (eg: on sand, on rock slab, on boulders, in mangroves etc).
- Transects are to be located at least 50m from beach access point (ideally not located both sides of access points, unless different habitat types).
- Transects should be located at least 50 meters apart (ideally 100 meters).
- Transect to include two meters into continual terrestrial vegetation (See pic below).

To set up your GPS.

1. go to the setup page
2. blah blah
3. want it on decimal degrees

Have your data sheets ready at the "Marine Debris Beach Survey" page

1) Walk towards the beach, where you enter the beach, take a GPS reading, this is to go into the Data Sheet as "Access point", photo below shows access point.

2) Before you move on, fill out the rest of the details on the "Marine Debris Beach Survey" page (surveyor and site details)

3) It doesn't matter if you go to the left or right of the access point for transects, on small beaches or to survey different habitat types you may have to go on both sides. Choose a side and walk at least 50m, make it 100m or more if you can. Also, if possible try to have natural vegetation at the backshore (might be grasses, shrubs or trees, try not to have a 'manicured lawn).

4) Once away 50 – 100m from the access point, at the waters edge, put in one of your transect markers. If possible use a random method to select the final location of the transect (for example pick a random number and walk the number of steps). Fill in as much of the first page of the "transect data" as you can (note: this will be transect 1)

5) Run the tape from the marker to 2m behind the line of continuous vegetation and put second marker here. (HINT - when laying out the tape try not to walk along the transect line, rather walk in an arc and straighten the tape once at the end of the transect)

6) Note the length of the transect. Divide this by 10 to get the intervals for collecting the size class data on debris and write this down in the first box (blank) of the size class table on the second page of the "transect data" sheet. You will need to know these intervals as you survey for debris

Size classes: Sample debris type and size class at ten points along each transect.

	Distance from water (m)	Size code ##	Type / colour
1			
2			

7) Go back to the marker at the waters edge, 0cm, and take a GPS reading here, this will be the start location. **Record the time – this is your starting time. Take a photo of the transect looking towards the shore – this is you start photo.**

8) Have one person on each side of the tape looking for debris out to one meter from the tape. When looking for debris, DO NOT bend over, walk upright, just looking down with your eyes. Pick up anything you are unsure of for closer inspection as lots of shells look like plastic and visa versa. Walk towards the backshore sampling the beach as you go.

9) If you find something record it in the transect debris table and if necessary on the size class table (see size class data collection notes below)

Rubbish Type		Colour of debris									
		Clear/ translucent	White	Red/ pink	Blue/ purple	Brown	Green	Yellow	Orange	Black	
Plastic	Hard plastic										
	Plastic bags										
	Film-like plastics (glad wrap and chip bags)										
	Other soft plastics										
	Plastic packing straps										
	Net (estimate size)										
	Fishing line										
	Plastic (string, twine, rope)										
Cloth	Non-plastic (string, twine, rope)										
Glass	Glass										
Metal	Fish hook										
	Metal (hard)										
	Metal (soft, tinfoil)										
Rubber	Balloon										
	Other rubber items										
Foam	Polystyrene (foam, from esky's bouys etc.)										
	Other foam										
Timber	Wood (posts, beams, ship hulls)										
Paper	Cigarette butts										
	Paper										

Size class collection data

We need to collect the first piece of debris encountered in every 1/10th transect length interval (up to 10 pieces of debris in total) and record their size. To do this divide the total transect length by 10 (see note 6 above). This will give us the intervals at which to collect our debris for size class, eg: if your transect is 45m total length then we want to record a size class every 4.5m. We do this by recording the size class (classes given on second sheet of survey documents) of the first item we see at every interval. If for example we don't see our first piece of debris until 23m, this goes into the sixth row of debris size class table for the 45m transect length. You may not get 10 size classes per transect, don't worry, just record the size class of the first item you see in each interval.

10) Continue your survey, recording everything you find until you are 2m into the backshore vegetation.

11) When you reach the second marker in the backshore veg, take another GPS reading and this will be your end location. Also record the time for ending the transect and take a photo.
12) Now you have completed one transect move another 50m (preferably 100m or more) down the beach and repeat for another transect.
13) Remember there is a minimum of 3 transects per beach so repeat again. If time is available you can do up to six transects per beach.

EMU PARADE Guidelines

The Emu Parade is a simpler method for sampling marine debris. For an 'Emu Parade' divide students into groups of 10 or less, with each group designated a specific section of the beach. Set up transects according to the following specifications-

- Transects are 30m wide (can be wider) along the beach.
- Transects are located at least 50m from main beach access point, wherever possible.
- Transects are located at least 25 metres apart (ideally 50 metres).
- Transect to run two metres into continual terrestrial vegetation (at the back of the beach, in the dune area, for example).
- Minimum of three transects and maximum of six per site/beach.

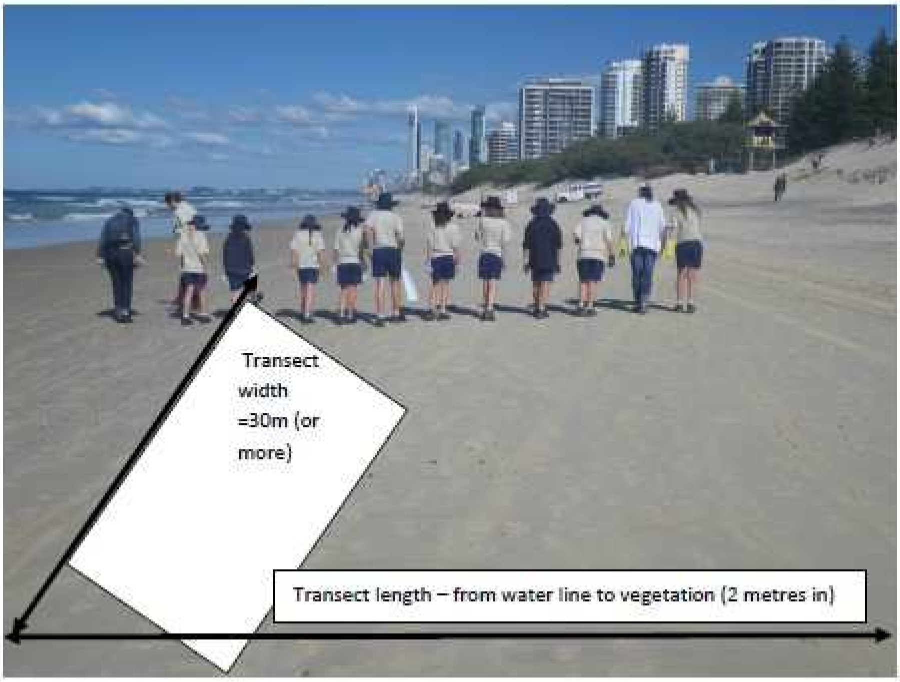


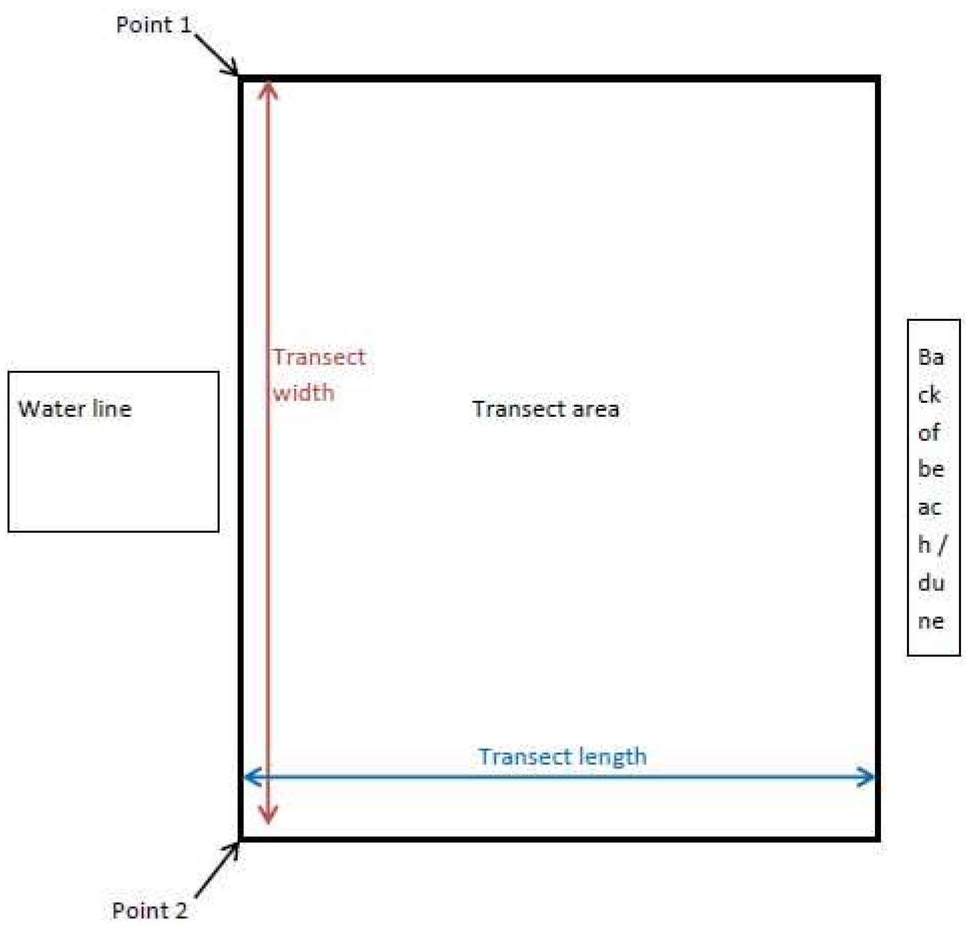
Photo- Earthwatch

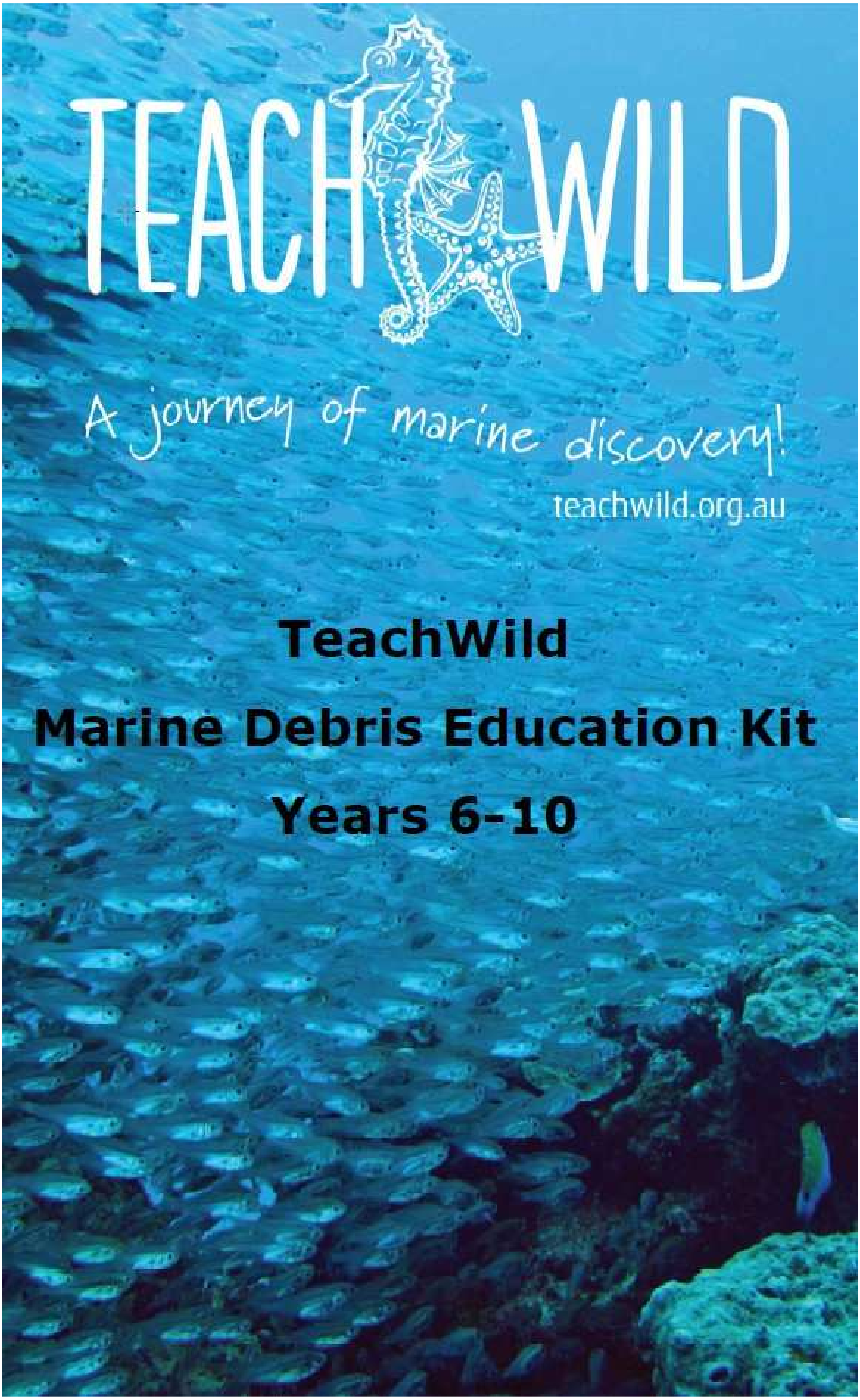
Surveying Method

- Record the start of the transect using a GPS point, mark on map or use itracker.
- Place a marker at that point to mark Point 1, measure out the length of the transect and place another marker to designate Point 2.
- Participants walk in a line formation, approximately shoulder to shoulder along the transect, for the total width of the transect (30m, can be wider).

Continue to walk in line formation, back and forth along the transect width, until the length of the transect (from the water line to into the vegetation at the back of the beach) has been sampled.

- All marine debris found within the transect area is collected in a bag and brought back to the classroom for recording.
- Debris is sorted into groups according to size using the Marine Debris Size Chart to classify the different types of debris into size classes 1-5. A separate data sheet is used for each size classification.
- For each size classification, the type and colour of marine debris is recorded on the datasheet.
- Data is then put into the National Marine Debris database and/or sent to CSIRO for entry.




TEACH WILD
A journey of marine discovery!
teachwild.org.au
TeachWild
Marine Debris Education Kit
Years 6-10

Contents

TeachWild is an exciting innovative education program from Earthwatch Institute Australia. At Earthwatch we are committed to educating future generations on the need to protect and conserve our environment. In partnership with Shell and the CSIRO we are proud to offer a comprehensive education kit for years 6-10 on the worldwide issue of marine debris.

Introduction

TeachWild is an enquiry based learning program addressing the impacts of marine debris on our marine environment. The program actively engages students in becoming citizen scientists and this includes hands-on learning in scientific methodology, data collection and analysis of marine debris. This data will be uploaded onto the TeachWild website to become part of a National Marine Debris database.

Overview

The purpose of marine debris education is to create an understanding for students of the impacts marine debris has on our ocean health. Throughout the course of study students will develop problem solving skills in cross curricular areas including oceanography, biology, chemistry, physics and mathematics. They will learn about the impacts that marine debris has on vertebrate marine life and will be able to identify different types of rubbish and determine possible sources and how marine debris moves in the marine environment.

The Problem

Marine debris is a major global threat to biodiversity. For instance, more than six million tons of fishing gear alone is lost in the ocean each year (Derraik 2002). Despite this staggering amount of marine waste, fishing gear forms only a small percentage of the total volume of debris in the ocean, not even making the list of the top 10 most common items found during coastal cleanup operations (Ocean Conservancy 2010).

The data collected for this project will contribute to addressing the four fundamental questions on marine debris:

1) What are the sources, distribution, and ultimate fate of marine debris?
2) What is the exposure of marine wildlife to debris?
3) When wildlife are exposed to debris, what factors determine whether animals ingest or are entangled by debris?
4) What is the effect of ingestion or entanglement on marine wildlife populations?

Marine debris is any human-made object that can be intentionally or unintentionally discarded, disposed of or abandoned that enters our marine environment. Marine debris has known impacts on our marine life and the marine environment such as-

- Ingestion and entanglement in the marine debris
- Bioaccumulation
- Plastic debris can be regurgitated as food for hatchlings (adult birds will regurgitate food for their young which may contain plastic)
- Animals can become entangled which can lead to infection or loss of limbs.

Marine Debris impacts upon a range of species and it is estimated that **250 species** are known to be affected worldwide.

Photo- NOAA

Marine Debris can be classed as coming from two different areas- land based sources and from ship based sources. Both create an immediate threat to our marine life.

Land Based

Litter from Land Based sources can find its way into our oceans through run off from urban areas. Our catchment areas become heavily polluted through poor rubbish disposal practices on land. The origin of land debris is often from runoff, stormwater drains, air-borne debris and irresponsible disposal of rubbish by beach goers and campers.

Ship Based

Every day ships jettison 5.5 million items of waste at sea, this includes waste such as- fishing lines and nets, offshore oil and gas rig/ platform debris, merchant ship, ferry and cruiser line waste, recreational and tourist vessel garbage. (Clean Up Australia)

The increased use of plastics over the last few decades, particularly for packaging and the slow rate in which plastic degrades has led to the increase of plastics in surveyed debris. It is very difficult to distinguish between those pieces of litter that have entered the ocean recently and those that have been there for years, this is due to plastics being very durable and long-lived.

Debris can be classified into groups- degradable, biodegradable and non degradable. Objects are classed as degradable if they can be broken down by natural forces, wood, natural rubber and cloth are only moderately persistent because they can biodegrade. Paper is not persistent because it is biodegradable and can be torn apart easily. Plastic, glass, synthetic rubber, synthetic fabrics and metal are typically resistant to biodegradation and tend to persist in the environment for a long time. Individual items of debris can circulate in the world's oceans for years; as a result no area regardless of whether it is remote or easily accessible is immune to the threat of marine debris.

The Solution

Solutions to the marine debris problem are dependent on the reduction of rubbish entering our waterways in the first place. Education campaigns are our best weapon in the fight against marine debris. The 3 R's Reduce, Reuse, Recycle is an important educational campaign that has been around for many years; by harnessing pollution prevention activities marine debris will ultimately be reduced creating a cleaner, healthier marine environment.

The information uploaded onto the TeachWild website by students will be used as part of the National Marine Debris database. The data collected will be used in important scientific research, it is through increased understanding of the marine debris problem that scientists will be able to draw accurate conclusions and in turn develop strategies to manage this worldwide threat.

The TeachWild Kit

The purpose of this kit is to provide students with a comprehensive and interactive learning experience on marine debris. The kit adheres to The Australian Curriculum and provides scope for expansion with nominated extension exercises and additional resources. The kit is designed to be easy to follow with Fact Sheets, Student Work Sheets and Curriculum Objectives achieved available for teacher and student support.

Website linkages are identified to provide necessary background information to assist students in activity completion. Video footage of the marine environment under stress gives students visible evidence of the problem. Field trips as part of the CSIRO Scientists for a Day Program are designed so students can get hands on experience with data collection. It is through evidence based enquiry that students will be able to develop probable solutions to the problem that is marine debris.

Students will come to understand that through education, incentives and regulation the problem of marine debris can be better managed. It is important that this issue is addressed now as it is having a severe impact on our marine life, the fishing industry and the tourism industry. As students are the future custodians of our environment the responsibility to protect the environment is left in their hands, so it is imperative that they understand the value of the marine environment in its current and future state.

Aims

- Identify the impacts marine debris has on the marine environment
- Make connections between practices on land and determine how they can influence water quality.
- Understand the water cycle and how marine debris is transported through oceanic currents
- Develop an understanding that there is an interrelationship between the Earth's environment and human activities.
- Investigate the responsibilities of Australia and other countries in managing the marine debris problem.

Progressive Learning Overview

Step 1- In the in classroom activity, students are introduced to the concept of marine debris and are asked what the possible impacts on the marine environment are.

Step 2- Students visit a local beach with one of our Scientists as part of the CSIRO Scientist in Schools Program to collect data.

Step 3- Students process their findings in groups and draw conclusions as to the severity of the pollution problem. These results are discussed in class.

Step 4- The classes' collective data is then sent to the TeachWild website for upload onto the National Marine Debris database.

Step 5- Students do quarterly follow up monitoring with data entered into the website regularly. Any good footage of students collecting data and explaining the need to do so will be uploaded onto the TeachWild website for other students to access.

Step 6- Students research will be used as part of national monitoring program on the levels of marine debris. Students will have gained a deeper understanding of the subject matter through investigation and will now understand why marine debris is a problem that affects all of us. With this knowledge students will develop strategies as to how we can all make a difference.

Data Collection

The project objectives to marine debris surveys are-

1) The characterisation of marine debris for identification of sources for development control and if possible enforcement.
2) Create understanding of the threat of marine debris to marine life and the marine environment.
3) Creation of public awareness of marine debris issues and threats.
4) Cleaner beaches.

Summary

Through monitoring of the beach area students will gain a deeper understanding of the problem that is marine debris. Students have looked at their own consumption and disposal habits and those of others and have determined some of the impacts rubbish is having on the marine environment and marine life. Through surveying students have seen the results of their cleanup efforts with a cleaner coastal environment. As students will have their data published on the TeachWild website and used in research they will have achieved a sense of pride in being part of a National Marine Debris monitoring effort.

Contacts

For further information please contact us-

Website- www.teachwild.org.au

For teachers and students interested in being involved:
teachwild@earthwatch.org.au

For volunteers- state agencies-members of the public wanting to be involved:
denise.hardesty@csiro.au

TEACH WILD

Marine Debris Beach Survey

Year 6	Year 7	Year 8	Year 9	Year 10
ACMMG135 ACMMG136 Geography- Manage data and information collected and look for patterns and relationships	ACSIS125 ACMSP167	ACSIS146	ACSIS170 Geography- Planning, collecting and evaluating	Geography- Planning, collecting and evaluating

See Australian Curriculum in Appendix 1

Field Equipment for Scientist for a Day

- Markers for start and finish of the transect line
- Tape measures (rope/string can be used also for transect measurement)
- Camera with gps for start and finish coordinates or Google map reference.
- Data sheets- Transect Data Sheet, Marine Debris Beach Survey Sheet, Marine Debris Size Chart Sheet.
- Wind indicator
- Compasses
- Coastal seashores identification book
- Tangaroa Blue Ocean Care Society Marine Debris ID Manual http://www.oceancare.org.au/site/index.php?option=com_rokdownloads&view=folder&Itemid=1000100&id=20:marine-debris-id-manual

Equipment for schools to supply

- Gloves (reinforced)
- Hessian/chicken feed bags (these will be reused for future clean ups)
- Pens/Pencils

- Clipboards
- Tongs
- Data sheets- Transect Data Sheet, Marine Debris Beach Survey Sheet, Marine Debris Size Chart Sheet.

Pre Surveying

Prior to the commencement of the excursion certain preparations need to be made such as-

- Tides need to be checked-www.bom.gov.au/oceanography/tides/ with a low tide being preferable as rubbish would have just washed ashore after a high tide.
- Safety brief of the area prior to commencement of activity, including rules such as students are not to pick up any hazardous substances or objects eg sharps and litter that has come into contact with bodily fluids. Please refer to Earthwatch Risk Assessment for beach survey safety analysis which is available for download on the TeachWild website.

Students are to make observations and record data on the Marine Debris Beach Survey Sheet and Transect Data Sheet prior to the commencement of data collection including-

- Drawing a mud map of the beach and surrounding areas. If a GPS is available map out the points for each site and record for upload onto the website.
- Weather conditions before, during and after the excursion will determine how much debris is on the beach.
- Landforms, is the beach flat or sloping? Is there evidence of recent storm activity, erosion etc.
- Is there anything else worthy of note?

Procedure

Divide students into groups, with each group designated a specific section of the beach. Ask students to collect any debris they find washed up on the beach and in the dune area along the transect line. They are to follow the methodology below to ensure a standardised method of data collection is achieved. Explain to students that if all schools that are participating in the survey do not follow the same methodology then the data used for research will not be as accurate as it needs to be.

Guidelines

Set up Transects according to the following specifications-

- Transects are located at least 50m from beach access point.
- Transects are located at least 25 metres apart (ideally 50 metres)
- Transect to include two metres into continual terrestrial vegetation.
- Transects are 2m wide (can be wider).
- One survey form is to be completed per team.
- Minimum of three transects and maximum of six per site.
- Minimum of one transect located within each major habitat type. (Transects are to be proportional to habitat type).

Photo- CSIRO

Surveying Method

- One student is to be nominated as the recorder for the group with the other group members responsible for sampling.
- Record the start of the transect using a GPS point.
- Place a marker at that point to mark Point 1, measure out the length of the transect and place another marker to designate Point 2.
- Two students are to walk on each side of the transect line collecting, identifying and classifying rubbish that is within 1m of their side of the

transect and placing in bags as they go. The total width of the Transect is 2m.

- Students use the Marine Debris Size Chart to classify the different types of debris from 1-5.
- Once rubbish is identified and classified the student sampler tells the recorder who writes the information down on the datasheet.
- Once data is collected by students, all datasheets are to be collected by teachers and collated and put into the National Marine Debris database by the teacher or a nominated student.

Photo- TeachWild

MARINE DEBRIS BEACH SURVEY

Survey Guidelines:

- Complete one Beach survey form per site and one transect data form for each transect at the site. Record all co-ordinated in WGS84 datum only.
- Minimum of three transects and minimum of six per site.

* Minimum of one transect located within each major habitat type (transects proportional to habitat type).
* Transects located at least 50 m from beach access point (ideally not located both sides of access points, unless different habitat types).
* Transects located at least 25 meters apart (ideally 50 meters).
* Transect to include two meters into continual terrestrial vegetation.

SURVEYOR DETAILS		
Organisation		*Organisation responsible for survey*
Surveyor name		*Name of chief surveyor*
Contact number		*Contact number for surveyor*
Access point location	Latitude: Longitude:	*Latitude and longitude of access point where you enter the beach (dd.dddd)*
GPS accuracy		*Accuracy (meters) of GPS at time of reading*

SITE DETAILS		
State / Territory		*State or territory where beach is located within Australia*
Beach name		*Unique name of beach , if known*
Survey date		*Date survey was undertaken (dd.mm.yyyy)*
Current weather conditions	Clear Rain / Storm Overcast Drizzle	*Select best option to describe the weather*
Wind speed	0 1 2 3 4 5	*Speed estimate:* *0 : calm (flat ocean)* *1: light breeze (wavelets, <10km/h , <6 knots)* *2 : moderate breeze (small waves braking crests, 10-25km/h, 6-20 knots)* *3 : strong breeze (waves and many white caps, 25-49km/h, 21- 26 knots)* *4 : high wind (white caps and airborne spray, 50-65 km/h , 27-35 knots)* *5 : gale (high waves, foam and spray present, 65-85 km/h, 35-45 knots)*
Wind direction (compass)	N NE E SE S SW W NW N/A	*Direction from which wind is coming measured by the compass. N/A if no wind.*
Wind direction (relative to shore)	on shore off shore side shore side off side on	*On shore : wind blowing towards shore* *Off shore: wind blowing towards sea* *Side shore: wind blowing parallel to shore* *Side on: wind blowing sideways and towards shore* *Side off: wind blowing sideways and towards sea*
Date of last clean up		*If known*
Number of humans	Time of day (00:00):__________ Visible distance (m):__________ No. of people:__________	*Number of people counted in the visible area measured by instantaneous count. Visible distance is length of shore with a clear and unobstructed view.*
Comments:		*For example: entangled fauna, storms, shipwrecks etc. boat ramp in close proximity, signs of coastal erosion or conditions that may affect the survey.*

Official use only
Beach number (unique identity code): Survey Area (A,B,C,D,E,F) :

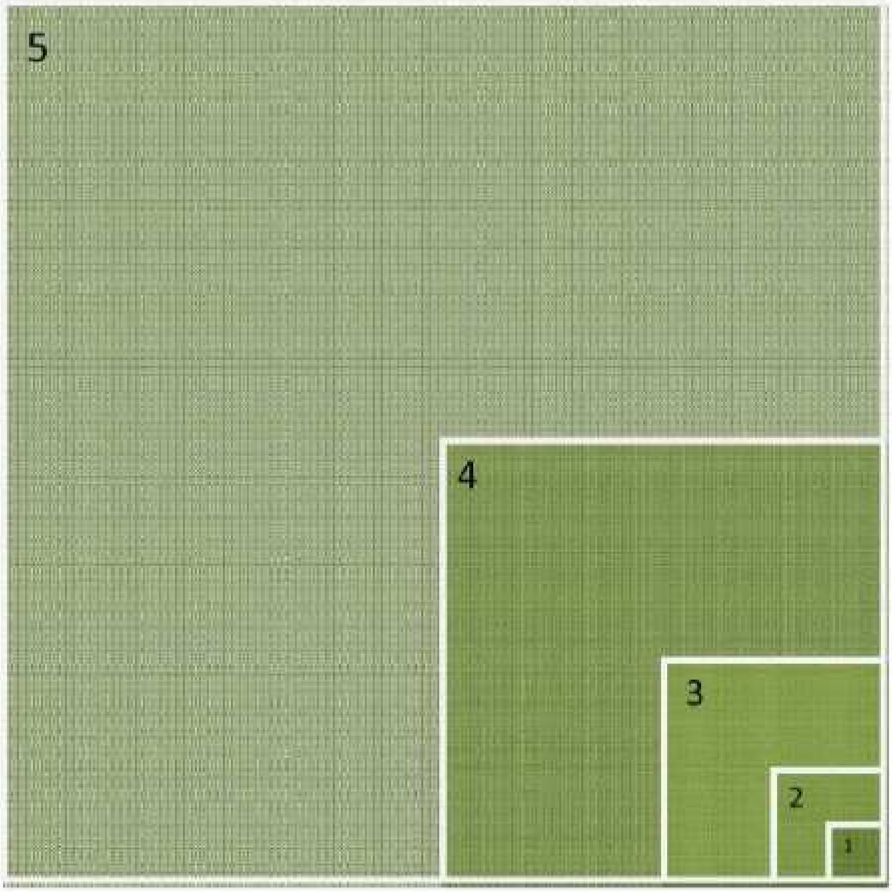
Marine Debris Size Chart

Guidelines:

* This chart should be used as a guide to help estimate the size of marine debris during each beach transect (see transect sheet)
* The squares below represent different size classes

1 = 0 – 1 cm^2 ; 2 = 1-2 cm^2 ; 3 = 2-4 cm^2 ; 4 = 4-8 cm^2 ; 5 = 8-16 cm^2 ; 6 = >16 cm^2

* To estimate area, determine which square the object will fit into.
* Note. It may be helpful to fold objects that are long and thin in order to picture the total areas. For example a plastic straw



Transect Data

Beach Name		Transect width (m)	
Transect Number		Start time (00:00)	
Name of surveyors		End Time (00:00)	

Number of surveyors		*Total number of people looking for rubbish.*
Transect start	Latitude: Longitude: GPS Accuracy:	*Latitude and longitude recorded in decimal degrees (dd.dddd).* *Accuracy (in meters) of the GPS at time of reading*
Transect end	Latitude: Longitude: GPS Accuracy:	*Latitude and longitude recorded in decimal degrees (dd.dddd).* *Accuracy (in meters) of the GPS at time of reading*
Distance to dominant debris line (m)		*Distance from water edge to major debris line (in meters) at time of survey. Example 23 meters. If no obvious debris line use NA.*
Photo number		*Number of transect photo, taken from transect end point.*
Transect length (m)		*From waters edge to two meters into continual terrestrial vegetation (meters).*
Beach gradient	1 2 3 4 5	*Difference in elevation from start to end of transect.* *1 = < 1 m (less than hip height)* *2 = 1-2 m (hip to head height)* *3 = 2-4 m (1-2 body length)* *4 = 4-8 m (2-4 body lengths)* *5 = > 8 m (more than 4 body lengths)*
Substrate type	Mud Sand Pebble/ Gravel Boulders Rock slab Mangrove	*Major substrate type.*
Substrate colour	White / cream Yellow Orange Brown Black Grey Red	*Predominant colour of substrate*
Backshore type	Cliff Seawall Urban building Forest/ Tree (> 3m) Shrub (< 3m) Dune Grass – tussock Grass – pasture Mangrove	*Physical structure of backshore, where beach meets terrestrial vegetation.*
Beach exposure or shape	Concave (cove) Straight Convex (headland)	*Shape of beach where survey is conducted. Based on 25m each side of transect.*
Aspect	N NE E SE S SW W NW	*Direction when you are facing the water.*

Size classes:

Debris type and size class should be sampled at ten points along each transect..

1. Divide the total transect length by 10 to determine sampling interval. For example if transect is 35 m, sampling interval = 3.5 m.
2. At each interval record the type and size of the first piece of rubbish encountered. If no rubbish detected within the interval draw a line through the box and continue to next interval.

For example: If no rubbish is found within the second interval (3.5 – 7m), but six pieces were detected in the third interval (7 -10.5m) mark a line in the box for sample 2, and record the size and type for only the first item detected in sample 3.

Transect debris (type and colour) : Record one hash mark (IIIII) for each piece of rubbish larger than 1cm2 in size, within 1 meter each side of the transect line. If you find items other than those listed, add details to bottom of table

Rubbish Type		Colour of debris									
		Clear/ translucent	White	Red/ pink	Orange	Yellow	Green	Blue/ purple	Brown	Black	Grey/ silver
Plastic	Hard plastic										
	Plastic bags										
	Film-like plastics (glad wrap and chip bags)										
	Other soft plastics										
	Plastic packing straps										
	Net (estimate size)										
	Fishing line										
	Plastic (string, twine, rope)										
Cloth	Non-plastic (string, twine, rope)										
Glass	Glass										
Metal	Fish hook										
	Metal (hard)										
	Metal (soft, tinfoil)										
Rubber	Balloon										
	Other rubber items										
Foam	Polystyrene (foam, from esky's bouys etc.)										
	Other foam										
Timber	Wood (posts, beams, ship hulls)										
Paper	Cigarette butts										
	Paper										
Other											

Size classes: Sample debris type and size class at ten points along each transect.

	Distance from water (m)	Size code ##	Type / colour
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

1. Divide the total transect length by 10 to determine sampling interval. For example if transect is 35 m, sampling interval = 3.5 m.

2. At each interval record the type and size of the first piece of rubbish encountered. If no rubbish detected within the interval draw a line through the box and continue to next interval. **For example:** If no rubbish is found within the second interval (3.5 – 7m), but six pieces were detected in the third interval (7 -10.5m) mark a line in the box for sample 2, and record the size and type for only the first item detected in sample 3.

Post Survey

Students can clean up the beach area of any additional rubbish that is found if time permits. Scientists and teachers are to ensure that this rubbish is not mixed up with the rubbish that has been recorded on the datasheet.

Back in the classroom

At the end of the activity once the rubbish has been identified, divide it into two separate piles recyclables and non recyclables. Explain the importance of the need to dispose of all waste thoughtfully and state the fact that in nature there is no waste due to natural cycles, waste is a human invention that is not easily broken down or managed by natural means.

Ask students questions about-

- What was the most common piece of rubbish?
- Why do they think that is so?
- How can they reduce that type of rubbish occurring on the beach?

Ask students to think of reasons why people may be reluctant to changes their ways in regards to consumption. Reinforce to them that it is doable; look at successful clean up campaigns such as the elimination of plastic water bottles from some towns and schools and the green bag movement.

Conclusion

Ask students to discuss their findings in their groups, they are to draw conclusions from the data and discuss with their classmates. From that data ask students to formulate questions for the visiting scientist.

- Why are certain types of rubbish more transportable than others?
- What impacts can prolonged exposure of some plastics in seawater cause?
- Why is ingestion and entanglement of marine life a very real danger?
- What can be done to educate others about the problem of marine debris?

Collate data and upload all of the data collected onto the TeachWild website to become part of the National Marine Debris Database. Arrange to conduct follow up surveys quarterly with the class unassisted by TeachWild staff.

Further Learning

This activity is designed to be ongoing with further investigation undertaken by students and teachers quarterly. Teachers will be given access to the TeachWild website to upload any additional data and will be provided with online support via the website. This data will be used as part of the National Marine Debris Database and will be used in scientific research.

Years 8-10 could be involved in a more intensive sampling of marine debris with an accompanying module of chemistry, biology, physics or other area designed to address some of the key elements of that unit of study. Teachers are responsible for the development of this content.

To further increase student's knowledge of the marine debris issue the following Fact Sheets and Student Work Sheets have been developed and can be completed in class to complement the field activity or in classroom activity conducted by TeachWild staff. These activities can also be used as a refresher for students in the lead up to the quarterly sampling led by teachers or as a pre cursor to the first TeachWild visit.

The aim of additional resources is to further increase student's awareness of the problem and inspire continued appreciation and commitment to the preservation of the marine environment.

Clean Up Days

Throughout the year there are numerous clean up campaigns designed to help combat the impact marine debris is having on our marine environment. Student involvement is advisable where possible.

Some of the key initiatives are-

Clean up Australia Day

http://www.cleanupaustraliaday.org.au/

Project Aware International Clean Up Day

http://www.projectaware.org/

Any day is a good day to organise a cleanup, whether it be the whole school, a class or group of individuals it all counts in combating the marine debris problem.

Activities Summary Table

Year	Activity	Theme	Key Concepts	Adaptable for Year
6	How long is too long?	Chemistry	Waste Degradation Timeline Waste Reduction Waste Disposal	All Years
7	Plastics as food	Chemistry Biology	Classification of Marine Debris Properties of Plastic Trophic Levels Food Chains	All Years
8	Marine Animal Entanglement	Biology Physics	Marine Animal Entanglement and Ingestion of Marine Debris	All Years
9	Marine Debris- A Global Problem	Oceanography	Great Pacific Garbage Patch Ghost Nets	10
10	Ocean Currents	Oceanography Physics	Ocean Currents Movement of Marine Debris Great Pacific Ocean Patch	9

Teachers Note- All activities are designed to be adapted to suit different year levels, this table can be used as a guide when preparing alternate Lesson Plans.

TEACH WILD

Lesson Plan- How long is too long?

Year	Subject	Code	Key Words	Materials	Duration
6	Geography Science	Processing data and information collected and look for patterns or relationships. ACSIS232	degrade, natural cycles, awareness	rubbish from classroom bin	1 hour

See Australian Curriculum in Appendix 1

Overview

Students look at the timeline of the rubbish breakdown and from this look at their own consumptive behaviour and that of others. They understand the complexity involved in the degradation of everyday items. Through analysis of their own rubbish students will understand how they are impacting on the environment as an individual and develop practical solutions to decreasing that impact.

Objectives

- Students collect information and analyse it.
- They look at the cause and effects of littering and suggest and evaluate possible future scenarios, giving reasons for their preferred options.
- Develop an understanding of the methodology and cause and effect of littering.

Activity

Introduce students to the concept of marine debris. In the classroom take students through the Fact Sheet- How long is too long. Lead a class discussion on the different types of rubbish and the timeline each takes to degrade. Were students shocked by how long some everyday objects take to degrade? If so which ones? After the discussion, ask students to complete the questions on the Student Work Sheet. Students can calculate their savings on reducing waste using the following equation- Savings per month x bank charges for account=net savings rate x time= total savings.

FACT SHEET- How long is too long?

Rubbish is often not easily degraded or managed by natural means. Degradation doesn't equal disappearance with degraded rubbish continuing to persist in the marine environment. The amount of waste that the Earth cannot cope with is increasing. It is important that we understand and create awareness of the time it takes for everyday rubbish to break down.

Item	Time
Apple Core	2 months (in water)
Aluminium can	200-500 years
Cardboard box	2 months (in water)
Disposable nappy	450 years (in water)
Fishing line	600 years (in water)
Glass Bottle	forever
Leather	up to 50 years
Nylon fabric	30-40 years
Orange/banana peel	up to 2 years
Plastic Bag	500+ years
Plastic Bottle	Forever
Plastic coated paper	5 years
Plastic film container	20 -30 years
Styrofoam/ Polystyrene	Forever
Tin can	50 years
Wool socks	1-5 years

Source- www.createyourowneden.org.nz

STUDENT WORK SHEET

1. Are you surprised by how long some everyday items took to break down? If so what items?

____

____

____

____

____

2. What's in your waste? (refer to list)

Item	Components
1. ____________________	4. ____________________
2. ____________________	5. ____________________
3. ____________________	6. ____________________

3. Can you trace back every piece of waste in your classrooms bin? Create a timeline of 10 items and the time it takes for each item to break down in the space below-

Waste bin

6weeks 6months 5 years 50 years 400 years

4. Create a timeline of 10 items found on the beach in the space below-

Beach

6weeks 6months 5 years 50 years 400 years

5. Compare the two timelines, does rubbish from the beach have a different timeline to rubbish from the bin? Yes/ No

6. Why do you think this is the case?

____

____

____

7. Think about the waste in your bin at home. Where does the majority of your waste come from?

____
____
____
____

8. Where does your waste end up? Provide three possible answers-

______________________ ______________________

____

9. Did the waste in the bin and the waste found on the beach survey differ?

____
____

10. What type of waste did you find most on the beach?

____
____
____
____

11. As consumers, what could we do to reduce this type of waste on the beach?

____
____
____
____

12. How much will you save per month by reducing your waste?

____
____
____

13. What are the three R's?

______________________ ______________________

____

Lesson Plan- Plastics as Food

Year	Subject	Code	Key Words	Materials	Duration
7	Science	ACSIS124 ACSSU112	plastic, plankton, size categories, food chain	Assortment of different sized plastic pieces and rubbish	45 minutes

See Australian Curriculum in Appendix 1

Overview

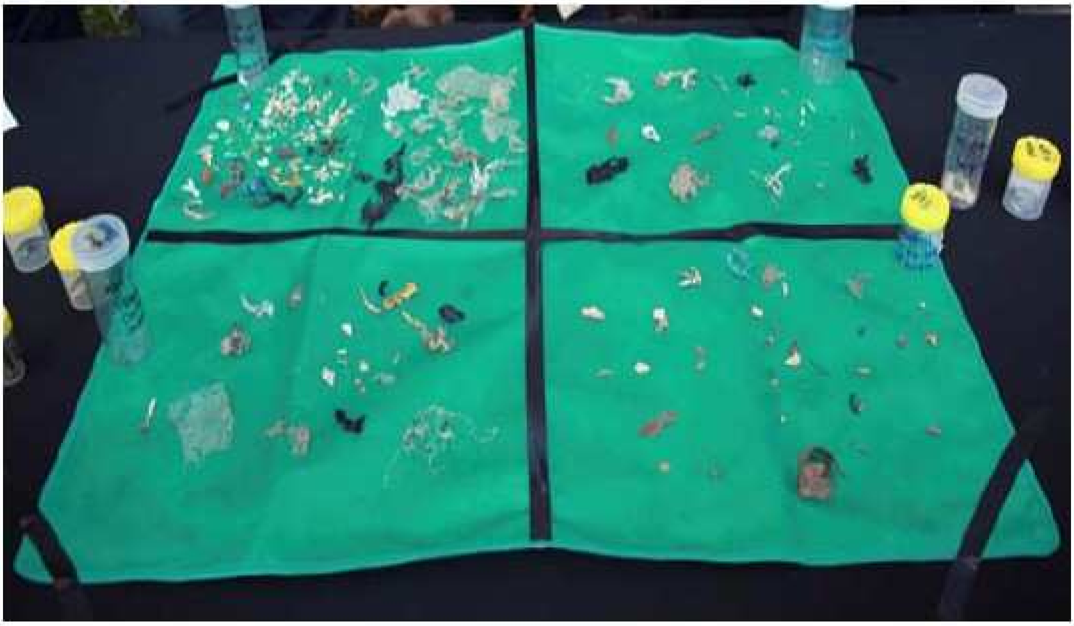
In class students are to look at the degradation of debris. Students will look at the rate at which rubbish takes to degrade and in turn will understand how persistent debris is in the marine environment. They will begin to understand the effects that our consumer behaviour can have on the environment. They will look at the properties of plastics and understand that the rate in which plastic breaks down in the marine environment is slow and that plastic readily enters food chains, often with disastrous results.

Objectives

- Students develop an understanding of the properties of plastics and the impact they have on the marine environment.
- Students work collaboratively by discussing the problems associated with persistent plastics in the marine environment and investigate the impact on marine food chains.
- Students look at their own consumptive behaviour and that of others considering that social, cultural, economic and moral aspects need to be taken into account to solve the marine debris problem, not just scientific investigation.
- Student will use information and knowledge of their previous investigations of marine debris to predict the outcomes of the possible impacts of variation in the size of the plastics on marine animals.

Activity

Introduce students to the plastic problem using the Fact Sheet-Plastics as Food. Divide the class into groups of four, give them a pile of plastics and rubbish to sort and classify using the Marine Debris Size Chart. Students are to look at the size of the pieces and the colours and separate accordingly. Ask students to answer the questions on the Student Work Sheet.



Discuss with the class that there are numerous implications for marine debris on a moral, social, cultural and economic level. Reiterate to students that we are polluting the environment at a cost to future generations. Intergenerational equity means that future generations should be able to enjoy the environment inherited from past generations in a reasonable condition. The cost to the environment and individuals from the impacts of marine debris is high. The cultural impacts of marine debris are often felt by aboriginal communities where traditional fishing practices are impacted upon.

Students are to look at the movement of plastic through the food chain, introduce students to the different trophic levels-

Quaternary Consumer- a carnivore at the topmost level of the food chain that has little or no natural enemies. Feed on tertiary consumers.

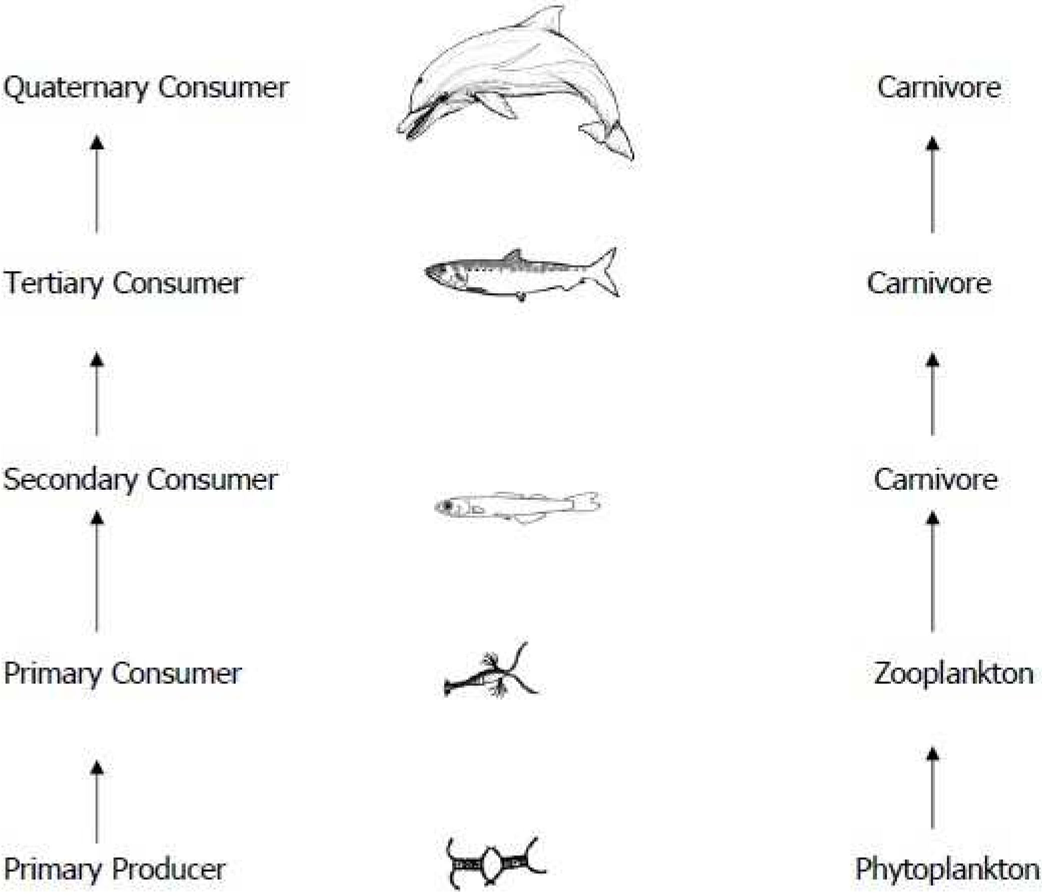
Tertiary consumer- feeds on other carnivores; an animal that feeds only on secondary consumers.

Secondary consumer-a carnivore that feeds only upon herbivores.

Primary consumer- an animal that feeds on plants; a herbivore.

Primary producer-any green plant or any of the various microorganisms that can convert light energy or chemical energy into organic matter.

Explain to students that plastic will move through the food chain through the different trophic levels. They are to document this on the Student Work Sheet, below is an example of a simple food chain



FACT SHEET- Plastics as Food

Plastic is estimated to constitute 90% of all trash floating in the world's ocean. In some areas the plastic outweighs plankton by a ratio of 6-1. Plankton is the life force of the oceans and is a crucial food source to numerous species including fish and whales. Without these drifting organisms (animals, plants, archaea, bacteria) our ocean health would be severely lacking. Those animals that rely on plankton as a food source often get confused and instead eat pieces of indigestible plastic that can cause blockages and even death. Toxic chemicals used in the process of creating plastic often leeches out when exposed to water.

Sorting marine debris into size categories gives scientists a good idea of how long the debris may have been in our oceans for, important signs of degradation are changes in the shape, colour and size of the item. The smaller the pieces of plastic the easier it is for plankton feeders to mistake for food and ingest. This then enters the food chain and may make its way to the higher level consumers who by eating those small organisms then ingest the debris those organisms have eaten. The higher an animal is on the food chain the greater the quantity of debris that is consumed and accumulated.

One of the more problematic types of plastics is Plastic Resin Pellets (PRP) which are pre production plastic resin pellets typically less than 5mm in diameter found outside of the typical plastics manufacturing stream. These pellets are an intermediate good used to produce the final plastic product. The longer these pellets remain in seawater the more toxic they become. PRPs resemble fish eggs and are often ingested by birds and fish who mistake them for food.

Photo- NOAA

Student Work Sheet

1. After sampling take a look at the different size categories, what size of debris did you see most of?

____

____

2. What size of debris do you think poses the greatest danger to the marine environment?

____

3. Why did you choose this size?____________________________________

4. What colour plastic do you think is most attractive to marine animals and why?____

____

____

5. List 6 items you use on a daily basis that has the greatest chance of becoming marine debris? What makes you think that? List the items below and the reason for selecting the item-

	Item	Reason
1.	____________________	____________________
2.	____________________	____________________
3.	____________________	____________________
4.	____________________	____________________
5.	____________________	____________________
6.	____________________	____________________

6. Why are persistent plastics a problem in the marine environment?

____

____

____

____

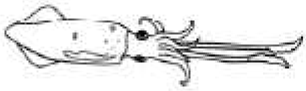
7. Pick one marine organism listed below. Decide what it eats, and what eats it. How does it eat its food?

Phytoplankton

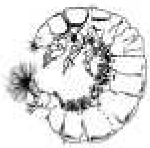
Zooplankton

Mesopelagics

Small Pelagics

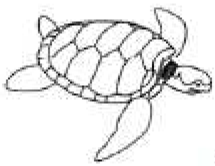


Squid

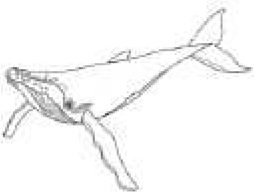


Benthic Invertebrates

Benthic Fish

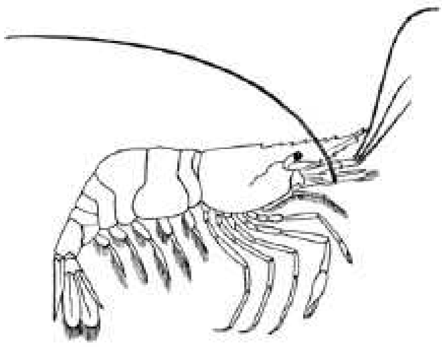


Marine Reptiles



Marine Mammal

8. When plastic enters a food chain where does it end up? In groups of four, trace a Plastic Resin Pellet (PRP) that has been ingested by a prawn, where could this piece of plastic end up in a food chain? Draw the food chain in space below.



9. What are the social, cultural, economic or moral implications of not addressing the plastics problem?

Social______________________________ Cultural_____________________________

Economic____________________________Moral______________________________

Lesson Plan- Marine Animal Entanglement

Year	Subject	Code	Key Words	Materials	Duration
8	Science	ACSIS148	entanglement, ingestion, health	Plastic drinking bottle A3 paper Assortment of rubbish	45 minutes

See Australian Curriculum in Appendix 1

Overview

Students look at the significance of the marine debris problem and how this relates to marine animals. Entanglement and ingestion of marine debris by marine animals is discussed with the impacts thoroughly examined. During the activity students experience a simulation of what it is like to be entangled by marine debris. They then develop an education campaign aimed at members of the public; this will show students the importance of educating others about the marine debris problem to incite change within the community.

Objectives

- Students identify the effect of marine debris on marine animals.
- Develop an education campaign to draw attention to the marine debris problem using digital media.
- Students ensure that science ideas are communicated to the public using appropriate language and representations that the intended audience are able to identify with.

Activity-Marine Animal Entanglement

Introduce students to the concept of marine animal entanglement- how marine animals become entangled and the likely impacts on the animal using the Fact Sheet. Create a simulation of the entanglement of a marine animal in different types of marine debris. A plastic bag, mesh netting, a tin can, rope, strapping band and paper can be used to "entangle" the marine animal.

1. Fill a sink or large tub with water
2. Attach a piece of lightweight rope to a drink bottle; fill the drink bottle ¼ full with water so that it partially sinks.
3. Wrap the first piece of rubbish around the bottle so that it will not come off the bottle easily.
4. Using the rope slowly drag the bottle through the water.

Make sure that you attempt to bring the bottle to the surface now and then throughout the demonstration so students can get an idea of how problematic it will be for surface breathing animals. Students are to observe what happens with each of the pieces of rubbish and record on the Student Work Sheet.

Students are to put together a poster aimed at educating the general public on the impacts of marine debris on marine animals. Students are to use a variety of media in the development of the poster including digital technologies and are to incorporate a slogan, a photo depicting a marine animal entangled in marine debris, a sentence to invoke emotion in the audience (students can draw on their experience from observing entanglement) and a confronting fact they have researched; such as 250 species are known to be affected by marine debris.

Collect all of the class slides and put together into a single PowerPoint Presentation, play this back to the class. Ask them how they felt after watching the slide show. How could they get this information out to their target audience? Devise strategies with students and implement any good ideas that students come up with.

FACT SHEET-Marine Animal Entanglement

Marine animals are at great risk when they come into contact with marine debris. Marine Debris does not discriminate or target one particular species; it can affect a vast majority of species with an estimated 250 species currently known to be affected.

Marine Debris affects numerous species each year, including seabirds, marine mammals and sea turtles which die after becoming entangled or ingest marine debris which they have mistaken for food.

Entanglement

Entanglement is when an animal gets caught in the loops or opening of marine debris. It can occur accidently or when an animal is curious about an object or is looking for shelter.

It is harmful because it can cause-

- Drowning
- Disruption or prevention of feeding by the animal
- Restrict movement or ability to swim
- Increase vulnerability to predators
- Result in infection or loss of limbs
- Hunting and efficiency

Photo- NOAA

Monofilament line, derelict fishing gear, rope and strapping bands are common items that entangle marine life.

Ingestion

Ingestion is when an animal mistakes marine debris for food, eats it and the animal's body cannot process it. Degraded debris can also be ingested by filter feeding organisms leading to problems in the food chain affecting plankton to top order predators.

It is harmful because it can cause-

- Blockages of the oesophagus and the intestinal tract killing the animal.
- Sharp objects can cause injuries and infections.
- Toxins can accumulate in an animal's tissues affecting the health and wellness of the animal.

TEACH WILD

STUDENT WORK SHEET

1. How do you think the rubbish can affect a marine animal?

Immediately____

1 week later____

1 year later (if it does not die)________________________________

2. In the table below record your observations (e.g. time taken to move through the water, drag created from the marine debris, the ability for object to "surface" etc) include what animals would likely be affected by each item of rubbish.

Item	Observation	Animal

3. How do different items affect drag?____________________________
____
____
____

4. Conduct research on the internet to find a photo of a marine animal entangled in marine debris. Use the photo as the central part of an advertising campaign aimed at bringing attention to the problem to the general public. Create an emotive slogan for the campaign using your observations of entanglement as inspiration and a fact on marine animal entanglement researched on the internet. Using an A3 piece of paper create a draft of your campaign poster. Once you are happy with the layout create a poster of a professional standard using Microsoft PowerPoint.

Lesson Plan- Marine Debris- A Global Problem

Year	Subject	Code	Key Words	Materials	Duration
9	Science	ACSIS164	Great Pacific Garbage Patch, gyre, ghost nets, species diversity, relative abundance.	Access to the internet	1 hour

See Australian Curriculum in Appendix 1

Overview

Students look at the marine debris problem on a local and a global scale. They develop a sense of understanding that it is not restricted to one particular area but it is widespread. Students identify why the Great Pacific Garbage Patch exists and explore the possibilities of one occurring on the Australian coastline. The issue of ghost nets is also explored with the need to do something to prevent/control the problem increasingly evident to the student. Students identify methods for tackling the ghost net problem.

Objectives

- Students use the internet to distinguish that marine debris is a problem that affects all of us.
- Students compare local data to worldwide data as part of the research process and refine their line of questioning to target specific information and data collection to find possible solutions to the Great Pacific Garbage Patch.
- Students look at the ghost nets issue, determining what is needed to address the problem and make further investigations as to possible solutions.

Activity

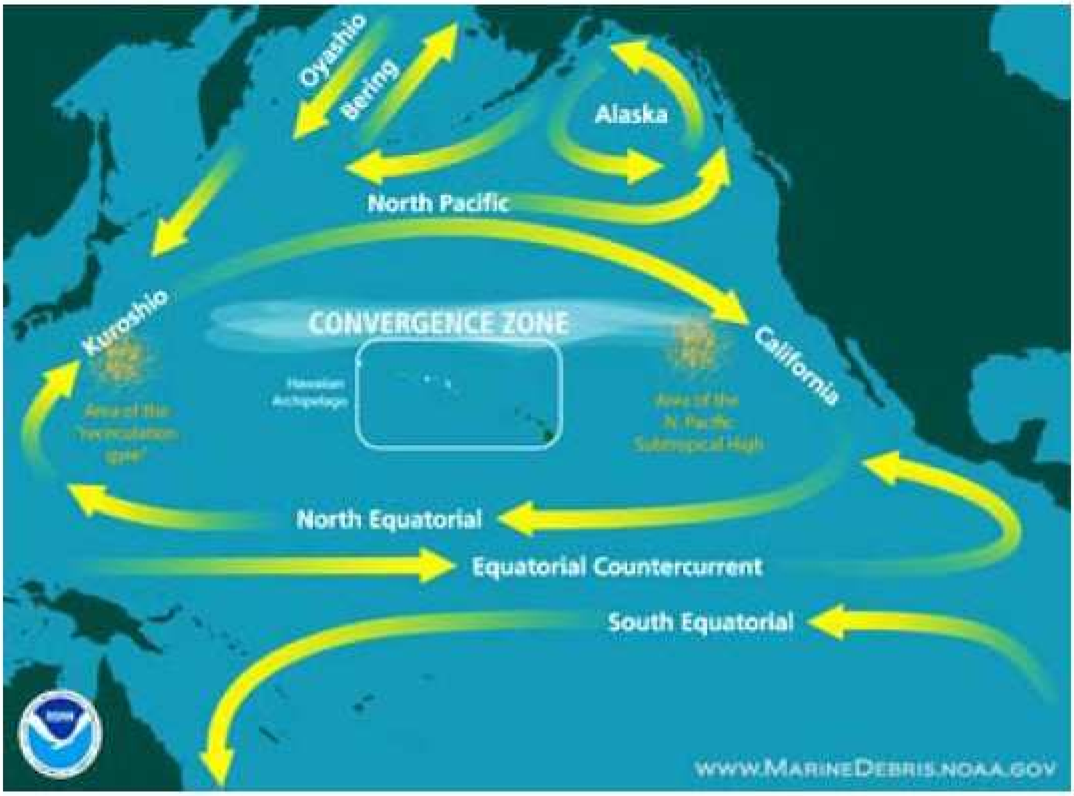
Introduce students to the significance of the Great Pacific Garbage Patch and the ghost nets problem using the Fact Sheet- Marine Debris- A Global Problem. Discuss with students how this issue is not just localised; it is a global issue that needs to be addressed on a global scale. Explain that economics has a major impact on what can and cannot be done to address this problem. Students are to spend the first half of the lesson investigating the Great Pacific Garbage Patch using resources from the internet. They are to look at the scope of the issue and try and determine how it can be better managed or cleaned up. Once students have adequately researched the problem they are to answer the questions on the Student Work Sheet. After the completion of the Student Work Sheet lead an in class discussion on the students answers.

Photo- NOAA PIFC

FACT SHEET- Marine Debris- A Global Problem

The Great Pacific Garbage Patch

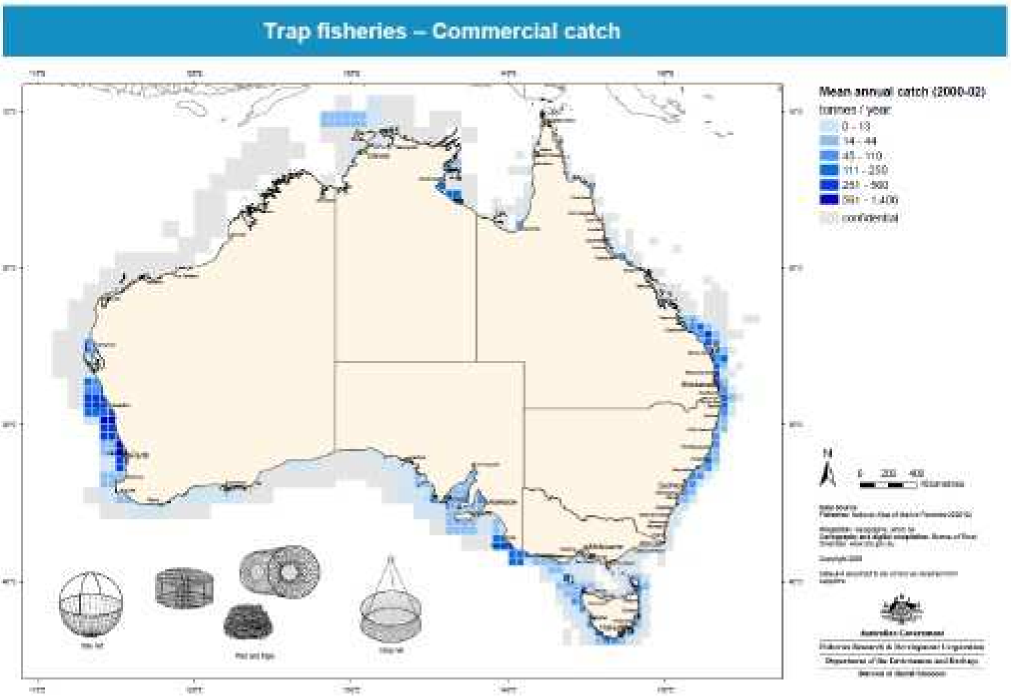
It is one of the most identifying features of the marine debris problem, spanning an area of 1 760 000 sq kilometres this patch of garbage is bigger than QLD. It is an area where a large quantity of marine debris ends up swirling around causing a deadly soup that impacts marine life often killing them either by ingestion or entanglement. It has come about due to oceanic forces bringing all of the debris together into the one area. The North Pacific gyre is one of the five major oceanic gyres. A gyre in oceanography is a large system of rotating currents; gyres are caused by coriolis effect, planetary vorticity along with vertical and horizontal friction. The North Pacific Gyre comprises of four prevailing ocean currents, the North Pacific current to the North, the Californian current to the East, the North Equatorial current to the South and the Kuroshio current to the West.



Ghost Nets

Fishing nets, fishing line, crab and lobster pots or other fishing gear lost or discarded can continue to fish for marine life long after being left behind by fishermen. Commercial fishing nets can be very long and can be transported by currents and waves for long distances and can become concentrated in relatively small areas by winds and currents, continuously ghost fishing for long periods of time. Ghost fishing can catch seabirds, fish, sharks, sea turtles and other marine creatures that cannot free themselves before drowning or dying from starvation. Derelict fishing gear is also dangerous to aquatic habitats including coral reefs, sea grass beds and shallow areas of an estuary. The synthetic materials used in ghost nets decay very slowly.

Ghost fishing also kills a number of fish that may have been sold at the market or would have spawned the next generation. The continual loss of animals from ghost fishing can impact upon both the recreational and commercial fishing industry dramatically. Species diversity and the relative abundance of those species can be affected.



Tackling the issue

Ghost nets are a major problem in our world's oceans. These nets are increasing in our oceans with buy back schemes helping to combat some of the problem but the effectiveness of these schemes yet to be felt in developing countries where it is often easier to discard the net offshore then bring it back to land for correct disposal.

STUDENT WORK SHEET

In groups of four discuss the following questions-

1. How did the Great Pacific Garbage Patch come to exist?

____

____

____

____

2. Why does it exist in that area?

____

____

____

____

3. Name three possible solutions to the Great Pacific Garbage Patch problem-

____

____

____

4. Is it possible for a Garbage Patch to occur in our ocean? Why/Why Not?

____

____

____

5. What current measures are in place to prevent rubbish moving into your local waterway?

____

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____

6. Who is responsible for ensuring rubbish does not enter our ocean?

____

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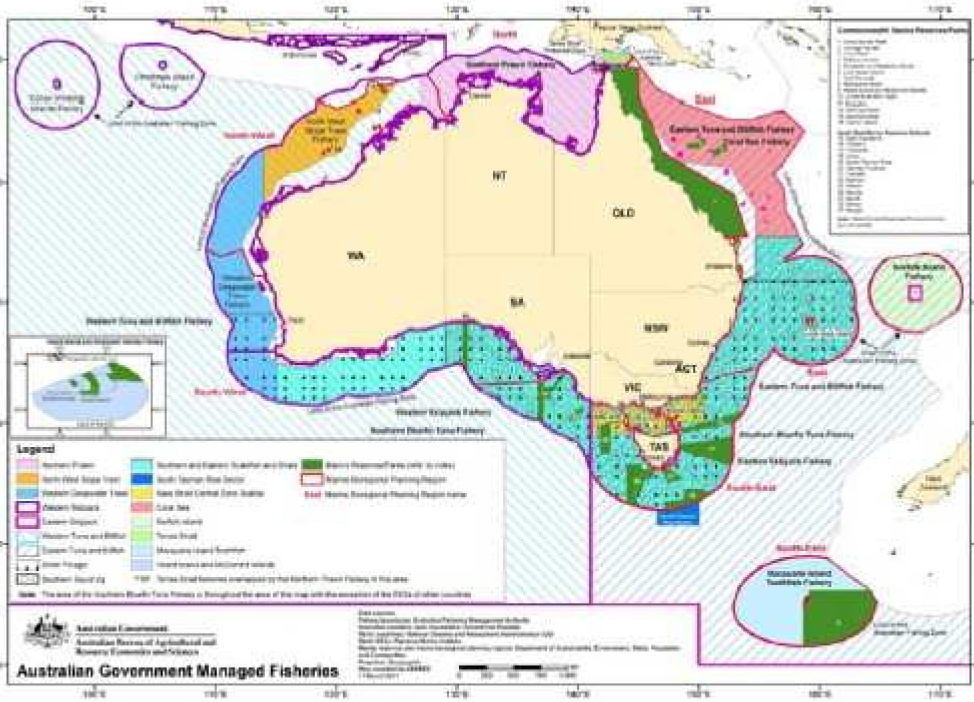
____

7. What are the Ghost Net hotspots along the coastline of Australia? Mark them using a red pen and an X on the map below



8. Does the area where ghost nets occur have any correlation to the type of fishing taking place in that area? Yes/ No

9. List three environmental impacts from ghost nets-

____________________________ ____________________________

____

10. Name two programs currently running in Australia that aim to eliminate the Ghost Net problem.

____________________________ ____________________________

Lesson Plan- Ocean Currents

Year	Subject	Code	Key Words	Materials	Duration
10	Science	ACSIS198 ACSIS206 ACMSP247	Great Pacific Garbage Patch, ghost nets, ocean currents, modelling, media	Access to the internet	2X1 hour lessons

See Australian Curriculum in Appendix 1

Overview

Students look at the effect ocean currents have on the transportation of marine debris. They analyse the movement of a piece of debris using scientific modelling techniques and pinpoint the origin. They develop an understanding of the role media plays in relaying information on the issue of marine debris to the public.

Objectives

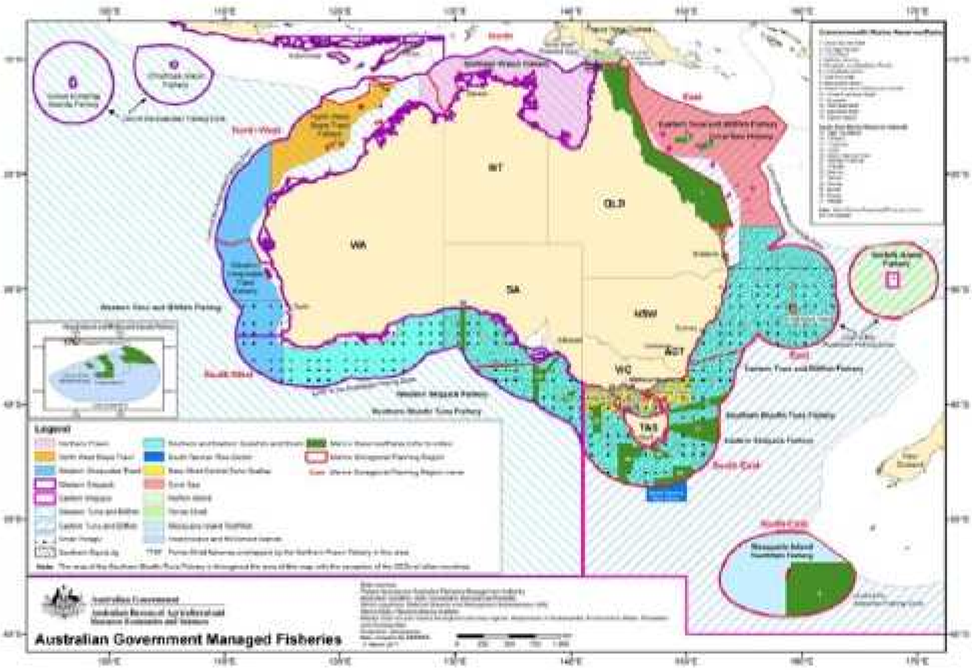
- Students develop an understanding of the movement of ocean currents.
- Students look at the modelling of ocean currents and develop an understanding of how they influence the transportation of marine debris.
- Students are to develop a hypothesis about the movement of marine debris on ocean currents.
- Students are to identify that the Great Pacific Garbage Patch has come about due to ocean currents and identify the problems that are associated with the marine debris that is found in this area.

Activity

This activity will need to be undertaken over two lessons with the first lesson covering ocean currents and the movement of marine debris and the second lesson covering ghost nets and the effect they have on marine animals.

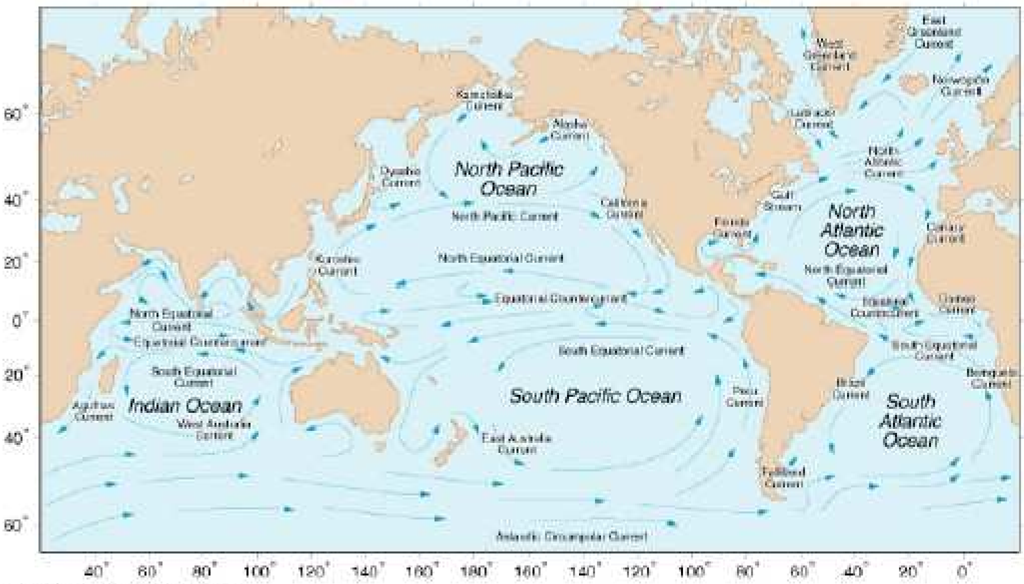
Introduce students to ocean currents using the Fact Sheet- Ocean Currents and explain how the movement of marine debris can be modelled along these ocean currents, with the country of origin often able to be determined. The CSIRO modelling system can accurately determine where an article of marine debris has come from and determine where it has been. Use this website www.csiro.au/connie2/ to help students predict the journey their piece of marine debris may take. Run students through the work sheet and ask them to answer the questions.

In Lesson 2 give students an overview of what is involved in researching whether it be collecting data themselves or reviewing data from secondary sources. Explain to students that once essays are completed students are subject to peer review whereby they will gain an understanding of the process involved in preparing a paper for publication. They will need to ensure that the information in the paper is fact checked and accurate. Discuss with students that presenting accurate factual information is important. Students should identify that there is often discrepancies in the facts from different sources, discuss with them why this can be the case- the media sometimes misrepresents the facts to the public to sensationalise the story, data may not be collected accurately by different organisations putting forward the facts so there may be some variations. Ask students to write an essay on the ethical, economic and social arguments for problems associated with ghost nets in developing countries, such as incorrect disposal of nets at sea.



FACT SHEET Ocean Currents

Ocean currents is a continuous directed movement of ocean water generated by forces acting upon the mean flow such as breaking waves, wind, Coriolis effect, cabbeling, temperature and salinity differences and tides caused by the gravitational pull of the moon and the sun. Depth, contours and shoreline configurations and interactions with other currents influence the currents direction and strength. Ocean currents are responsible for the movement of marine debris across the globe.



The movement of marine debris along oceanic currents is often complex and is dependent on the properties of the debris. Marine debris that is buoyant tends to move greater distances than that which sinks to the bottom. Buoyant pieces of debris moves more easily along wind, water and waves. It is due to these properties that buoyant pieces of debris can move over vast difference, far from its point of origin. The more buoyant types of debris are made from plastic and some types of rubber, these materials tend to be non biodegradable and persistent in the marine environment.

If a piece of rubbish is degradable it will gradually break down in the marine environment due to natural forces. Natural materials are more degradable than synthetic materials and tend to not be as long lasting, however debris from natural resources can still be a threat to marine life and the marine environment.

Modelling of oceanic currents can aide in the investigation of the source of the debris, helping to pinpoint problem areas where marine debris is frequently originating from.

STUDENT WORK SHEET 1- Ocean Currents

1. How does rubbish finds its way into our ocean and become marine debris?

____

____

2. Why is management of stormwater runoff important?

____

____

3. Once the rubbish is in the ocean how does it travel?

____

4. To understand where the rubbish originated from fill in the following details-

item_______________________description_______________________

Where item was found-

latitude_______________________longitude_______________________

5. The source the debris was from LAND\SEA (please circle)
6. What is the information we need to find out-

Language on item_______________________ Country of origin_______________

Possible city 1_______________________ Possible city 2_______________

Possible currents the debris followed_______________________________

7. Before using the CSIRO website, develop your own hypothesis of where the rubbish has come from, take into account the oceanic currents and probable origin of the rubbish from the other identifying features.

____

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____

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____

Use the CSIRO website, did you have an accurate idea of the origin? Was your hypothesis proven? If not you will need to revise your hypothesis and test the theory again.

8. Where did your debris originate from?________________________________

9. Did the path you predicted follow the path on the map? YES\NO (circle)

10. What ocean currents were involved?________________________________

11. Develop a hypothesis of where you think the item will have ended up after one year and what state the debris would have been in, think of the probability of the object being in a degraded state.

____

____

____

12. The North Pacific Gyre is an area where marine debris accumulates and is known as the Great Pacific Garbage Patch, why do you think that is? (refer to your map)

____

____

____

Student Work Sheet 2- Marine Debris in the Spotlight

In groups investigate some recent reports in the media on ghost nets; discuss your findings in your group. As individuals write a one page essay on the ethical, economic and social arguments for the problems associated with ghost nets within developing countries, include statistical information to validate the argument, including the amount of ghost nets entering our waterways each year, the amount of marine life entangled each year as a result of ghost nets and the dollar value of lost tourism on both a global and local scale. Language such as 'given', 'of', knowing that' is to be included in the text to tie the statistics together with your conclusions from your research.

Lesson Plan Analysis of data

Year	Subject	Codes	Key Words	Materials	Duration
7-9	Maths	Year 7- ACMSP172 Year 8- ACMDP206 ACSIS145 Year 9- ACMSP283	Statistical analysis, mean, median, range, analysis.	Computer with Microsoft Excel.	45 minutes

See Australian Curriculum in Appendix 1

Overview

Students will further analyse data collected from the field trip or in class to draw accurate conclusions. They will be able to identify the mean, median and range and discuss with their classmates the significance of each.

Objectives

- Create a graphical representation of data
- Analyse data and draw conclusions from the bar chart
- Calculate the mean, median and range of the results
- Discuss findings in a group

Activity

Students are to further analyse the data collected via surveying or as part of the in classroom sorting activity using a bar chart. Students are required to input the data into an excel spreadsheet. They are to compare the data and identify the mean, median, and range of these results. By looking at these comparisons students are to identify the common trends in the data and discuss with their classmates what they can conclude from this.

Analysis of data

After completing the in classroom activities students will conduct an analysis of data using either a bar graph created in excel or the TeachWild website. Analysis of the data will vary depending on the year in which the students are in.

To enter the data into an excel spreadsheet use the following steps-

On the board tally up all of the class's data. Use Microsoft Excel to further analyse data with students to create a bar chart as a graphical representation of the class results.

To do this-

Step 1- Enter data into an Excel spreadsheet with name of rubbish on the left hand side and the corresponding amount of rubbish on the right hand side.

Step 2- Click on Insert, Bar Chart.

Under the more functions tab calculate the mean, median and range of the results.

Discuss the following questions in class-

After students have analysed the data, ask them are they surprised by the results?

What outliers could have affected these results?

Would this be a result of incorrect methodology being used in surveying or could it be a result of some areas being more prone to marine debris then others due to beach characteristics and oceanic currents?

How much does wind influence the movement of rubbish along the beach?

Where on the beach would you expect to find the different types of rubbish?

Access the TeachWild website, go through the data that has been collected by other students and analysed. Did the conclusions students reached as part of their analysis match those of the other students? If not how did it compare? Why do they think it was different? Was the methodology followed correctly?

Create a mind map on the board of the student's conclusions.

Extension Exercises

Year 6

Ask students to collect rubbish at home for a marine debris artwork. The artwork is to represent marine life in their natural habitat. Explain to students that through education we create awareness, get them to sit down with a family member and ask the student to talk to them about what they have learned about marine debris.

Once the artwork is completed hold an exhibition at school where students can present their works to the community. Actively involve students in the lead up to the exhibition by developing a promotions committee who will be responsible for ensuring the success of the exhibition. Get students to promote the event using environmentally friendly methods such as e-brochures, radio and tv interviews.

Year 7

Students to look at the effects that marine debris can have on marine food chains. Share the resource link, a news report on the affect marine debris is having on Flesh Footed Shearwaters on Lord Howe Island.

Once students have seen the report, ask them to look at food chains in the marine environment. How does the plastic end up in the stomach of the seabirds? Why is it so hard for the bird to process the plastic? How does it end up in the food chain in the first place and what are the repercussions of this for Threatened Species? What can they do to ensure that one of the more pristine places in the world remains that way?

Resources

http://www.abc.net.au/7.30/content/2012/s3405538.htm

Year 8

In class brainstorm ideas and initiatives to combat marine debris, use these ideas to develop a Marine Life Warriors campaign. The campaign is to encourage the public to protect and conserve our oceans and marine life. Divide students into groups and set a research task on the topic, what impacts can students see marine debris having on our environment, 5 years, 10 years, 25 years and 100 years down the track. How can students combat this now? How can they best target polluters? Students are to present their campaign to the class and the class is to decide what campaign is the best. The nominated campaign is to be shared with other schools on the TeachWild website.

Year 9

Students are to develop an education campaign aimed at commercial fishers on the effects of improper disposal of fishing nets at sea. Students are to look at ways in which to educate different cultures from around the globe about the proper disposal of nets. This campaign is to be accompanied by an outline of the affects of ghost nets on the marine environment and marine life if they are left to continually fish in our seas.

Resources

http://www.ghostnets.com.au/

Year 10

Students are to simulate the transportation of rubbish on ocean currents and identify how rubbish on land ends up becoming marine debris. Fill a tub with water and sand. Get one person to make waves at one end and slowly put pieces of rubbish into the water. Watch as the movement of the water pushes the rubbish onto the sand, create smaller then larger waves. Ask students why they think storm swells produce more marine debris on the beach and what effect oceanic currents have on the transportation of rubbish across the globe. What types of debris are easily transported? Are degradable or non degradable items more easily transported.

In Classroom Marine Debris Monitoring

As all students are unable to actively participate in surveying out in the field, the in classroom activities have been designed to provide a similar experience. All students will learn the required skills to sort and classify examples of debris using the field data sheets- Transect Debris (type and colour) and Marine Debris Size Chart. They will also grasp the concept of marine debris beach surveying and understand why scientists use the methodology they do for data collection and how that data is then used in scientific research. A PowerPoint presentation and support notes can be used to guide students through these activities and is available for download as a separate component to this kit.

Teachers Note

Keeping a box of marine debris handy for further analysis by students is advised. For students unable to visit aquatic habitats, seeing and handling of debris will show them the different properties of debris thus increasing their understanding of the potential effects.

For inland schools that wish to use this kit, terminology will need to be adjusted with marine debris replaced by aquatic debris and activities adapted accordingly.

Lesson Plan Marine Debris Monitoring

Year	Subject	Codes	Key Words	Materials	Duration
6-10	Science, Maths, Geography	Year 6- ACSIS232, ACSIS105 Year 7-ACSIS125, ACMSP167, Geographical Inquiry and Skills-Observing and Questioning. Year 8- ACSIS146, Geographical Inquiry and Skills-Observing and Questioning. Year 9- ACSIS170, ACMSP283 Year 10- ASIS198	marine debris, entanglement, behaviour, prevention.	PowerPoint presentation, projector, laptop, variety of rubbish to sort, Transect Debris Sheet, Marine Debris Size Chart Sheet.	1hour

See Australian Curriculum in Appendix 1

Overview

Students are introduced to the concept of marine debris by TeachWild staff. They look at the structural properties of different type of debris and begin to understand the significance of the issue. Marine animal entanglement and habitat destruction are also explored in depth with the impacts of each discussed with students. The ability for rubbish to stay in the marine environment for long periods of time and the rate at which certain everyday items degrades is highlighted to students. A hands on activity involving sorting of marine debris is undertaken by students and is supervised by TeachWild staff. Students look at the methodology behind marine debris surveying and gain a clear insight as to why it is important to monitor it. They discuss possible solutions to the marine debris problem with scientists and develop an understanding of the importance of changing our behaviour to address the problem.

Objectives

- To develop a clear understanding of the problem of marine debris.
- Discuss problems associated with marine debris, including marine animal entanglement, habitat destruction and the impacts on humans.
- Participate in marine debris sorting, analysis of data collected and make conclusions from this data.
- Communicate findings from the investigation.
- To understand how marine debris can affect a community and to learn that people can make a difference.
- Recommend actions for remediation and pollution prevention.

Activity

This activity is in two parts with the PowerPoint Presentation designed to be an introduction to the marine debris problem and key concepts. The PowerPoint presentation will be followed on by the Marine Debris Sorting Activity where students will actively participate in collection of data by sorting and classifying of debris in groups.

Marine Debris Sorting Activity

1. Students are divided into groups of three and are handed a bag of rubbish.
2. Each group is to nominate a recorder for the group who will be responsible for accurately recording the data using both the Transect Debris Sheet and Marine Debris Size Chart. One of the other students will identify the rubbish while the other classifies the rubbish in regards to size.
3. Once the data has been collected, scientists will ask students if they can see any clear results and what conclusions they can derive from the raw data, such as- Is there one item that is more common than other items? What size of debris is most common? What impact might this size have on marine animals?
4. If time permits students are to enter data into excel and develop a bar graph and further discuss results. Scientists ask students if the analysed data matches up with the students hypothesises of the raw data? Is so why do they think this is the case? If the hypothesis was inaccurate why do they think this is so?

Additional Activities

The following activities are designed to be undertaken at the end of the lesson if time permits, each is to run for between 5-10 minutes and will expand upon the information already learnt by students in the classroom and out in the field.

Activity 1- Recyclables and Non Recyclables- Year 6

After the sorting activity students are to identify recyclables and non recyclables. Students are to look at the codes on the base of the different items, codes from 1-5 are recyclable with any over that number not able to be recycled, these items end up in our garbage dumps as land fill. Explain to students that what products we choose to buy has an impact on our environment. If they had a choice would they choose a product if the container it came in could not be recycled? Explain the value of choosing a recyclable option. Reiterate to students that we as individuals can all make a difference if we choose what we buy wisely; being wise with our waste is one of the most important things we can do to combat the marine debris problem.

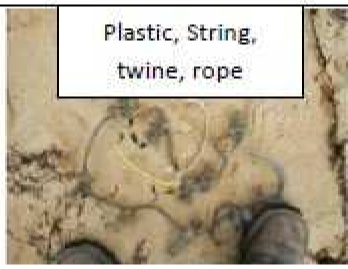
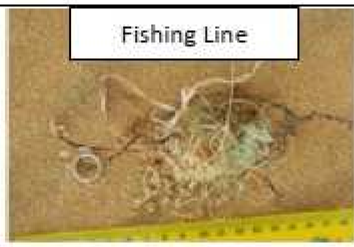
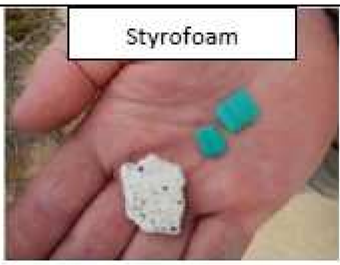
Activity 2- Degradation of Plastic- Year 7

Students are to look at the rate at which plastic degrades within the marine environment, using two spoons, one made of plastic and the other made out of corn starch. Put each spoon in hot water and look at how long it takes to degrade. This may take some time but students will get to see how slowly plastic degrades in the marine environment. They will see how gradually the plastic will break down into smaller and smaller pieces. Ask students how these fragments would affect marine animals.

Activity 3- How Harmful is it? - Year 8

Hand out to students the following photographs and ask them to comment on how harmful they think each piece of rubbish is to a marine animal with a rating out of 10. On the back of each of the photographs students are to comment on how the piece of rubbish may affect a marine animal, for example a fishing line may become entangled around a seabirds beak, this will severely limit the birds ability to eat resulting in the slow painful death of the seabird.

How Harmful is it?

Hard Plastic 	Plastic Bag 	Film Like Plastic 
Soft Plastic 	Plastic, String, twine, rope 	Fishing Line 
Metal-hard 	Metal-soft 	Balloon 
Styrofoam 	Wood 	Paper 

Activity 4- Marine Debris Quiz- Year 9

Divide the class into groups of four for a quiz on marine debris. The first group that raises their hand and answers correctly gets a point on the board with the group with the most points announced as the marine debris champions. Ask students to answer the following questions-

Q-What is marine debris?
A-Any man-made object that can be intentionally or unintentionally discarded, disposed of or abandoned that enters our marine environment

Q-How does rubbish from land end up in our waterways?
A-The origin of land debris is often from runoff, stormwater drains, air-borne debris and irresponsible disposal of rubbish by beach goers and campers.

Q- How does marine debris travel?
A- Marine debris travels along wind, water and waves.

Q- Why is marine debris a problem?
A- It impacts upon our marine environment in a negative way, including marine animal entanglement and ingestion, degrades and visibly pollutes beaches and there is economic loss of revenue for the fishing and tourism industries.

Q- How many tonnes of marine debris enters our waterways each year?
A- 7 billion tonnes

Q- What are the 3 R's?
A- Reduce, Reuse, Recycle

Q- What can be done to combat the marine debris problem?
A- Education and research creates an understanding and awareness of the issue. The National Marine Debris database will utilise important data in furthering research efforts and increase knowledge on the extent of the problem, students are doing their part by monitoring marine debris in their local area.

Activity 5- Marine Debris Movement- Year 10

A fan and a tub of water are required for this activity. Students will be looking at the buoyancy and movement of the different types of rubbish. Using the rubbish from the sorting activity put each different type of rubbish in front of the fan. Ask students to keep an eye on how far the rubbish moves and determine how it moves through the air, e.g. does it spiral through the air, or drift? When all pieces of debris have been passed in front of the fan, ask students the following questions-

- Which piece of rubbish moved the greatest distance and how easily did it move?
- Why do they think this is so?

Put the tub of water in front of the fan and repeat the process.

- Did the presence of water slow the more moveable pieces of rubbish down or was it more buoyant?
- What types of rubbish will move the greatest distances?
- Will this type of rubbish persist more in the marine environment or not?

Once the activity is completed reiterate to students that ocean currents drive marine debris all over the world and that the properties of an item can determine how far it will go e.g. moveability in wind, buoyancy and the ability to persist in the marine environment are all factors in modelling the movement of marine debris.

Student/Teacher Website Resource List

This resource list has been compiled to provide background information on marine debris to further enhance students learning experience. Earthwatch is not responsible for changes to content on any of the following websites aside from the TeachWild website and accepts no responsibility should content change and not be of an acceptable standard.

TeachWild

teachwild@earthwatch.org.au

Wikipedia Marine Debris Definition

http://en.wikipedia.org/wiki/Marine_debris

Reef Watch South Australia

http://www.reefwatch.asn.au/

The Australian Marine Conservation Society

http://www.amcs.org.au/default2.asp?active-page-id=114

Ghostnets Australia

http://www.ghostnets.com.au/

Humane Society International Australia

http://www.hsi.org.au/?catID=117

Australian Government, Department of Sustainability, Environment, Water, Population and Communities, Australian Antarctic Division

http://www.antarctica.gov.au/science/australian-antarctic-science-strategy-200405-201011/impact-of-human-activities-in-antarctica/past-research/marine-debris

The Conservation Beta

http://theconversation.edu.au/marine-debris-biodiversity-impacts-and-potential-solutions-2131

Surfrider Australian Foundation

http://www.surfrider.org.au/2011/02/national-marine-debris-initiative/

Australian Government- Great Barrier Reef Marine Park http://kurrawa.gbrmpa.gov.au/corp_site/info_services/publications/sotr/shipping/page_04.html

Oceanwatch Australia

http://www.oceanwatch.org.au/?s=marine+debris

Education Kits

Tangaroa Blue Ocean Care Society Marine Debris ID Manual

http://www.oceancare.org.au/site/index.php?option=com_rokdownloads&view=folder&Itemid=1000100&id=20:marine-debris-id-manual

Marine Waters Western Australian Teacher Education Resources

http://marinewaters.fish.wa.gov.au/marine-biology/

Marine or Ocean Pollution

http://www.teachers.ash.org.au/jmresources/seaweek/links.htm

Perth Beachcombers Education Kit

http://www.fish.wa.gov.au/beachcombers-kit/coastal-uses-impacts/marine-debris/

Healthy Waterways

http://www.healthywaterways.org/HealthyWaterways/Education/Litterandwasteresources/Games/EducationalResources.aspx

Articles

Sea Sheppard- The Plastic Sea

http://www.seashepherd.org/commentary-and-editorials/2008/10/30/the-plastic-sea-372

ABC-Whale Death Article

http://www.abc.net.au/local/stories/2011/10/18/3342237.htm

Jennifer Lavers- Plastic Pollution – A Global Problem

http://www.jenniferlavers.org/plastic-pollution/

Ghost Nets in Northern Australia

http://www.ghostnets.com.au/pdf/emr_525.pdf

7.30 report- Lord Howe 's muttonbird population in decline http://www.abc.net.au/7.30/content/2012/s3405538.htm

National Oceanic and Atmospheric Administration- United States Department of Commerce-

NOAA Marine Debris Program

http://marinedebris.noaa.gov/outreach/welcome.html

National Ocean Service

http://oceanservice.noaa.gov/education/

Great Pacific Garbage Patch

http://marinedebris.noaa.gov/info/patch.html

New Zealand

Ministry for the Environment

http://www.mfe.govt.nz/issues/oceans/kids/reducing-pollution.html

Appendix 1- The Australian Curriculum

The Australian Curriculum sets out the core knowledge, understanding, skills and general capabilities important for all Australian students. In the development of this kit three main areas of the curriculum were explored- Science, Maths and Geography. The Geography syllabus is currently in draft stage with key learning areas for students identified and outlined. The curriculum has been reviewed and key learning areas that are achieved by each year through use of the kit identified and addressed during classroom and field based activities. An expanded version of the curriculum can be found at-

http://www.australiancurriculum.edu.au/

Science

Year 6

Code ACSIS232

With guidance, pose questions to clarify practical problems or inform a scientific investigation and predict what the findings of an investigation might be-

- Refining questions to enable scientific investigation
- Asking questions to understand the scope or nature of a problem
- Applying experience from previous investigations to predict the outcomes of investigations in new contexts.

Code ACSIS105

Use equipment and materials safely, identifying potential risks

- Discussing possible hazards involved in conducting investigations and how these risks can be reduced.

Code ACSIS232- Prior to field work, scientists discuss with students the reasons for undertaking marine debris surveying. Students determine why they think marine debris surveying is important and what methods they think should be used. They are asked to predict the outcome of the survey. During the classroom activity students are able to use experience gained from the field investigation and apply this to their predictions of the differences in the decay of rubbish from the bin and on the beach.

Code ACSIS105- Prior to fieldwork; students are asked what they think the risks associated with fieldwork are and students are to determine how they may be mitigated.

Year 7

Code ACSIS124

Identify questions and problems that can be investigated scientifically and make predictions based on scientific knowledge

- Working collaboratively to identify a problem to investigate.
- Recognising that the solution of some questions and problems requires consideration of social, cultural, economic or moral aspects rather than or as well as scientific investigation.
- Using information and knowledge from previous investigations to predict the expected results from an investigation.

Code ACSIS125

Collaboratively and individually plan and conduct a range of investigation types, including fieldwork and experiments ensuring safety and ethical guidelines are followed-

- Working collaboratively to decide how to approach an investigation
- Learning and applying specific skills and rules relating to the safe use of scientific equipment
- Identifying whether the use of their own observations and experiments or the use of other research materials is appropriate for their investigation.
- Developing strategies and techniques for effective research using secondary sources, including use of the internet.

Code ACSSU112

Interactions between organisms can be described in terms of food chains and food webs; human activity can affect these interactions.

- sing food chains to show feeding relationships in a habitat
- constructing and interpreting food webs to show relationships between organisms in an environment
- classifying organisms of an environment according to their position in a food chain
- recognising the role of microorganisms within food chains and food webs

Code ACSIS124- Working in groups students investigate the problem of marine debris. Students look at the impact plastics are having on marine food chains. They look at their own and others consumptive behaviour obtaining a greater *understanding of the scale of the issue from a social, cultural, economic and moral point of view rather than or as well as scientific investigation through fieldwork.*

Code ACSIS125- Working in groups students discuss the sampling method prior to the surveying. Through guidance from scientists students will learn and apply skills and rules in the use of scientific equipment used in the surveying of marine debris. Students are encouraged to make their own observations of the results and discuss their findings with the scientist at the end of the survey. Students then use the internet to identify possible strategies and techniques to enhance their research.

Code ACSSU112- Students look at the different trophic levels and identify where different types of organisms fit into the food chain. Students develop their own food chain and trace the movement of a piece of plastic up that food chain. They also identify the role of microorganisms within food chains and food webs.

Year 8

Code ACSIS145

Summarise data from students own investigation and secondary sources, and use scientific understanding to identify relationships and draw conclusions-

- Constructing tables, graphs, keys and models to represent relationships and trends in collected data.
- Drawing conclusions based on a range of evidence including primary and secondary sources.

Code ACSIS146

Reflect on the method used to investigate a question or solve a problem, including evaluating the quality of the data collected and identify improvements to the method.

- Suggesting improvements to investigation methods that would improve the accuracy of the data.

Code ACSIS148

Communicate ideas, findings and solutions to problems using scientific language and representations using digital technologies as appropriate

- Using digital technologies to construct a range of text types to present scientific ideas
- Selecting and using appropriate language and representations to communicate science ideas within a specified text type and for a specified audience.

Code ACSIS145- In the classroom, prior to uploading the data onto the TeachWild website, students analyse the data themselves by creating a graph in excel of all the data collected. Students draw their own conclusions from the data and compare this to the results published on the TeachWild website.

Code ACSIS146- Students identify any faults they can find with the survey method and determine how they think the survey method can be improved to collect more accurate data.

Code ACSIS148- Students develop a poster targeted at the general public which includes the use of digital technologies and emotive language to communicate scientific ideas concluded from their simulated experience of marine debris entanglement.

Year 9

Code ACSIS164

Formulate questions or hypotheses that can be investigated scientifically

- Using internet research to identify problems that can be investigated
- Evaluating information from secondary sources as part of the research process
- Revising and refining research questions to target specific information and data collection or finding a solution to the specific problem identified
- Developing ideas from students own or others' investigations and experiences to investigate further

Code ACSIS169

Analyses patterns and trends in data, including describing relationships between variables and identifying inconsistencies.

- Using spreadsheets to present data in tables and graphical forms and to carry out mathematical analyses on data.
- Describing sample properties (such as mean, median, range, large gaps visible on graph) to predict characteristics of the larger population
- Designing and constructing appropriate graphs to represent data and analysing graphs for trends and patterns.

Code ACSIS170

Use knowledge of scientific concepts to draw conclusions that are consistent with evidence

- Comparing conclusions with earlier predictions and reviewing scientific understanding where appropriate
- Suggesting more than one possible explanation of the data presented.

Code ACSIS164- Through researching marine debris on a local and global scale students identify the problem that is the Great Pacific Garbage Patch. They evaluate the information gathered from this research and determine why the Great Pacific Garbage Patch exists in that area. As individuals, students discuss the problem with their classmates and determine how to best investigate the issue further.

Code ACSIS169- With the data collected from sampling students enter it into an excel spreadsheet for further analysis. Students use the data to develop a graph which shows the comparison between the trends and patterns of the data.

Code ACSIS170- Prior to the excursion taking place students predict what they think the outcome of it will likely be, including if they think there will be a lot of rubbish washed up on the shoreline and what piece of rubbish they think will be the most common. After conducting fieldwork students compare actual conclusions with hypotheses derived from the previous in classroom discussion. Post survey, students discuss with scientists what is the scientific basis for the modelling of marine debris and what they expect the predicted outcomes from the modelling of the debris to be. In the group discussion students suggest two possible reasons for the data results and explain how they came to these conclusions.

Year 10

Code ACSIS198

Formulate questions or hypotheses that can be investigated scientifically

- Developing hypotheses based on well developed models and theories.
- Using internet research to identify problems that can be investigated.
- Formulating questions that can be investigated within the scope of the classroom or field with available resources.
- Developing ideas from students own or other's investigation and experiences to investigate further.
- Evaluating information from secondary sources as part of the research process.

Code ACSIS206

Critically analyse the validity of information in secondary sources and evaluate the approaches used to solve problems.

- Researching the methods used by scientists in studies reported in the media.

- Judging the validity of science- related media reports and how these reports might be interpreted by the public.
- Describing how scientific arguments as well as ethical, economic and social arguments are used to make decisions regarding personal and community issues.

Code ACSIS198- Students develop a hypothesis on the movement of marine debris based on oceanic currents. Students are able to identify the problem of the Great Pacific Garbage Patch and investigate further using secondary sources and the internet.

Code ACSIS206- Using the Student/Teacher Website Resource List as guidance, students investigate some recent reports in the media on marine debris. They write an essay that is peer reviewed, through their research student's look at the validity of science found in media reports and develop an understanding of how these reports may be interpreted to the public. Students comment on the ethical, economic and social arguments for the problems associated with ghost nets within developing countries.

Mathematics

Year 6

Code ACMMG135

Connect decimal representations to the metric system.

- Recognising the equivalence of measurements such as 1.25metres and 125 centimetres.

Code ACMMG136

Convert between common metric units of length, mass and capacity

- Identifying and using the correct operations when converting units including millimetres, centimetres, metres, kilometres, milligram, grams, kilograms, tonnes, millilitres, litres, kilolitres and mega litres
- Recognising the significance of the prefixes in units of measurements.

Code ACMMG135- During sampling students use transects to map sampling area, measuring tapes are used and centimetres converted to metres.

Code ACMMG136- Students convert centimetres to metres whilst using a measuring tape and recognise the significance of the use of cm and m.

Year 7

Code ACMSP167

Construct sample spaces for single- step experiments with equally likely outcomes

- Distinguish between "equally likely" outcomes and outcomes "not equally likely".
- Discussing the meaning of probability terminology (for example probability, sample space, favourable outcomes, trial, chance events and experiments)

Code ACMSP172

Describe and interpret data displays and the relationship between the median and mean

- Using mean and median to compare data sets and explaining how outliers may affect the comparison.
- Locating mean, median and range on graphs and connecting them to real life.

Code ACMSP167- Prior to the excursion discuss with students the equally likely outcome of finding a large amount of marine debris on the beach as opposed to small amount. Through surveying students will discuss such terminology as probability of there being rubbish, the sample space of the survey and what trials have been conducted previously to develop a standardised methodology for sampling. They will also look at what role chance events such as weather conditions play in the quantity of marine debris collected and how experimental design plays a role in the quality of data collected and used for analysis.

Code ACMSP172- Using excel students create a bar chart and identify the mean, range and median from the data. Students look at what outliers could have affected the results. They understand that it could be a result of incorrect methodology being used in surveying or it could be a result of some areas being more prone to marine debris then others due to beach characteristics and oceanic currents.

Year 8

Code ACMSP206

Explore the practicalities and implications of obtaining representative data using a variety of investigative processes.

- Understanding that making decisions and drawing conclusions based on data may differ from those based on preferences and beliefs.

- Investigating an international issue where media reporting and the use of data reflects different cultural or social emphases (for example whaling, football World Cup outcomes)

Code ACMSP206- From the data collected and conclusions drawn from the previous investigation, students will be able to distinguish between conclusions based on preference and beliefs. By investigating the international issue of marine debris students will be able to determine how data can reflect a different cultural or social emphasis in the media by using the Student/Teacher Website Resource List to aide further investigation on the effects marine debris has on marine animals.

Year 9

Code ACMSP283

Compare data displays using mean, median and range to describe and interpret numerical datasets in terms of location (centre) and spread.

Code ACMSP283- Post surveying students look at the data collected and each group determines the mean, median and range. They then discuss these results in class and interpret the datasheets in terms of location (centre) and spread. Results from student's data are then compared to the National Marine Debris Database on the TeachWild website.

Year 10

Code ACMSP247

Use the language of if... then 'given', 'of', ' knowing that' to investigate conditional statements and identify common mistakes in interpreting such language.

- Evaluating media reports that refer to data from a range of contexts, where the evaluation allows students to demonstrate their statistical literacy.

Code ACMSP247- Using the Teacher/Student Website Resources List students research some of the statistics on marine debris including- the amount of ghost nets entering our waterways each year, the amount of marine life entangled each year as a result of ghost nets and the dollar value of lost tourism on a local and global scale. Students sift through media reports to find answers to these questions, it is through this investigation that they will find discrepancies in the facts , they will acknowledge that common mistakes are made in the interpretation of statistics and understand that it is dependent on the correct interpretation of statistical language. Students essay writing includes the current statistics on ghost nets using language such as 'given, 'of'' knowing that' to tie statistical information together.

Geography

Year 6

Processing data and information collected and look for patterns or relationships

Manage data and information collected and look for patterns or relationships

- Converting data into a useful form, such as a spreadsheet, display, graph or distribution map, then making decisions informed by trends in data or information.
- Creating or adding to maps (such as grid maps), including a scale and demonstrating specific features or relationships,
- Using tables and charts to compare information from different information sources.

Combine data and information to draw and share conclusions, considering their impacts

- Explaining a situation in terms of cause and effect and suggesting and evaluating possible future scenarios, giving reasons for their preferred options.
- Considering their findings or conclusions and identifying the probable reactions and responses of those who hold other viewpoints.

Survey- Using the mud map students developed of the survey site, students map out the areas that have been surveyed and record using symbols on the map of the areas that are dense with rubbish. Students then identify trends with the data collected.

In the classroom- Students look at the degradable properties of rubbish and develop an understanding of how long common articles of rubbish can take to break down in the environment. They consider their findings and identify how waste can be broken down in the environment. Students identify how the general public will react to the timeline of rubbish through their own reactions and that of their classmates.

Year 7&8

Geographical Inquiry and Skills

Observing and Questioning

Determine a focus for the inquiry within an area of interest, for example, make a prediction or develop a key question.

- Considering an area of study or current event to generate ideas for an inquiry, such as describing their response and developing an inquiry from that.
- Distinguish between the geographical and other kinds of questions, for example, "so what" questions about effects, 'what ought' questions about what should happen, 'what might happen' questions about the future and 'what if' questions about alternatives in a geographical context.

In the classroom- Prior to the excursion students will look at the marine debris problem. They will develop an inquiry by looking at the effects marine debris is having across the globe. In class scientists will take students through the scale and nature of the problem and apply it in a local and global context. Students will be asked questions in a geographical context such as- So what if people litter and it ends up in our oceans? What ought to be the repercussions of this? What might happen to marine life? What if this continues to happen across the globe? Students will then be able to answer these questions and determine probable solutions to the marine debris problem.

Year 9&10

Planning, collecting and evaluating

Determine a purpose and operational scale of the geographical inquiry and independently design the inquiry.

- Considering what answers or explanations are needed and at what scale, for example, at the local or global scales.
- Design the inquiry and develop a plan to determine which data will be needed and to locate this data from fieldwork, library and online research using spatial technologies, maps, statistics, photographs and other images.
- Collecting primary data and secondary data, including fieldwork techniques such as interviews, surveys, observation, taking photographs, annotating maps and land use surveys
- Determining which information sources will provide relevant, reliable and representative data, and addressing issues, for example, using another collection method such as a survey or soil testing.

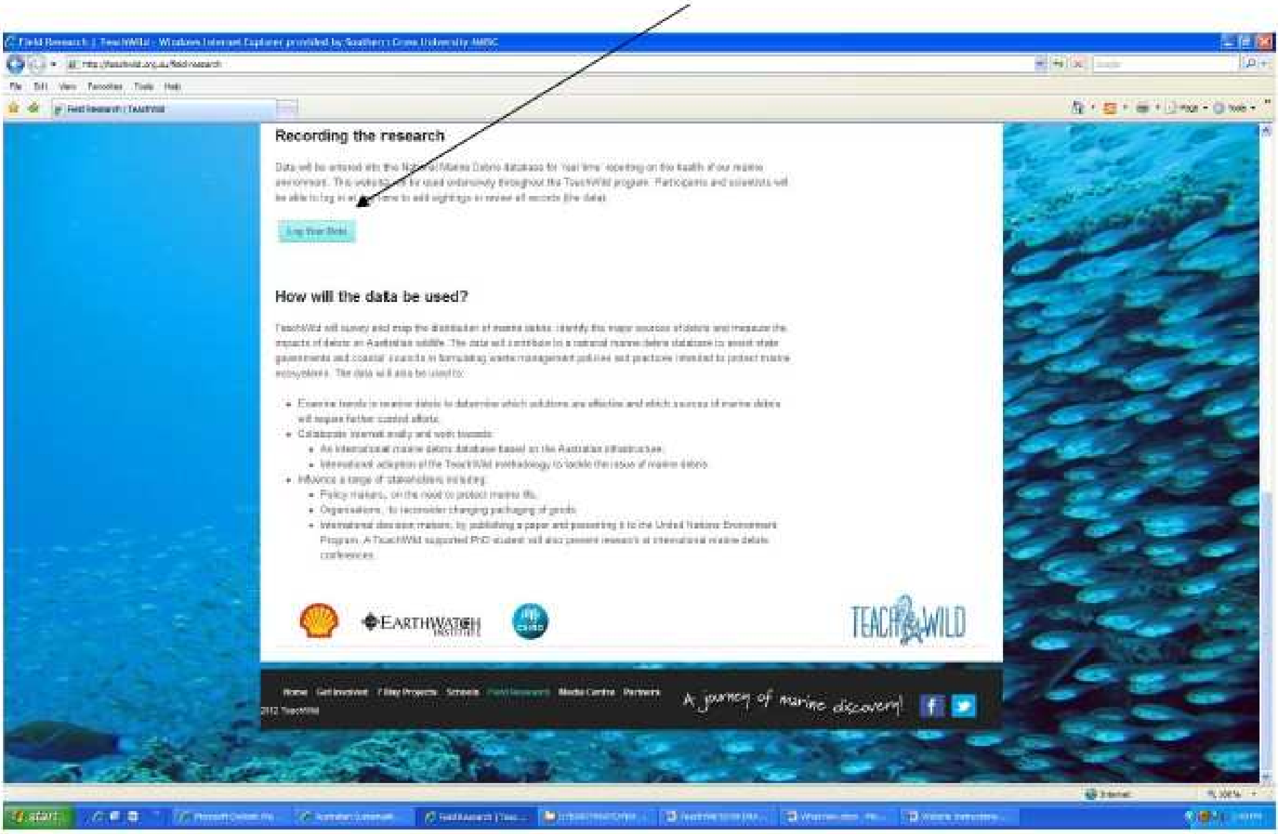
In the classroom- Students are to formulate questions as to why surveying of marine debris is necessary. They are then to develop a clear plan of what data is needed and how this data would best be collected. During fieldwork students will look at the methodology used by the scientists in the surveying process .Prior to surveying students investigate how they think the scientist's methodology will achieve accurate results. Students are responsible for the collection of data and fieldwork techniques, including transects. Once fieldwork is completed students can use other information *collected during the fieldtrip such as photographs, maps and observations and upload this onto the TeachWild website to share with other schools. Students comment on this information and explain what the cumulative data means on both a local and global scale in an open forum.*

Appendix 2- Website Instructions

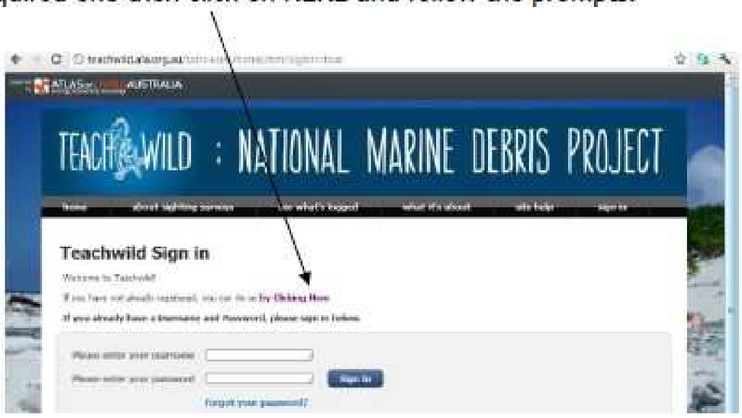
TeachWild Website

To upload your marine debris data onto the Atlas of Living Australia (ALA) access the TeachWild site- www.teachwild.org.au and follow these simple steps-

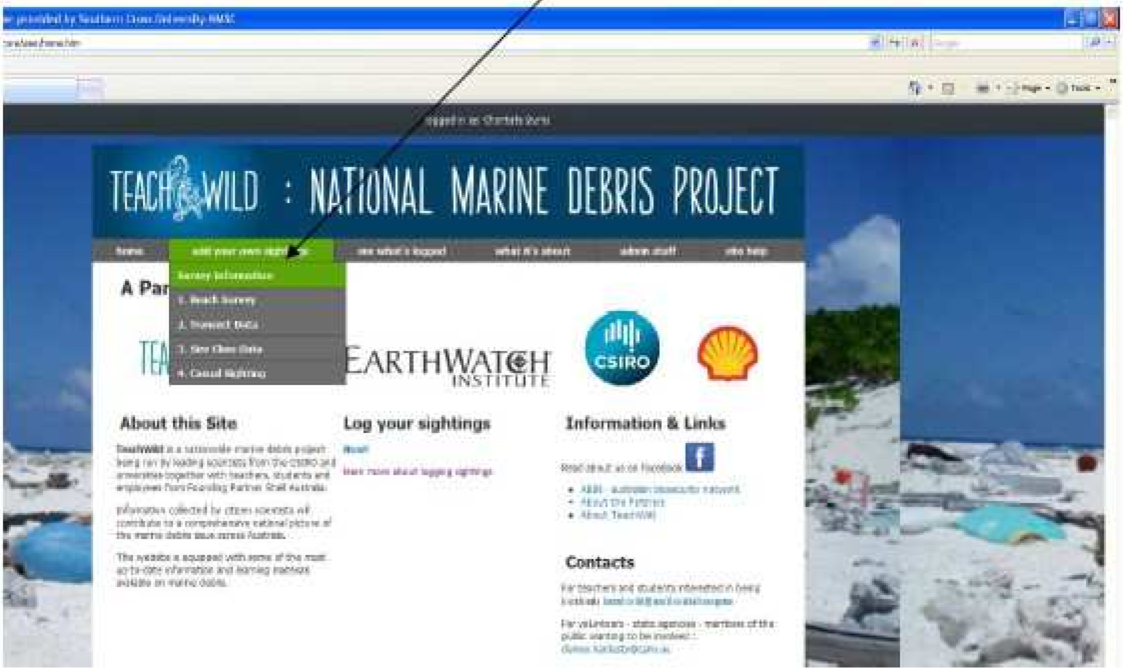
1. Click on FIELD RESEARCH on the top right hand side of the page.
2. Scroll down the page to the icon LOG YOUR DATA.



3. Click the SIGN IN tab on the top right hand side of the page. A screen will come up asking for your username and password, if you have not already acquired one then click on HERE and follow the prompts.



4. Go to ADD YOUR SIGHTINGS tab and choose whether it is a beach survey, transect data, size class data or casual sighting you need to enter data for.



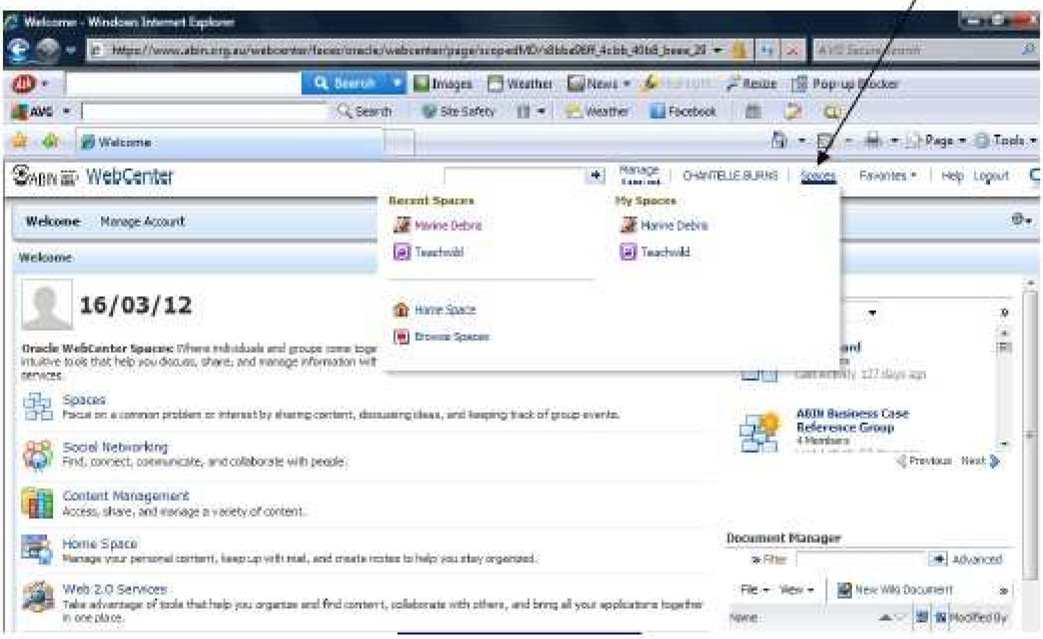
5. In each of the survey types detailed instructions are available; follow them step by step to input your data accurately.
6. Under the ADMIN STUFF tab you can edit your profile to make it easier to input data by pre-saving favourite locations of where you are conducting your surveys (through the My Locations function). This section is also where you can change any of your personal details, including your password and registered email address.
7. You can see what data has already been entered by clicking the SEE WHAT'S LOGGED tab.

Australian Biosecurity Intelligence Network (ABIN) Website

Visit www.abin.org.au to download field resources share images and experiences with other schools in the program and view upcoming events for TeachWild. To access this site you will need to register, this may take a few days so ensure it is done prior to your fieldtrip.

1. To REGISTER click on the top right hand corner icon and then follow the prompts. Make sure you request access to the TeachWild Community (page).

2. Once your registration has been approved click LOGIN on the webpage above (top right hand corner icon). Make sure you keep your username and password in a safe place as you get three incorrect attempts to LOGIN before you are locked out of the site.
3. You will come to the HOMEPAGE; on the top right hand side click SPACES



4. Click on TeachWild and the HOMEPAGE will appear on the screen.

5. On the left hand side you have numerous options to keep connected to your class and others involved in the project.
6. You can download copies of the documents needed for the beach surveys on the right hand side of the page or by clicking the DOCUMENTS link in the left hand side menu.
7. You can also use the ABIN Connect Web Conference feature to connect to your students in the classroom from out in the field.

What Now?

By undertaking marine debris surveys your school is helping to make a difference by create awareness of the marine debris problem. There are numerous sustainability actions your school can become involved in to help combat marine debris further.

These include-

- School Clean ups- organise your whole school to do regular clean ups around the school grounds.

Control litter-

- Encourage students to bring a litter free lunch. This means no plastics aside from the lunchbox and a drink bottle just "nude" food.
- Make better use of materials; reuse waste where possible such as milk bottles to surround young seedlings in the school garden.
- Support initiatives such as the Take 3 campaign where you take 3 pieces of rubbish with you when you leave the beach, waterway or anywhere.
- Hold a waste challenge competition in class where students from each year are asked to cut back on their waste and document it. The class who has generated the least amount of waste is the winner and is known as the waste champions throughout the school; hold a presentation for the winners at the schools assembly. The winning class is to tell the assembly some of their top tips for cutting down on waste in their classroom.
- Follow the 3 R's- Reduce, Re-use and Recycle at school and at home.

Campaign for the cause-

- Develop a section in the schools newsletter dedicated to the environment, looking at a different issue affecting the marine environment per issue.
- Develop an environment committee at school.
- Get students to write a letter to their local MP or newspaper about the marine debris issue and point out what could be done on a local level to help combat the problem.
- Students can showcase some of what they have learnt about marine debris as a poster, these posters can be hung around the school and the community to promote awareness.
- Tell 2, ask students to tell two people they know about the marine debris problem, students are to specify two facts about marine debris to that person and request that they tell those facts to two people they know and so on.

You can also link up with some existing schools initiatives such as the Australian Sustainable Schools Initiative (AuSSI).
http://www.environment.gov.au/education/aussi/

Acknowledgements

Earthwatch is proud to provide this comprehensive marine debris education kit in partnership with CSIRO and Shell Australia.

Earthwatch Australia is the coordinating partner of TeachWild. Its global mission is to engage people in scientific field research and education in order to promote the understanding and action necessary for a sustainable environment. Since 1971, 100,000 citizen scientists have contribute 11 million hours to conservation science - equivalent to more than 5,000 years of solid hard work.

CSIRO, the Commonwealth Scientific and Industrial Research Organisation, is Australia's national science agency and one of the largest and most diverse research agencies in the world. The CSIRO Wealth from Oceans Flagship focuses on understanding Australia's oceans: their biodiversity, resources and relationships with the climate system. The flagship delivers practical science that enables governments, industries and communities to make informed decisions about the sustainable management of marine and coastal resources. It provides CSIRO's contribution towards national challenges in which oceans play a central role.

CSIRO is at the forefront of marine debris research; their assistance in implementing the program is invaluable to students and teachers. The CSIRO Scientists in Schools program enables scientists to share their passion for science and enhance science education in their classrooms. CSIRO are teaming up with Earthwatch in the field to bring students and teachers an active learning experience surveying marine debris.

Shell is a global group of energy and petrochemicals companies. With around 93,000 employees in more than 90 countries and territories, Shell helps to meet the world's growing demand for energy in economically, environmentally and socially responsible ways. Shell has a long history of involvement with the community across more than a century of business operations in Australia. As Shell's business in Australia grows, so too does its country social investment program which now focuses solely on education, including projects such as the TeachWild program which encourage an interest in science and technology.

Earthwatch would like thank the following for their input into the development and review of the kit- Geraldine Davis, Andy Donnelly from Earthwatch, Britta Denise Hardesty, Chris Wilcox from CSIRO, Jenny Odgers from Shell and Southern Cross University, National Marine Science Centre, Coffs Harbour.

Primary Writer Chantelle Burns.

Glossary

Biodegradable- capable of being decomposed by bacteria or other biological means.

Corolis effect- The observed effect of the Coriolis force, especially the deflection of an object moving above the earth, rightward in the northern hemisphere and leftward in the southern hemisphere.

Degradable- capable of being decomposed chemically or biologically.

Degrade- (*Chemistry)* to decompose or be decomposed into atoms or smaller molecules.

Food Chain- The feeding of one organism upon another in a sequence of food transfers is known as a food chain.

Gyre- A circular or spiral motion, especially a circular ocean current.

Invertebrate- any animal lacking a backbone, including all species not classified as vertebrates. Corals, insects, worms, jellyfish, starfish, and snails are invertebrates

Marine Debris- any human-made object that can be intentionally or unintentionally discarded, disposed of or abandoned that enters our marine environment

Non degradable- waste will not break down or will continue to persist for many years. Examples are plastics, metal and glass.

Non recyclable – not capable of being used again.

Pollutant- Something that pollutes, especially a waste material that contaminates air, soil, or water.

Recyclable - capable of being used again.

Trophic Level- A position in a food chain or Ecological Pyramid occupied by a group of organisms with similar feeding mode.

Vertebrate- any chordate animal of the subphylum *Vertebrata,* characterized by a bony or cartilaginous skeleton and a well-developed brain: the group contains fishes, amphibians, reptiles, birds, and mammals www.csiro.au

Appendix D. Understanding the effects of marine debris on wildlife: Year 2 Progress Report to Earthwatch Australia

Understanding the effects of marine debris on wildlife:

Year 2 progress report to Earthwatch Australia

Britta Denise Hardesty and Chris Wilcox (with TJ Lawson, Matt Lansdell and Tonya van der Velde)

30 July 2013

Prepared for Earthwatch Australia

Wealth from Oceans Flagship

Citation

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Copyright and disclaimer

Important disclaimer

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Acknowledgements

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Key CSIRO staff contributing to this project include TJ Lawson, Matt Lansdell, Tonya van der Velde, David Milton and Marg Miller. Without their knowledge, excellence and dedication we could not achieve the outcomes we achieve. Whether in project planning, carrying out fieldwork, engaging with students, building databases, sharing knowledge – they rise to every occasion and keep work fun.

We are also grateful to the numerous students, teachers, educators and other citizen scientists who have been interested in this project and who have contributed their time and efforts to the work. Finally, it would be remiss to not mention Geraldine Davis and her dedication to TeachWild. As always, it has been a pleasure working together this year.

1 Overview

Marine debris poses a global threat to biodiversity of immense proportion. For instance, more than six million tons of fishing gear alone is lost in the ocean each year (Derraik, 2002). Despite this staggering amount of marine waste, fishing gear forms only a small percentage of the total volume of debris in the ocean, not even making the list of the top 10 most common items found during coastal clean-up operations (Ocean Conservancy, 2012). The impacts of this threat on biodiversity are both broad and deep. Marine debris has been reported to have direct impacts on invertebrates, fish, amphibians, birds, reptiles, and mammals (Good et al., 2010). These impacts are known to be a significant threat to the persistence of several threatened or endangered marine species, and likely to be affecting many others. For example, up to 40,000 fur seals are killed each year by entanglement in debris (Derraik, 2002) and entanglement and ingestion are major causes of population decline for some marine mammals. Finally, the impacts from debris in the marine environment are rapidly intensifying, as the volume of refuse humans release into marine systems is growing at an exponential rate.

The goal of our research in this project is to develop a national risk assessment for wildlife species that are affected by marine debris, addressing a topic (marine debris) that has been identified as a 'key threatening process' to wildlife in Australia. The project integrates field, modelling, genetic and biochemical marker approaches to understand the impact of marine debris on fauna at the national scale. One of the critical aspects of this work is that we collaborate and engage heavily with school groups to promote science education and learning through a timely and relevant topic that is part of the national science curriculum, fitting in with maths, chemistry, physics, biology, oceanography and other parts of the national curriculum.

This project seeks to answer four fundamental questions:

1) What are the sources, distribution, and ultimate fate of marine debris?
2) What is the exposure of marine wildlife to debris?
3) When wildlife are exposed to debris, what factors determine whether animals ingest or are entangled by debris?
4) What is the effect of ingestion or entanglement on marine wildlife populations?

In 2011, a three year partnership was entered into by Shell, Earthwatch Australia and CSIRO with a goal of addressing the four fundamental questions listed above.

Our overall aims are to:

- Carry out a nation-wide risk analysis completed for focal species across multiple taxa
- See increased science learning and uptake for individuals, schools, communities and industry across the country
- Inform policy decisions based upon sound science
- Develop a priority list of 'at risk' species based upon distribution, encounter and impact of debris

- Engage with industries contributing to the marine debris issue (with potential solution-based approaches to resolving the issue) and
- Contribute to a change in behaviour resulting in decreased marine debris deposition across the country due to science learning at local scales.

At two years into the project we have made remarkable strides toward achieving our goals and addressing our four focal questions. We have achieved and exceeded the key milestones identified for year two (detailed in Section 2) and we are beginning to realise new opportunities and the impact of our work, as evidenced through engagement with a variety of stakeholders across the country and overseas. We look forward to the final year of the project bringing even greater achievements with it, and we hope to continue to grow this important work in collaboration with our partners, Earthwatch Australia and Shell.

2 Year One in Review (a brief synopsis)

Several key milestones were identified for the first year of the project in 2011-2012. These milestones included: 1) develop project curriculum that fit into the national science curriculum; 2) develop a web based resource for public profile and community engagement; 3) identify potential schools with which to engage in the TeachWild program, particularly focusing on schools in important Shell-identified focal areas; 4) initiate data collection and input; 5) carry out 'Scientist for a Day' excursions with schools; 6) carry out seven-day research expeditions with teachers and, if possible, 7) carry out sea-based research expeditions with teachers.

We met each of these milestone objectives (detailed in progress report for year one – Hardesty and Wilcox, 2012). Not only did we contribute significantly to curriculum content that was developed for TeachWild, but we worked with teachers to develop specific lesson plans for targeted student groups, beyond the TeachWild curriculum, that met the requirements of the national science curriculum.

We successfully developed an online data entry portal that utilised the Atlas of Living Australia's (ALA) Global Biodiversity Information Facility (GBIF). Through our CSIRO partnership with ALA, we were able to develop an open access and easily accessible national marine database that was available to volunteers, students, teachers, and citizen scientists. Here, data on beach surveys, incidental sightings and other site location information was initially collated. The host address for the site was http://www.TeachWild.ala.org.au. The data portal was established so that individuals and groups could input data and see summaries of information from across the country. Due to challenges with ease of data entry utilising the ALA system, however, in the last 12 months we have subsequently revised the web portal data entry site (see Appendices A and B).

In year one of the project we carried out coastal and at-sea debris surveys for a significant portion of the Australian coastline and we completed high-seas surveys to quantify marine debris offshore at more than 35 sites from a variety of research vessels.

In addition to identifying schools with whom to engage, we delivered the TeachWild program to more than 1,300 primary and secondary school aged students from around the country. We also took teachers on intensive weeklong research expeditions in which they significantly contributed to our fundamental research aims for the national marine debris project.

Overall, the first year of the project was tremendously successful in meeting our targets, and this was matched by the achievements in year two (see below).

3 Accomplishments and achievements in Year 2

In the second year of the national marine debris project we completed the rest of the coastal debris surveys (see Section 3.1). Our year two teacher and student engagement started with carrying out the Scientist for a Day program at several schools in Victoria. This intensive week visiting five schools in August 2012 was quickly followed by visiting schools and carrying out the 'Scientist for a Day' program in Broome and Darwin in September. Also in September, CSIRO scientist Chris Wilcox took three teachers on a 10-day excursion on CSIRO's research vessel *Southern Surveyor*, during which time Chris and the teachers from Western Australia, South Australia and the Northern Territory collected surface trawl data from Perth to Darwin. This was an important trip in terms of marine debris data collection from surface trawls (see Section 3.2 for details). We have also had intensive engagement with various interested parties from local, state and federal government and non-governmental organisations, and we have had excellent interest in our work in the international forum as well. Further description of our year 2 activities and media engagement is described in the following sections.

3.1 Coastal debris surveys

We have now completed the national survey for coastal debris around the mainland and the island state of Tasmania (Figure 1). We surveyed more than 170 coastal sites, many of which were remote. Access was by car and foot, via float plane (Broome to Darwin and west/southwest Tasmania) and via boat.

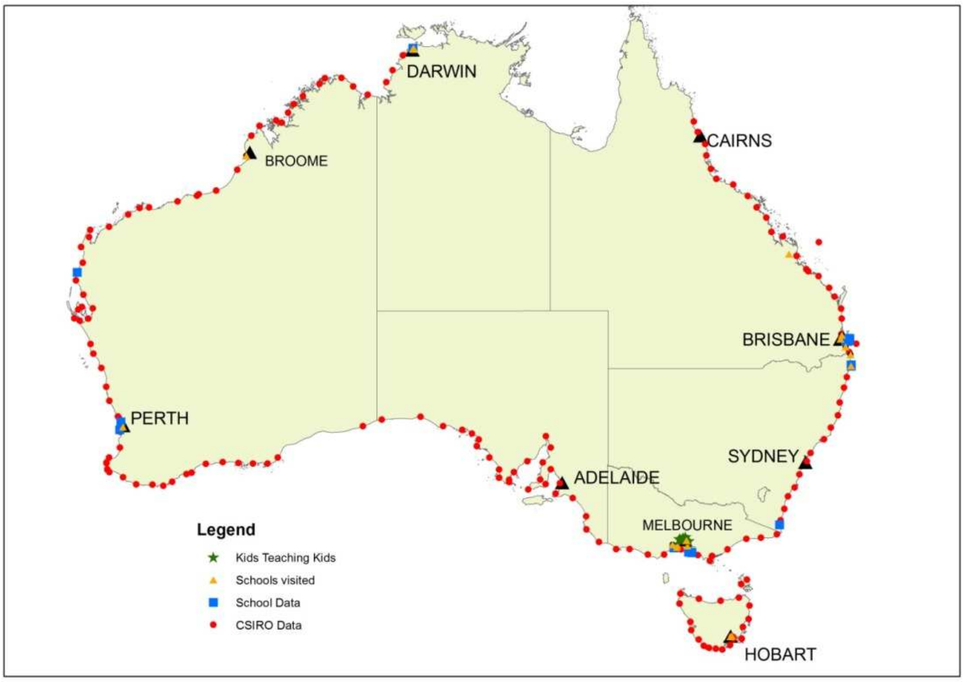


Figure 1. Map showing locations of coastal debris surveys around mainland Australia and the southern island state, Tasmania. This map includes locations of school debris surveys (blue squares), engagement with the 'Kids Teaching Kids' program (green stars) and CSIRO surveys (red circles).

The two last major areas that required surveying in the last year were across the Kimberley region (which required the use of a float plane to survey sites from Broome to Darwin) and Tasmania. Tasmania surveys were conducted by vehicle, on foot and via float plane (in the west and south west of the state where there is no road access). The national coastal debris surveys were completed in June 2013. We are particularly pleased to have completed this mammoth fieldwork component of the project without a single major health and safety incident!

From our CSIRO national coastal debris survey we estimate that there are more than 115 million bits of rubbish on Australia's coastline (including Tasmania but excluding the >350 outlying islands). This is based upon the coast being 35,877km in length and takes into account that we found an average of 6.439 items of anthropogenic debris on each 2m wide transect we carried out. Given that the population of Australia is estimated at 22.32 million people (population clock: http://www.abs.gov.au/ausstats/abs@.nsf/0/1647509ef7e25faaca2568a900154b63?OpenDocument), this averages about 5.2 pieces of debris for every person in the country.

Overall, we find that about 75% of all waste is plastic, 24% is glass and metal, and 1% is cloth. Of the plastics, it looks like 2% of debris is discarded monofilament (and hence is associated with recreational fishing). Because most plastics float whereas glass and metal sink, we can separate out to some extent the terrestrial versus marine components of debris we find on beaches.

In further analysing the data we consider a number of important components or inputs to marine debris along our coastline. We include two figures to describe the anthropogenic debris at the surveyed sites, and extend that, using model predictions for rubbish along the coast. The first figure (Figure 2) shows the density of debris along the coastline corrected for factors that would cause local sampling bias (such as shape of the coastline, substrate, steepness of the beach [gradient], and backshore substrate type). The second figure (Figure 3) incorporates corrections for sampling bias and incorporates factors that drive terrestrial inputs to debris such as local and regional population density, distances to roads, etc. The spatial pattern shown therefore represents the leftover or residual variation which is inferred to be the marine input of debris (with terrestrial sources and sampling variation removed).

Tasmania data are not included in either figure because we have not had time to input those data and analyse them given how recently surveys were completed. In the coming months we will complete analysis of the entire Australian coastline.

The map (below,) shows the relative density of anthropogenic debris along the Australian coast. This takes into account where surveys were carried out but extends to create a ribbon plot of coastal debris density based upon observed debris and factors that affect debris accumulation at sampling sites (e.g. variables such as shape of the coastline, substrate, gradient and backshore substrate type). Lighter colours represent more debris (note that in the top end of Australia the model predicts high levels of debris, though that region was not surveyed using our methodology). This high level is likely an artefact of the fact that the surrounding areas that were surveyed had increasing quantities of debris so the model predicts even more debris in the top end. This prediction should be ignored until further data can be collected. It is worth noting that the 'dirtiest' areas are not necessarily associated with the highest population densities. The southeast region of Australia and the northwest of the country look to have higher levels of debris than do other areas with lower population density.

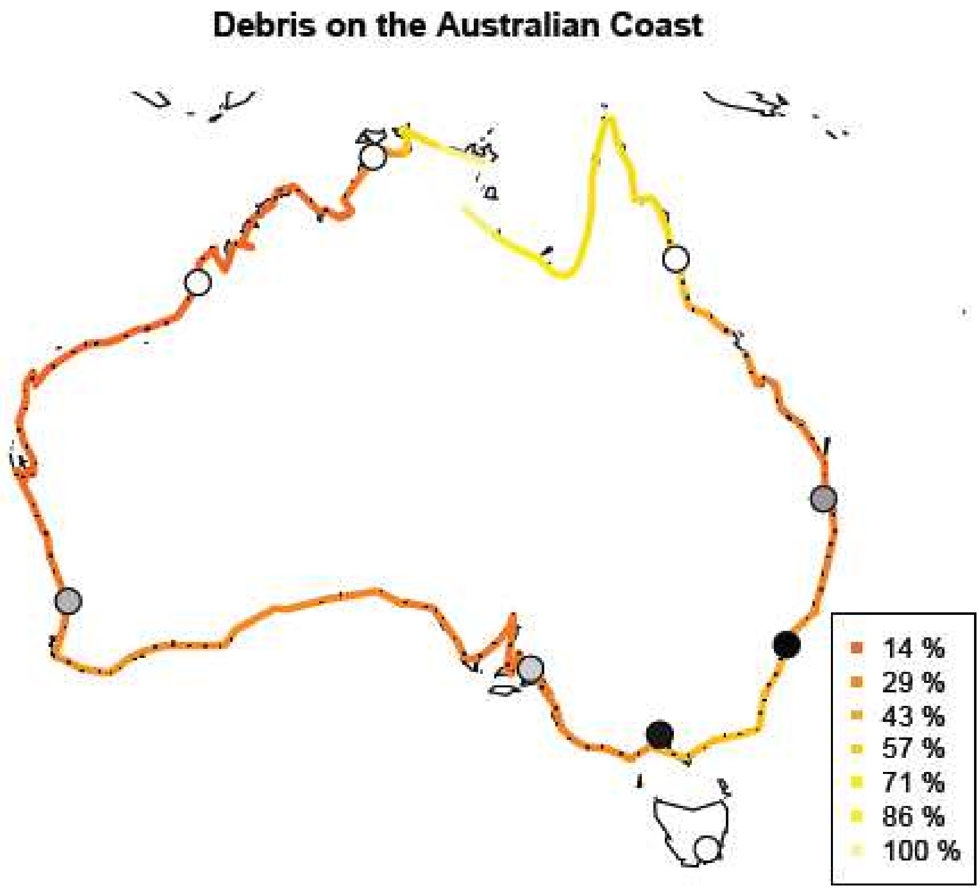


Figure 2. Relative density of anthropogenic debris along the Australian coast.

We next considered the component of debris that is likely coming from the marine environment. In the second model we included not only the shape of the coastline, substrate, gradient and backshore substrate type, but we also took into account the population within 5 km and within 50 km of the surveyed site as well as the distance from the survey site to the nearest road. In this second model, the population parameter at each of the two distances was significant. At 5 km radius from the survey site there is a negative relationship between population density and anthropogenic debris. At the 50 km distance category considering the population density there is a positive relationship. This suggests that at the local scale, where you have more people, you find beaches having less debris. At the regional scale in contrast, higher population density is associated with an increase in the amount of rubbish on beaches.

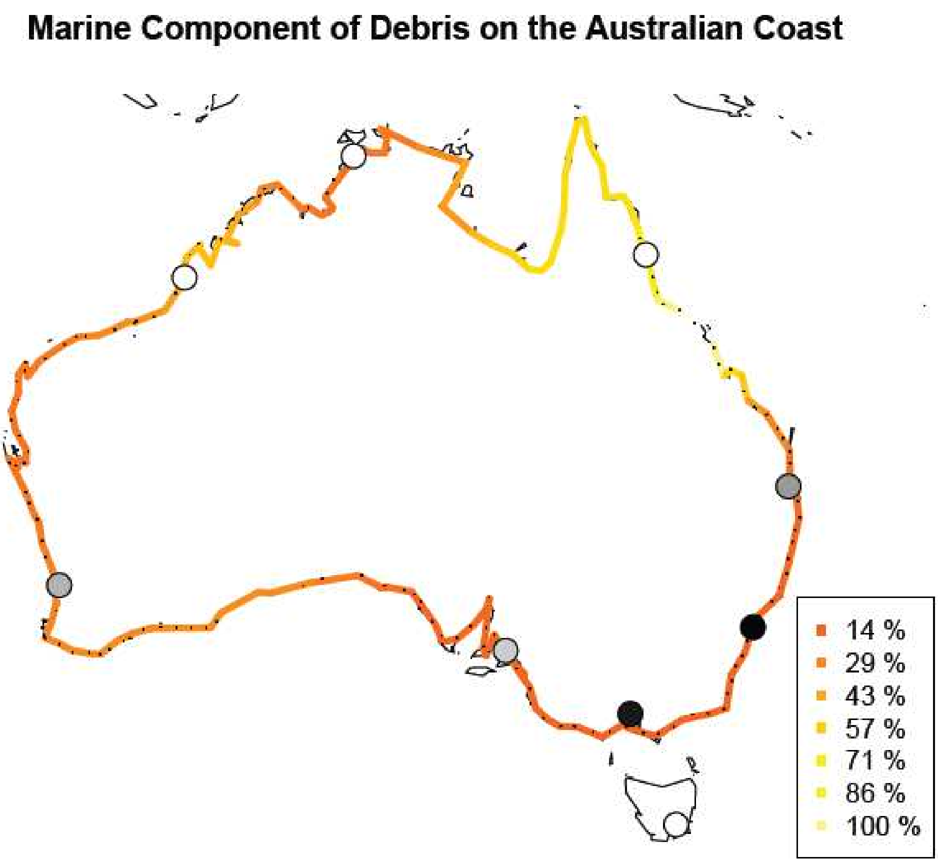


Figure 3. Component of debris that is likely coming from the marine environment.

We will soon be adding analyses from the Tasmania survey sites to the analysis, to complete the continental scale picture.

3.2 At sea surveys

In addition to the 10-day Southern Surveyor research expedition with teachers, we were able to take advantage of another vessel of opportunity to add to the data gaps for where marine debris is in our coastal and offshore waters. Early in 2013 the CSIRO team was able to hitch a ride on one of the AIMS research vessels that was working in Queensland. On board this vessel we were able to conduct more than ten sets of surface trawls in coastal Queensland waters (inside the Great Barrier Reef from north of Cairns to north of Brisbane).

The TeachWild intensive research expedition from Broome to Darwin was a tremendous success, in spite of initial rough conditions at sea which made for a challenging first few days at sea. Everyone adapted quickly to life on board the ship, and we were able to complete trawls at approximately 23 sampling stations – a tremendous feat!

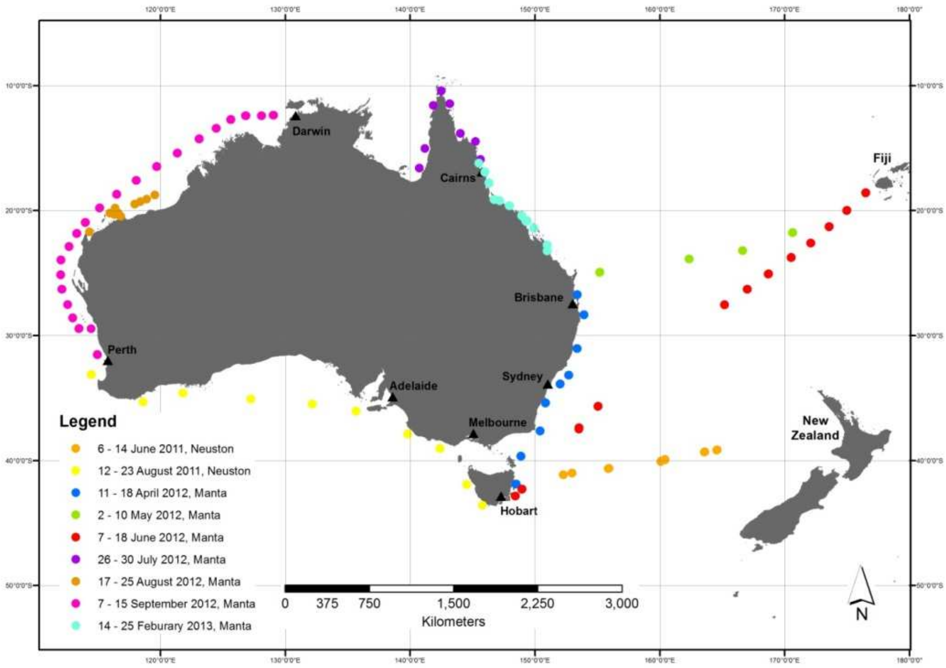


Figure 4. Map showing locations of surface trawl surveys around the continent. Different colours represent different research cruises. In total, marine debris trawls have taken place during nine different voyages and we have sampled at more than 60 sites around the country. Analyses of these data are underway and we hope to have publication of these results before the end of 2013.

Figure 5. Deploying the surface trawl net aboard the *Southern Surveyor*

Teachers have played an important role in collecting data for at-sea marine debris trawl samples. Sorting samples takes a lot of time and patience, but can be rewarded with seeing some exciting marine life as well!

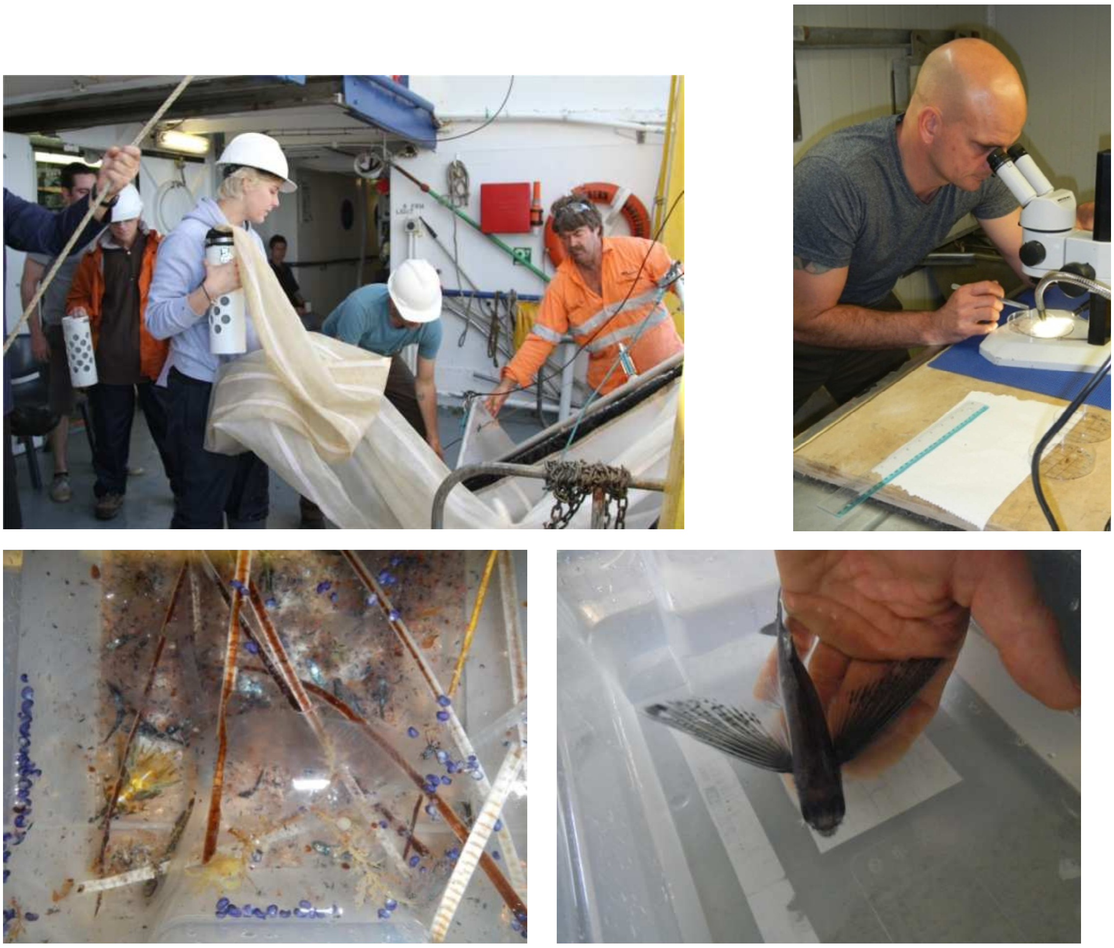


Figure 6. Photos of teachers and researchers collecting data and sorting samples above the *Southern Surveyor*.

3.3 National data portal (improvements)

The data portal was established in the first year of the project so that individuals and groups could input data and see summaries of information from across the country. However, in the course of using the database, a number of issues arose with the Atlas of Living Australia data portal site. While it was not within our area of the project to do so, CSIRO staff have now revised the web portal data entry site (see Appendices B and C) to make the site more user friendly and intuitive. The feedback regarding the changes has been positive.

3.4 Scientist for a Day

In the past twelve months we have carried out Scientist for a Day activities in Northern Territory, Victoria, Western Australia, Tasmania and Queensland. We spent a week each in the Melbourne surrounds in August 2012, a week in Exmouth, Carnarvon and surrounding areas in November 2012, a week in the greater Perth region in February 2013 and a week near Gladstone at the end of May 2013. TeachWild scientist visits to three schools in Tasmania have also taken place independently by CSIRO staff (April/May 2013).

In addition to these live face-to-face interactions with school groups, we have increased our Skype/videoconferencing interactions with school groups. CSIRO staff have had some fantastic Skype/web chats with numerous other primary and secondary school kids throughout the year, including talking with primary school students in Victoria and a year 11 Chemistry class from Western Australia. Having live chats with students while in the field allows us to not only teach kids about marine debris, but also shows them some of the opportunities available for careers in science.

In total, we have engaged with more than 3,000 students since the inception of the TeachWild program, exceeding our goal for numbers of students with whom to interact. Feedback from schools has been very positive and it is heartening to see and learn about some of the creative solutions to reducing rubbish that are being established and gaining traction in schools.

In addition to school engagement, we have delivered TeachWild to a number of Shell Graduates. Graduate days in Melbourne, on Rottnest Island near Perth and in Queensland have all received positive feedback. Importantly, they have provided us with an excellent opportunity to promote learnings from TeachWild to Shell staff, increasing their understanding of the marine debris issue and Shell's role in supporting leading research efforts and their commitment to social investment on extremely relevant and timely topics.

The clear message from Shell employees is that they appreciate the company they work for and they are excited about the opportunities provided by Shell. Learning about marine debris impacts on wildlife has been quite an eye opening experience for many of the participants (or so we understand from feedback from participants). It has been rewarding for us to see some of the personal and professional changes that some of the participants have been interested in developing and implementing at work, home and in their communities.

3.5 TeachWild Intensive Research Teams

In the second year of the TeachWild program we have delivered science and learning for five intensive experience trips for teachers. These have included:

- A *Southern Surveyor* voyage (3-12 September 2013) from Broome to Darwin with 3 teachers
- North Stradbroke Island (24-30 September 2013) with 8 teachers/educators
- Phillip Island (11-14 October 2012) with 9 teachers/educators
- Phillip Island (9-13 April 2013) with 10 teachers/educators
- Rottnest Island (18-20 April 2013) with 8 Shell staff

Activities for the intensive expeditions have been varied but have included coastal debris surveys, at-sea surface trawl surveys (and associated sorting of debris), necropsies of turtles and seabirds, spectrophotometry measurements to look at spectral characteristics of plastics, recording net and other material characteristics for items that have ensnared southern fur seals, and seabird colony surveys to look at debris levels in and near breeding colonies.

We have exceeded the goals and obligations for intensive field expeditions in the last year, and with agreement of all partners, we were able to move some of the deliverables for next year forward to this year. The intensive expeditions have been very successful and have contributed to important data collection needs by CSIRO staff and research partners.

It is worth mentioning that one of the fantastic educators we have worked with, teacher Karen Johns from Victoria, has not only been very inspired by her involvement in the program but she has also been exceptionally inspiring. After her participation in one of the Phillip Island trips she submitted a grant application to work in the Antarctic as part of the artists and educators in Antarctica program. CSIRO scientists wrote a support letter for her application and she continues to be an excellent educator as well as an enthusiastic ambassador for the TeachWild marine debris program. Karen has continued to work with CSIRO staff and will be co-author on a publication we aim to submit (based upon some of the net characteristics work she has been doing with us). She has also participated as a CSIRO volunteer in a second Phillip Island expedition, sharing her knowledge, enthusiasm and experience in TeachWild to further inspire others – students and teachers alike.

3.6 Other CSIRO research activities

Seabird risk analysis: We now have made global scale predictions of exposure to marine debris for 193 seabirds. The expected risk ranges over 7 orders of magnitude. We are now comparing predictions with observations from the literature (last 25 years of published works) addressing stomach contents. We aim to complete this and submit for publication in the coming few months.

Cetacean risk analysis (see IWC in section 3.8): After publication of the turtle risk assessment, the International Whaling Commission has contacted us asking about extending that approach to cetaceans. We have just gained access to species distribution information available and are looking to carry out a similar analysis to that described above for seabirds - though this will focus on entanglement rather than ingestion and it incorporates fishing effort and gear loss at a global scale.

Chemical marker assay: We have successfully developed a chemical marker assay to identify plastics exposure in seabirds. With a simple field-based method we can quickly and with minimal intrusion, swab the uropygial gland of a bird to test for some of the main plasticizers used in plastics manufacturing. Furthermore, we have initiated a collaboration with Bird Life International on chemical marker approaches to quantify plastics ingestion in seabirds. (Figure 7)

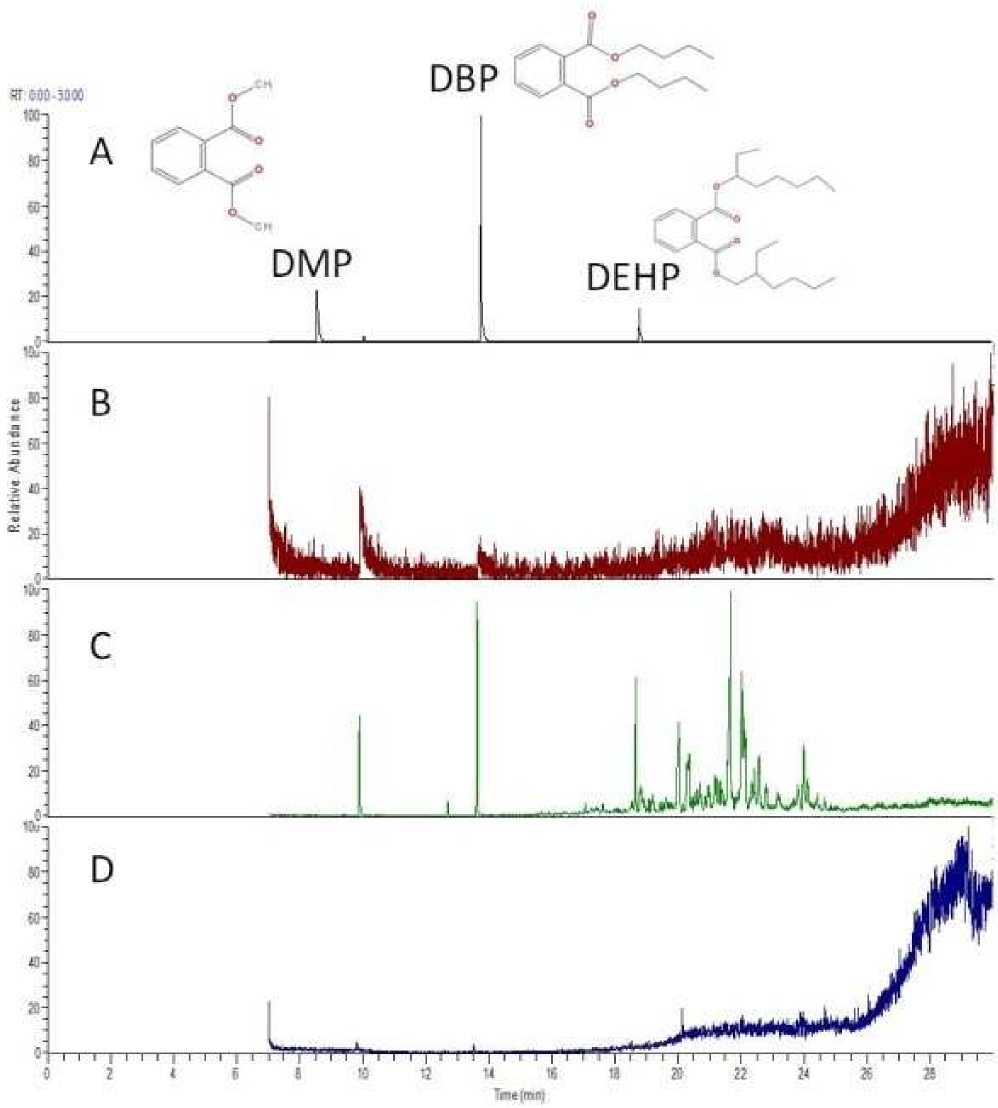


Figure 7. Chromatograms showing examples of phthalates (plasticizer residues) and their occurrence in different samples. (A) Three standards: dimethyl phthalate (DMP), dibutyl phthalate (DBP) and bis (2-ethylhexyl) phthalate (DEHP); (B) Procedural blank showing no phthalate residues; (C) Extract of preen oil collected from a dead Shearwater with abundant plastic content in stomach (contains DBP and DEHP); (D) Extract of preen oil collected from a live Bridled Tern, Houtman Abrolhos Is. (little or no plastic content in stomach).

Juvenile turtle movement and vision experiments: Denise spent a week at Heron Island working with University of Queensland (UQ) collaborators (Townsend, Schuyler and Marshall) focusing on some of the marine turtle components of the project. Satellite transmitters were attached to five juvenile green turtles to look at turtle movements and foraging patterns. This will contribute to our understanding of where and what age classes of turtles are more likely to encounter and be impacted by marine debris. We're already getting good tracking data and we can see where turtles at Heron Island are spending their time. (Figures 8 and 9)

How to catch a turtle ...

Satellite tag and flipper tag on turtle - prior to release …

We ensure that all is well with newly tagged turtles prior to release (swimming in tank at Heron Island Research Station).

Figure 8. Turtle tagging on Heron Island.

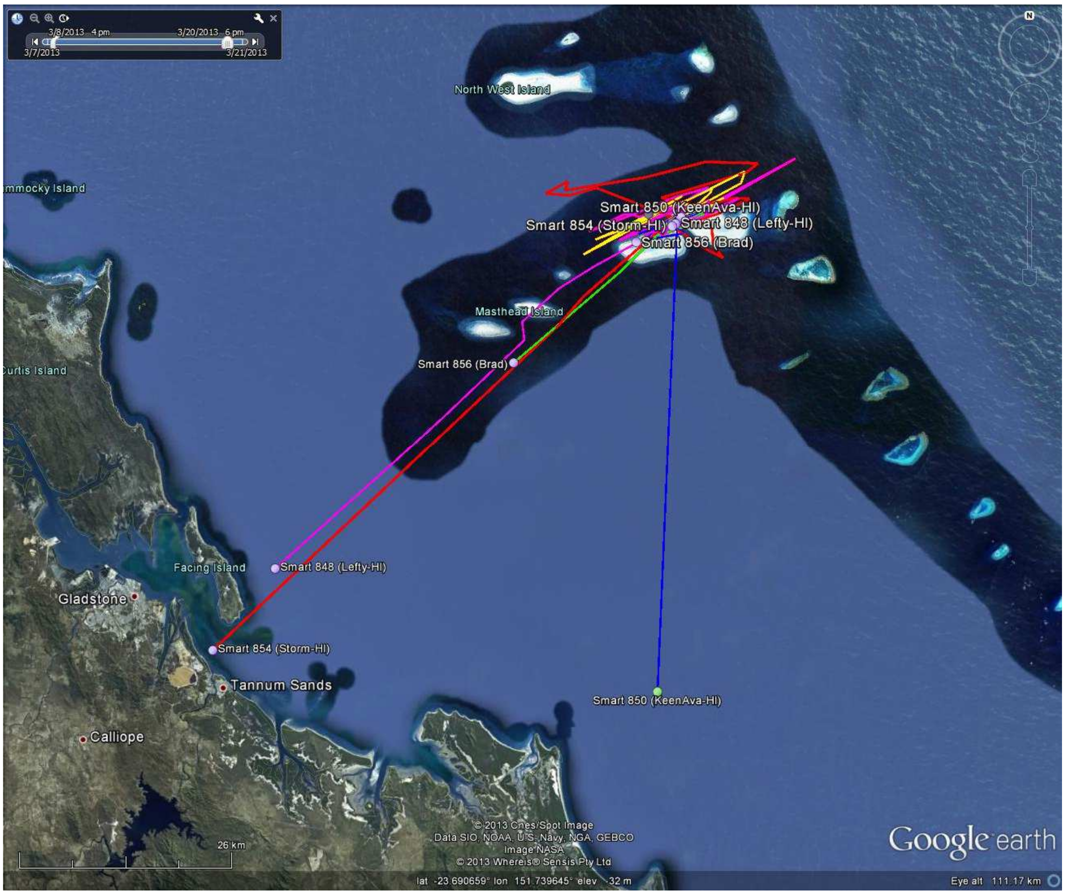


Figure 9. Tracks of turtle movement near Heron Island, Qld.

We also carried out experiments to look at how turtles see (turtle vision experiments) in an effort to better understand how and why turtles may mistake plastics for food. (Figure 10)

Figure 10. Experiment to investigate turtle vision. This is a focus of PhD student Qamar Schuyler's work. Results are not yet completed but will be by the end of 2013.

Waste management efficacy: With a visiting international student (Clementine Maureaud), we have also begun the process of carrying out surveys at the regional and state level to look at efficacy of council waste management strategies. Our aim is to link council practices, policies and efforts to our coastal debris survey data and identify policy effectiveness. Interviews have been completed for those regions with high and low quantities of rubbish at surveyed beaches from all states and territories. Data analysis is underway and will be completed before the end of 2013.

3.7 Stakeholder and policy impacts

CSIRO marine debris staff have been increasingly called on to act as experts and to share information about their marine debris research findings. In the last twelve months CSIRO staff have:

- Given an informal talk at the Coast to Coast Conference in Brisbane to participants/stakeholders as part of their field excursion to N. Stradbroke Island (September 2012)
- Presented our work as an invited speaker at a multi-agency task force/stakeholder meeting in Cairns which aimed to address issues around retrieval, disposal and data collection of ghost nets in Qld and Federal Waters (e.g. derelict fishing gear issues at sea). Talk title 'Identifying ghost net hotspots, looking for sources, and ameliorating the issue'. Participants included staff from SEWPAC, Cairns Turtle Rehab Centre, GhostNets Australia, QPWS, DAFF, AFMA, QDAFF, Customs and border Protection, SeaNet/Ocean Watch) (February 2013)
- Acted as a marine debris expert and panel advisor at the South Australia state marine debris workshop which involved NGO, state, UNEP, and SEWPaC staff. We shared our methodology, findings to date and encouraged engagement with numerous stakeholder groups who would like to share data and contribute to the national marine debris database (May 2013)
- Participated in a Marine Debris stakeholder meeting in Canberra (with attendees from CSIRO, GBRMPA, DAFF Fisheries, Dept. of Innovation, AMSA, GhostNets Australia, DIT, SEWPaC, JCU, and Tangaroa Blue. (March 2013). See handout (Appendix C) provided to participants
- Participated as keynote speaker at Tasmania Public Marine Debris Community Forum (Hobart, May 2013)
- Gave a World Ocean's Day presentation for Shell staff in Perth (May 2013)
- Participated as scientist in the TeachWild World Ocean's Day Event in Melbourne (May 2013)
- Gave invited public seminar on marine debris research for the Royal Society Southern Highlands group of New South Wales
- Participated as marine debris expert and panel advisor at the Airlie Beach Marine Debris stakeholder meeting in Queensland (June 2013). See handout (Appendix D) provided to participants

As a demonstration of project impact at State and Federal Levels, CSIRO scientists have also

- Had regular engagement/discussion with SEWPaC marine section staff
- Been invited as marine debris expert for meetings in SA, Qld, Tas, NSW
- Provided support for more than 5 organizations who asked for support as part of the recent Caring for Country Biodiversity fund applications for marine debris work

- Had their ghost nets marine debris work selected for a Prime Minister Science note "Hot Science Topic" (May 2013)

  Been invited to present research findings and provide comment on the proposed national container deposit scheme
- Been approached by and had multiple exchanges with the Australia Packaging Covenant/Australian Food and Grocery Council/Packaging Stewardship Forum about our marine debris findings

3.8 International engagement

CSIRO's international profile in marine debris work is being increasingly recognised. Not only do we receive emails and queries from people wanting to participate in the TeachWild program from overseas (US, Africa, Europe, Asia), but we have participated in a number of scientific and public outreach activities in the past twelve months:

- Invited speaker and workshop participant at the First International Marine Debris Entanglement Workshop hosted by the World Society for the Protection of Animals in Miami, Florida. We presented our work on ghost net impacts on globally threatened turtles. (USA, Dec 2012)
- Invited workshop participant at the marine debris working group supported by the National Center for Ecological Analysis and Synthesis working group in Santa Barbara, California. This is essentially a global think tank that brings together researchers to address hot topics in the ecological/ environmental fields. The weeklong workshop was fruitful and will undoubtedly result in additional publications with other globally recognised leaders in the field. It was clearly acknowledged and recognised that there is no comparable dataset by any researchers at any similar scale around the world – and certainly nothing of this scale has ever been done in the southern hemisphere – this was highlighted in regards to coastal surveys, at-sea surveys and citizen science engagement with school groups. There is a follow up meeting to this one scheduled for November 2013 which we hope to attend. (March 2013)
- Invited workshop participant and guest speaker at the International Whaling Commission Marine Debris workshop in Woods Hole, Maryland. The IWC is particularly interested in our risk analysis approach to cetacean entanglement and ingestion (USA, 13-17 May)
- Invited guest speaker at the African Marine Debris Summit in Cape Town, South Africa. Talk title Marine debris global garbage: (citizen) science tackling a global issue. CSIRO also led the field expedition to carry out a beach clean-up and marine debris survey. International adoption of the CSIRO developed coastal debris survey methodology by delegates from Kenya, South Africa and possibly other countries (5-9 June 2013). (see Appendix E)

3.9 Communications and media

In 2012-13 the national marine debris project was the subject of much media interest (see list below). This does not include media associated with the World Ocean's Day event in Melbourne, 7 June 2013, as that information has been summarised by the Red Agency and provided to Earthwatch Australia already.

In addition to the list of media below, National Geographic magazine is potentially interested in a story on our marine debris work.

It is worth noting the broad reach of ABC's Catalyst program and our marine debris project exposure on the show. This exposure has increased project profile at the national level and is a continued source of conversation. We often incorporate the Plastic Oceans episode into Scientist-for-a-Day and Intensive Field Excursions.

CSIRO organized, coordinated and gave an Ustream interview which was live-streamed to interested school groups and members of the public (November 2012). A follow up interview presenting results from research findings to date would be worth considering during the final year of the project.

The marine debris project has also been featured in CSIRO's internal newsletter *Monday Mail*, as well as on Twitter and Facebook. The CSIRO project team manages the Facebook page 'Marine Debris Australia'.

Recent media:

- http://www.csir.co.za/enews/2013_jun/19.html
- http://www.heraldsun.com.au/news/breaking-news/more-sea-debris-than-people-in-aust-csiro/story-fni0xqi4-1226658481849
- http://www.smh.com.au/environment/five-pieces-of-rubbish-per-person-on-our-beaches-20130606-2nrss.html
- http://www.heraldsun.com.au/news/victoria/schools-aid-litter-survey-and-expose-a-sea-full-of-rubbish/story-fni0fit3-1226658039656
- 9 May 2013. ABC radio Tasmania. The morning show
- 9 May 2013. ABC radio Hobart
- The Mercury Newspaper 9 May 2013. http://www.themercury.com.au/article/2013/05/09/378757_tasmania-news.html
- The Tasmanian Times 9 May 2013. http://tasmaniantimes.com/index.php?/pr-article/lets-start-talking-rubbish-/
- 10 April 2013. WIN television 6pm and late night news. National marine debris project
- http://www.smh.com.au/environment/litter-data-recycles-case-for-bottle-and-can-refund-20130410-2hlty.html
- ABC pm Radio Regional Queensland. 9 April 2013. CSIRO, GhostNets Australia and Ghostnets in the Gulf of Carpentaria
- ABC pm Radio Mackay. 9 April 2013. CSIRO and Ghostnets removal in the Gulf of Carpentaria
- ABC pm Radio Darwin. 8 April 2013. CSIRO and Ghostnets in the Gulf of Carpentaria
- ECOS magazine 11 Feb 2013. Sea turtles caught up in ghost nets' random harvest http://www.ecosmagazine.com/paper/EC13023.htm
- ABC News. http://www.abc.net.au/news/2013-01-28/experts-study-ghost-nets-impact/4487086?&section=news. 28 Jan 2013
- ABC Far North Radio. CSIRO scientists in the Gulf of Carpentaria. 25 Jan 2013
- ABC News Far North Radio. CSIRO scientists track disused fishing nets. 25 Jan 2013
- ABC Western Qld. CSIRO scientists in the Gulf of Carpentaria. 25 Jan 2013
- ABC Radio Pacific Islands. Phantom nets target turtles interview. 22 Jan 2013
- Torres Strait Radio interview, ghost net impacts on threatened turtles. 21 Jan 2013

- 2MCE radio. Indigenous rangers and scientists are working to track ghost nets. 21 Jan 2013
- NITV Sydney Indigenous rangers are helping to track down abandoned 'ghost' fishing nets. 21 Jan 2013
- ABC NQ Townsville. CSIRO interview about ghost nets. 21 Jan 2013
- Ghost nets threaten sea turtles in Australia. http://www.cusdn.org.cn/news_detail.php?id=242469 21 Jan 2013
- ABC News 24. Sydney weekend breakfast. Ghostnets interview on national morning news. 20 Jan 2013
- ABC1, Canberra Weekend News. Abandoned fishing nets drifting in Australian waters. 20 Jan 2013
- ABC Saturday evening news. http://www.abc.net.au/news/2013-01-21/ghost-busters/4473598 ?section=nt 19 Jan 2013
- ABC1 Hobart, ABC Weekend News. Abandoned fishing nets drifting in Australian waters. 19 Jan 2013
- ABC1 Adelaide, ABC Weekend News. Abandoned fishing nets drifting in Australian waters. 19 Jan 2013
- ABC1 Brisbane, ABC Weekend News. Abandoned fishing nets drifting in Australian waters. 19 Jan 2013
- ABC1 Darwin, ABC Weekend News. Abandoned fishing nets drifting in Australian waters. 19 Jan 2013
- ABC1 Perth, ABC Weekend News. Abandoned fishing nets drifting in Australian waters. 19 Jan 2013
- ABC1 Sydney, ABC Weekend News. Abandoned fishing nets drifting in Australian waters. 19 Jan 2013
- ABC News 24. Abandoned fishing nets drifting in Australian Waters. 19 Jan 201
- ABC Radio Australia News. http://www.radioaustralia.net.au/international/2013-01-19/scientists-rangers-team-up-to-track-ghost-nets/1075604 Scientists, rangers team up to track ghost nets. 19 Jan 2013
- ABC Radio, Ghost net impacts on marine turtles; interview with Ben Cole. 18 Jan 2013
- Program protects marine life. North Queensland register. Townsville, Qld. 17 Jan 2013
- ABC Northwest radio. CSIRO has uncovered hotspots where discarded nets threaten marine life. 16 Jan 2013
- 'Ghost nets' said to threaten marine life. Big News Network.com. 15 Jan 2013
- Ghost nets a menace to sea turtles in Australia. The Hindu. 15 Jan 2013
- 'Ghost nets' said to threaten marine life. Upi.com. 15 Jan 2013
- Phantom fishing nets endangering marine turtles in northern Australia. Wildlife Extra. 15 Jan 2013
- Lost fishing nets threatening marine biodiversity. The Fish Site. 15 Jan 2013
- Curtin FM Radio, Perth, Afternoons with Jenny Seaton. Ghostnets interview. 15 Jan 2013
- Radio 6RTR, Perth, Morning Magazine interview. 15 Jan 2013
- Ghost nets threaten sea turtles in Australia. China.org.cn 14 Jan 2013
- Ghost nets threaten sea turtles in Australia: CSIRO research. Shanghai Daily 14 Jan 2013
- John Stokes speaks to Denise Hardesty, Research Scientist at CSIRO. ABC Radio, Sunshine and Cooloola Coasts, 14 January 2013
- Channel 7 News Queensland. Study to save turtles from Plastic. 1 October 2012. http://au.news.yahoo.com/video/queensland/watch/f338e2c2-db1a-370f-9f32-11cc07929fd0/study-to-save-turtles-from-plastic/
- Behind the News: Plastic Oceans. ABC1. 18 September 2012. Re-aired 20 Sept 2012. http://www.abc.net.au/btn/story/s3591476.htm

- Marine debris interview. ABC Radio Morning Magazine Interview. 11 September 2012
- Marine Debris interview. Broome, ABC Radio WA. 6 September 2012
- Catalyst: Plastic Oceans. ABC. 6 September 2012; re-aired 8 Sept 2012. http://www.abc.net.au/catalyst/
- Scope Oceans Episode II, 16 August 2012. http://ten.com.au/video-player.htm?movideo_p=41452&movideo_m=213080
- Emphasis Newsletter, Scientists in Schools, August 2012. Spotlight on Citizen Science
- Marine debris project interview for ABC radio Queensland. 28 July 2012

3.10 Publications completed or in advances stages of preparation

It has been a productive year in terms of scientific output, with several papers already published and others in advanced stages of preparation and/or under review.

The research team has had a paper newly accepted for publication in the high-ranking international journal Conservation Biology:

> Schuyler, Q, BD Hardesty, C. Wilcox and K Townsend 2013*. A global analysis of anthropogenic debris ingestion by sea turtles.* The paper is in the final proof stages with the publisher and we will provide a copy of the paper when it is published.

We have also had a paper published that looks at transboundary issues, intervention points and livelihood issues in ghost net marine debris across the top end of Australia:

> JRA Butler, R Gunn, HL Berry, GA Wagey, BD Hardesty, C Wilcox. 2013. Value chain analysis of ghost nets in the Arafura Sea: identifying trans-boundary stakeholders, intervention points and livelihood trade-offs. Journal of Environmental Management 123: 14-25.

Our first risk analysis work has been completed and published in the top ranking international journal Conservation Letters:

> Wilcox, C, BD Hardesty, R Sharples, DA Griffin, TJ Lawson and R Gunn. 2013. Ghost net impacts on globally threatened turtles, a spatial risk analysis for northern Australia. Conservation Letters, DOI: 10.1111/conl.12001.

With our co-advised PhD student Qamar Schuyler and in association with UQ collaborator Kathy Townsend, a paper looking at debris selectivity by marine turtles in Australia has been published in the international journal PLOS One:

> Schuyler, Q, K Townsend, BD Hardesty and C Wilcox. 2012. To eat or not to eat: debris selectivity by marine turtles. PLOS One 7(7): e40884. DOI:10.1371/journal.pone.0040884.

In association with our Conservation Letters paper, we were asked to provide a popular article for The Conversation on our ghost nets work:

> Hardesty BD and CV Wilcox 31 Jan 2013. *Ghostnets fish on: marine rubbish threatens northern Australian turtles*. The Conversation http://theconversation.edu.au/ghostnets-fish-on-marine-rubbish-threatens-northern-australian-turtles-11585.

International masters student Heidi Acampora has completed her master's thesis entitled 'Assessing the impacts of plastic ingestion on short-tailed shearwaters (*Puffinus tenuirostris*) in northern Australia'. This thesis formed the basis for a paper which is in the final stages of preparation for submitting to Marine Pollution Bulletin:

> Acampora, H, Q Schuyler, K Townsend and BD Hardesty. 201. Quantification and an inter-annual comparison of marine debris ingestion by Short-tailed shearwaters (*Puffinus tenuirostris*). To submit to Marine Pollution Bulletin.

Due to our work in the marine debris field, Hardesty and Wilcox were asked to contribute to a review paper identifying the key threats and impacts of marine debris on wildlife:

> Vegter, A., Barletta, M., Beck, C., Borrero, L., Burton, H., Campbell, M., Eriksen, M., Eriksson, C., Estrades, A., Gilardi, K., Hardesty, B.D., Assunção I do Sul, J., Lavers, J., Lazar, B., Lebreton, L., Nichols, W.J., Ramirez Llodra, E., Ribic, C., Ryan, P.G., Schuyler, Q., Smith, S.D.A., Takada, H., Townsend, K., Wabnitz, C., Wilcox, C., Young, L., & Hamann, M. (2014). Global research priorities for the management and mitigation of plastic pollution on marine wildlife. *In press Endangered Species Research*.

In addition to the risk analysis work on marine turtles, we have recently carried out a global review of marine debris literature on seabirds and, coupled with oceanographic modelling, have completed a global risk analysis for marine debris ingestion in seabirds which we aim to submit to the journal 'Proceedings of the National Academy of Sciences of the United States of America':

> Wilcox, C, BD Hardesty, TJ Lawson, E van Sebille. 2013. A global risk analysis for marine debris ingestion in seabirds. In preparation for PNAS.

With one of our fantastic TeachWild teachers (Karen Johns of Victoria) and with one of our collaborators from Phillip Island Nature Parks (Roger Kirkwood), we have been working to analyse data to assess entanglement and net characteristics in Australian Fur Seals:

> Lawson, TJ, K Johns, R Kirkwood, BD Hardesty and C Wilcox. 2013. Net characteristics and entanglement in Australian Fur Seals. In preparation for Marine Pollution Bulletin.

With PhD student Julia Reisser, analyses of at-sea coastal debris surveys have been completed. This work compares where debris occurs at sea with where debris is predicted to occur, based upon oceanographic models and empirical data. The paper will be submitted to PLOS One before the end of 2013:

> Reisser, J, J Shaw, C Wilcox, BD Hardesty, M Proietti, M Thums and C Pattiatchi. Quantification and characterization of plastic debris in Australian waters. Submitted to PLOS One (July 2013).

4 Anticipated achievements in Year 3 (Looking forward)

We have high hopes for this final (third) year of the national marine debris project. In addition to visiting with schools in north Queensland (Townsville region), South Australia and NSW, we are excited for the upcoming intensive field programs we have scheduled at Phillip Island and North Stradbroke Island. We would like to ensure that all participants in TeachWild receive a Certificate of Participation, as we think this has value for students and teachers alike.

We would also like to see a web-based conference take place, as that was one of the aspirational goals of the project. We believe that a web conference would raise the profile of TeachWild, the important research being carried out, and would go a long way towards increasing our depth (not just breadth) of engagement with the many schools and students with whom we have engaged.

While it was identified as a challenge to overcome in the first year of the project, we still have not implemented a strategy for addressing the increasing numbers of ad-hoc inquiries. We had not envisaged such a broad and deep level of interest in the work, but it is a happy problem to have such interest in the project. We continue to strive to respond to every query and have done so 100% of the time. Ensuring we have the best communication possible between organisations will help to ensure enquiries do not 'fall through the gaps' and that interested parties see us all as being responsive and interested in engaging with as many group as we can.

With the increasingly high profile of the project and the strong scientific output has also come an increase in media attention. This certainly favours the project and points very strongly to the high impact of the marine debris work we are doing, but it also requires resources beyond those budgeted for and envisaged when we set out on this path. We are ensuring a mindful, professional and appropriate response to the many media enquiries, and paying particular attention to deliver the TeachWild message. This consistency is important in highlighting all TeachWild partners.

References

Derraik, JGB (2002). The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44: 842–852.

Good, T. P., June, J. A., Etnier, M., and Broadhurst, G. (2010) Derelict fishing nets in Puget Sound and the Northwest Straits: Patterns and threats to marine fauna. *Marine Pollution Bulletin* **60**, 39-50.

Hardesty, BD and C Wilcox (2012). Understanding the effects of marine debris on wildlife: A progress report prepared for Earthwatch Australia by CSIRO.

Ocean Conservancy. 2012 International Coastal Cleanup - Top 10 Items Found. Available at: http://www.oceanconservancy.org/our-work/international-coastal-cleanup/2012-ocean-trash-index.html

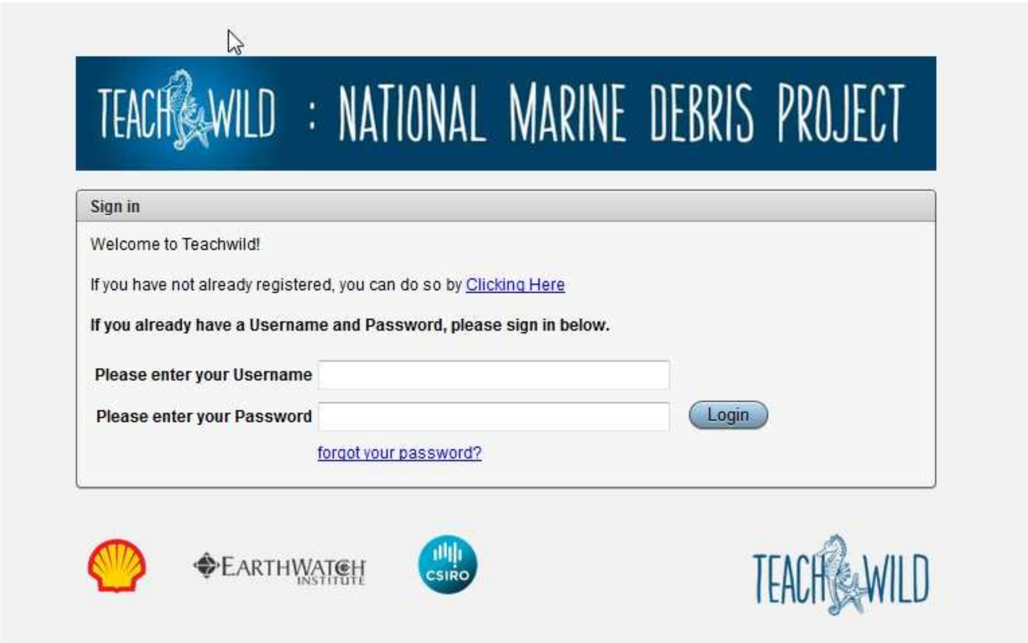
Appendix E. Instructions for data entry with updated data portal (Transects).

TeachWild: National Marine Debris Project

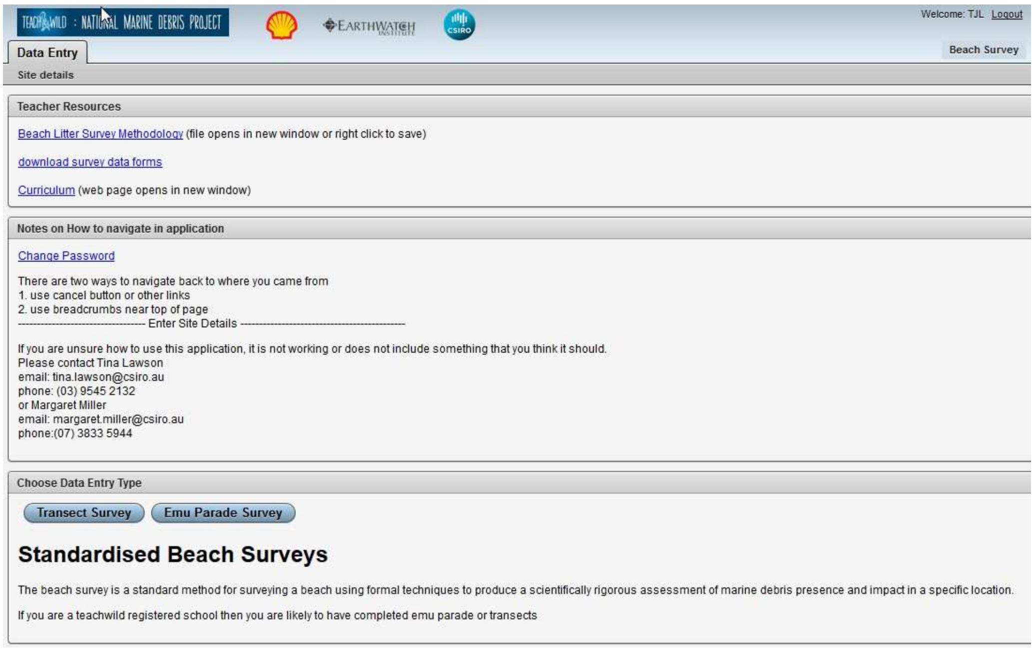
Database instructions: Transects

To enter data, you first need to be registered.

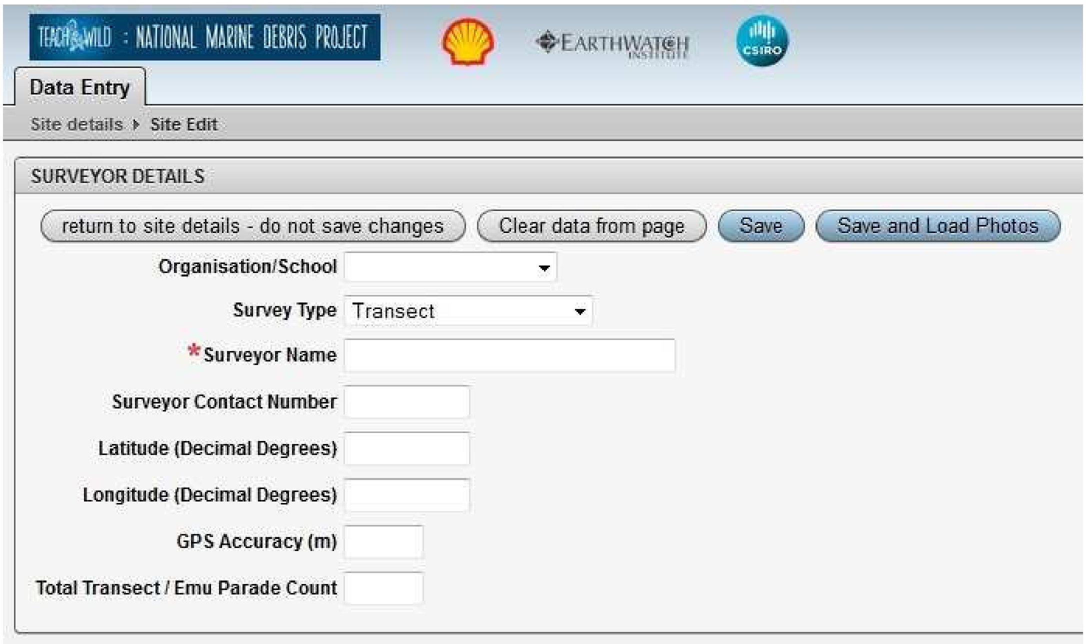
1) Enter your username and password, press the “Login” button.



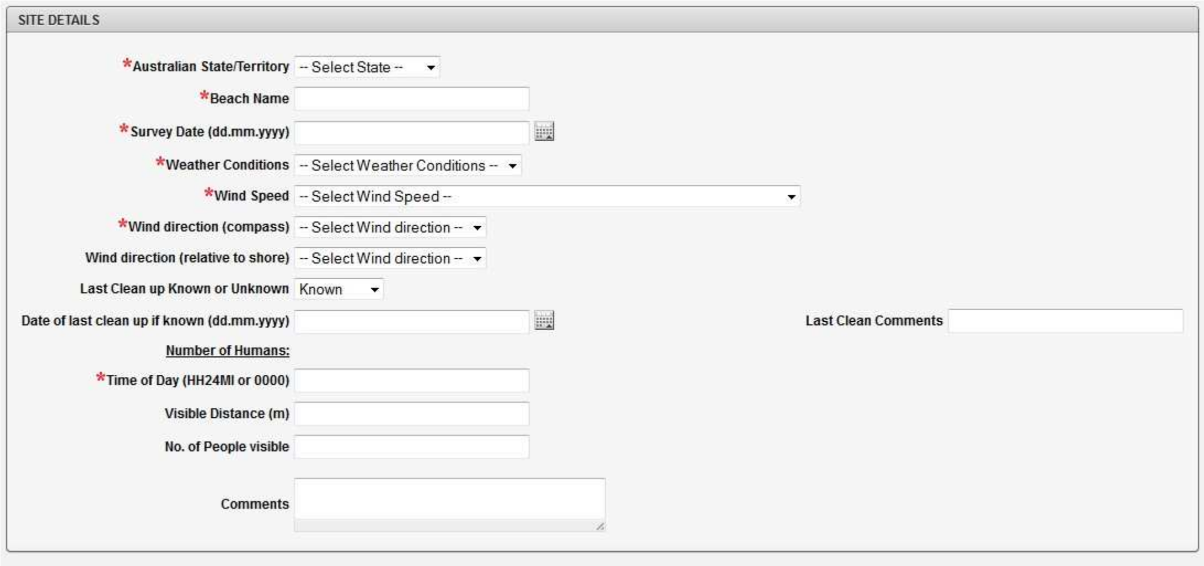
2) Click on the “Transect Survey” button.



3) Enter in the 'surveyor details', these are the same details as can be found on your 'Marine Debris Beach Survey' data sheets. NOTE: The "latitude (Decimal Degrees)" field must be negative (e.g. -35.12546).



4) Enter in the 'site details' as required, these are the same details found on your 'Marine Debris Beach Survey' data sheets.



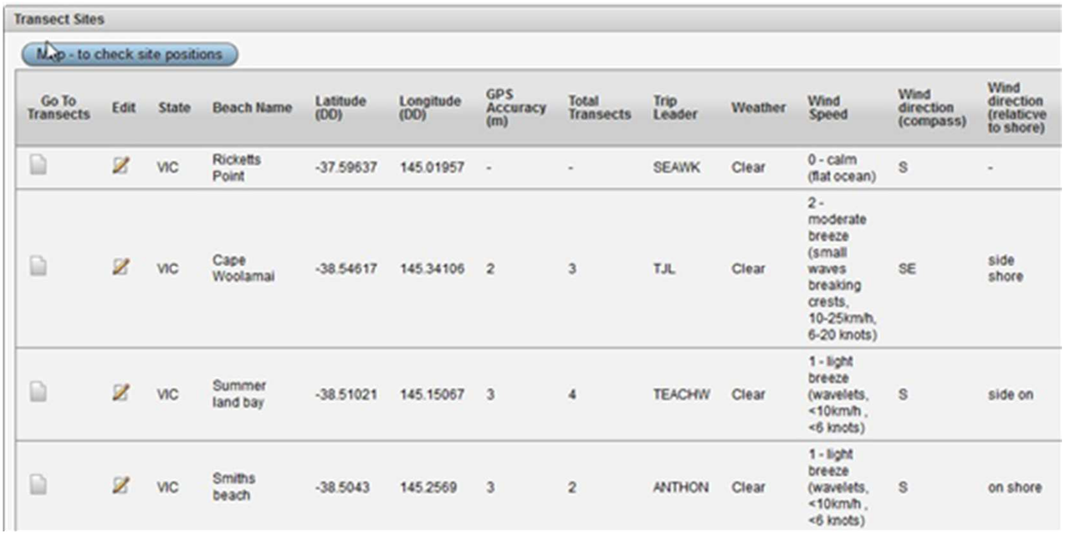
SITE DETAILS

*Australian State/Territory	-- Select State --
*Beach Name	
*Survey Date (dd.mm.yyyy)	
*Weather Conditions	-- Select Weather Conditions --
*Wind Speed	-- Select Wind Speed --
*Wind direction (compass)	-- Select Wind direction --
Wind direction (relative to shore)	-- Select Wind direction --
Last Clean up Known or Unknown	Known
Date of last clean up if known (dd.mm.yyyy)	
Last Clean Comments	
Number of Humans:	
*Time of Day (HH24MI or 0000)	
Visible Distance (m)	
No. of People visible	
Comments	

5) Click either the "save" or "save and load photos" button –

   a. If you clicked the "save and load photos" button, enter in a description such as 'beach looking north' then navigate to where your photo is stored, click on it then press the "upload" button. The screen will come up with an 'action processed' box (this means your data has been uploaded and you can load subsequent photos) then you will need to press the "cancel" button to get back to your site to enter transect details.

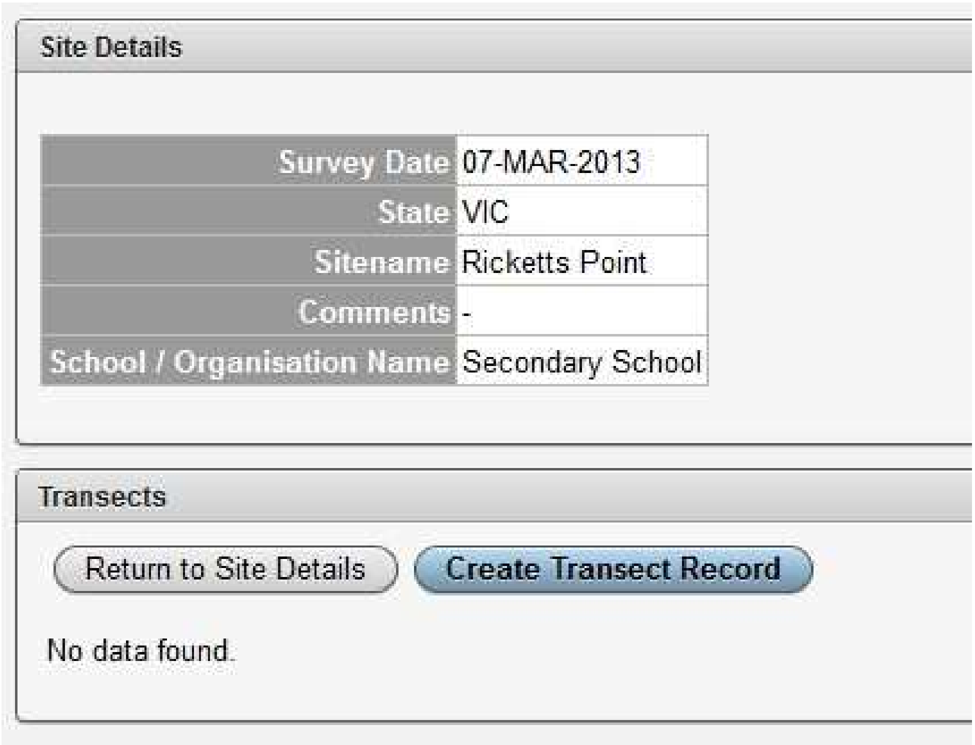
   b. Clicking "save" will take you back to the front screen where you can now enter your transect data.


Transect Sites

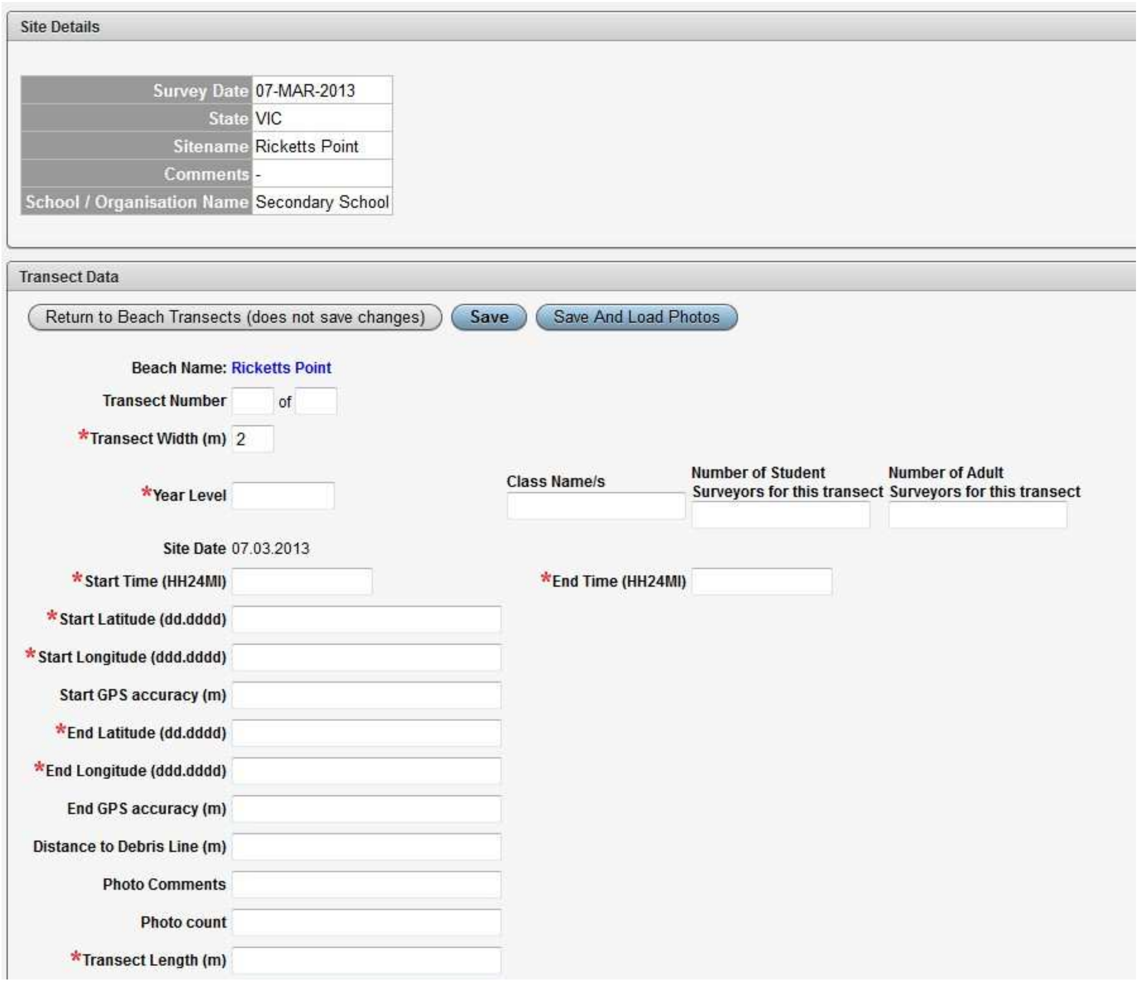
Map - to check site positions

Go To Transects	Edit	State	Beach Name	Latitude (DD)	Longitude (DD)	GPS Accuracy (m)	Total Transects	Trip Leader	Weather	Wind Speed	Wind direction (compass)	Wind direction (relaticve to shore)
		VIC	Ricketts Point	-37.59637	145.01957	-	-	SEAWK	Clear	0 - calm (flat ocean)	S	-
		VIC	Cape Woolamai	-38.54617	145.34106	2	3	TJL	Clear	2 - moderate breeze (small waves breaking crests, 10-25km/h, 6-20 knots)	SE	side shore
		VIC	Summer land bay	-38.51021	145.15067	3	4	TEACHW	Clear	1 - light breeze (wavelets, <10km/h , <6 knots)	S	side on
		VIC	Smiths beach	-38.5043	145.2569	3	2	ANTHON	Clear	1 - light breeze (wavelets, <10km/h , <6 knots)	S	on shore

6) To enter transect details, click on the  icon under 'go to transects', and then click on the "Create Transect Record" button.


Site Details
Survey Date 07-MAR-2013
State VIC
Sitename Ricketts Point
Comments -
School / Organisation Name Secondary School
Transects
Return to Site Details
Create Transect Record
No data found.

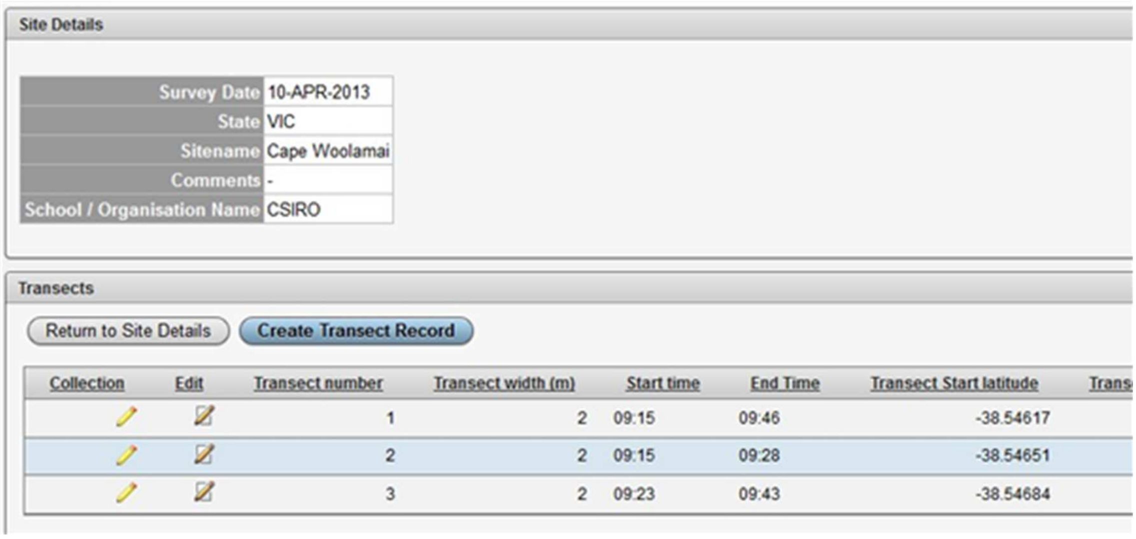
7) Enter in all the 'transect data' noting that these are the same details on your "Transect Data" data sheet. NOTE: Again the "latitude (Decimal Degrees)" must be negative (e.g. -35.12546).



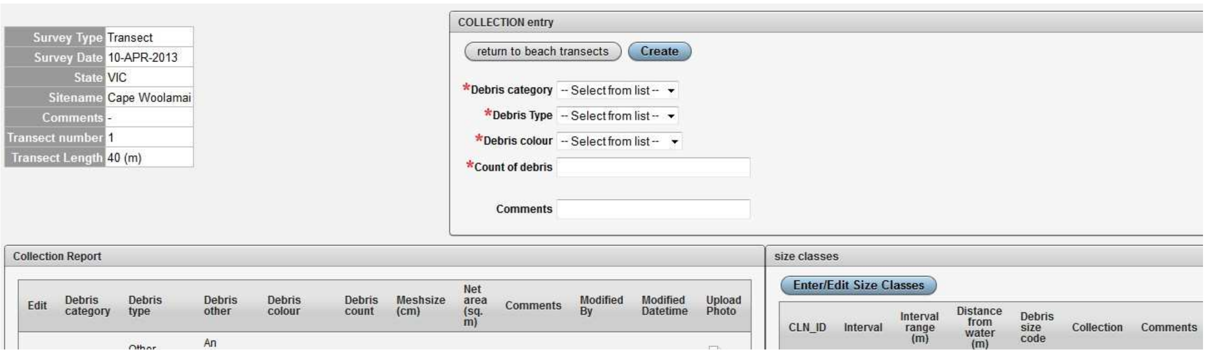
8) Click either the "save" or "save and load photos" button –

   a. If you clicked the "save and load photos" button, do the same steps as you did previously.

   b. Clicking "save" will take you back to the transect data screen where you can enter your collection data.



9) To enter your collection data, click on the  icon under 'collection', then enter all your data using the "create" button once you have entered in the debris category, type, color and number.



10) Click on the "enter/edit size classes" button, click on the "add ten rows" button and enter your size class data.

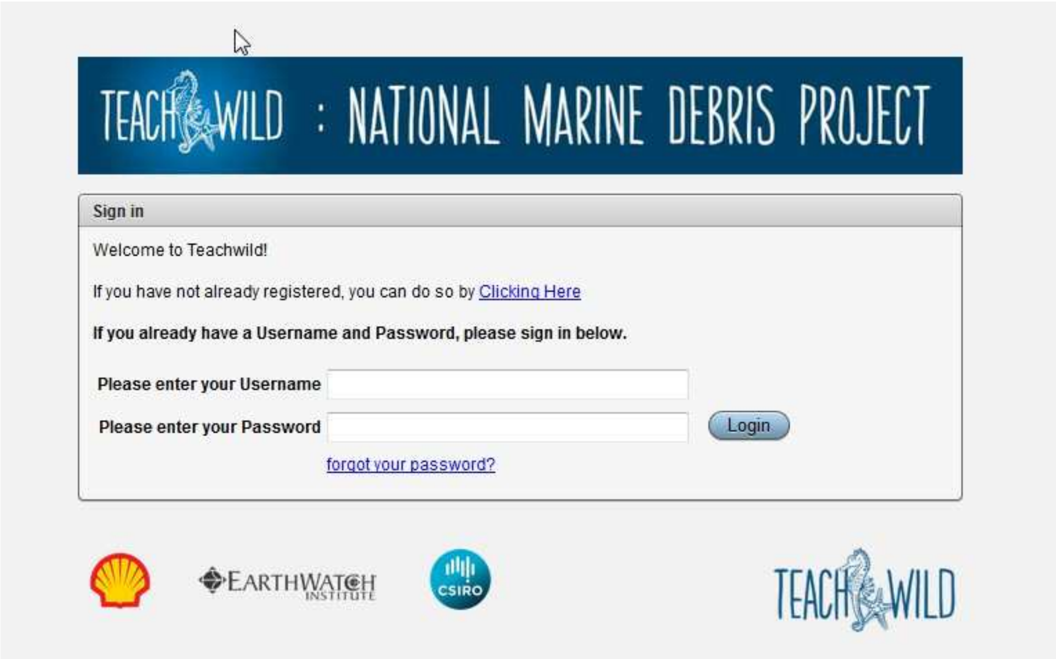
Repeat steps 6 to 10 for each transect.

Appendix F. Instructions for data entry with updated data portal (Emu parade). TeachWild: National Marine Debris Project

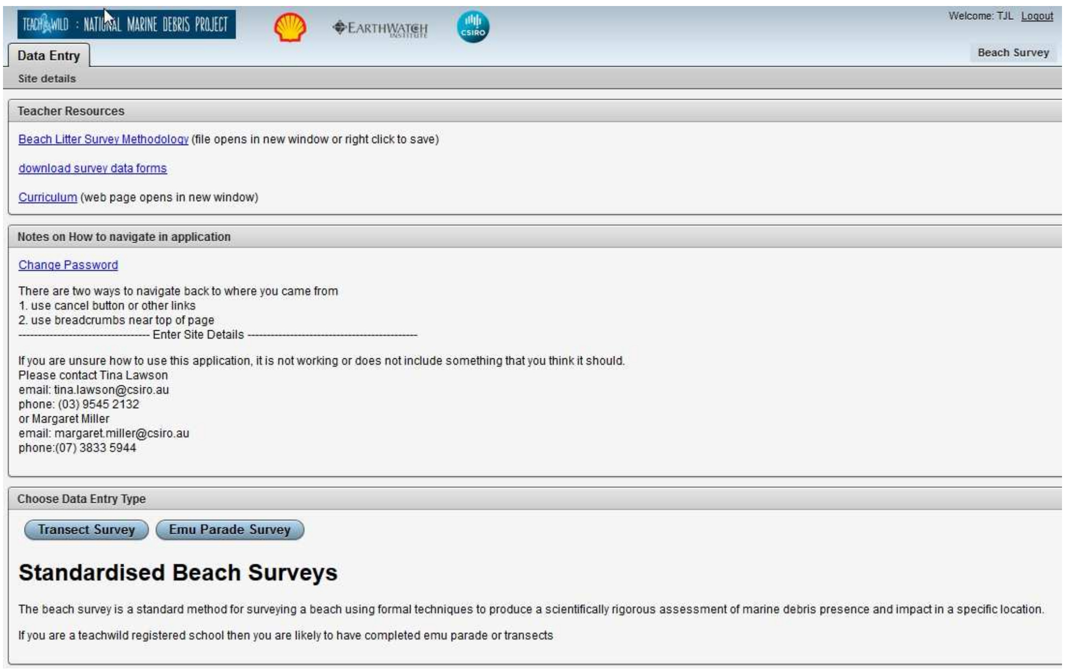
Database instructions: Emu Parade

To enter data, you first need to be registered.

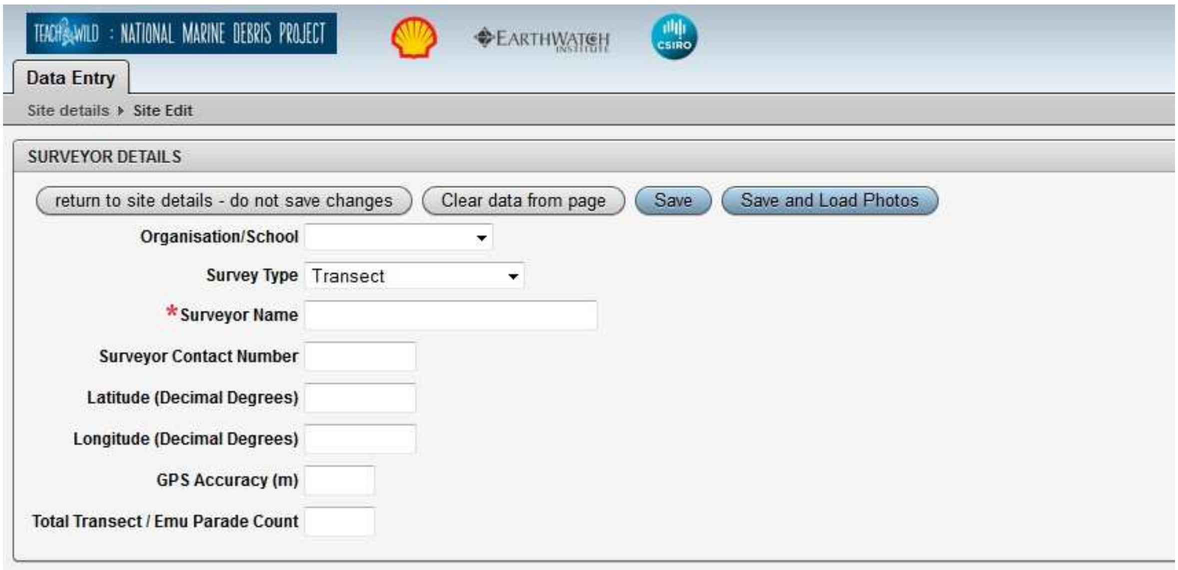
1) Enter your username and password, press the "Login" button.



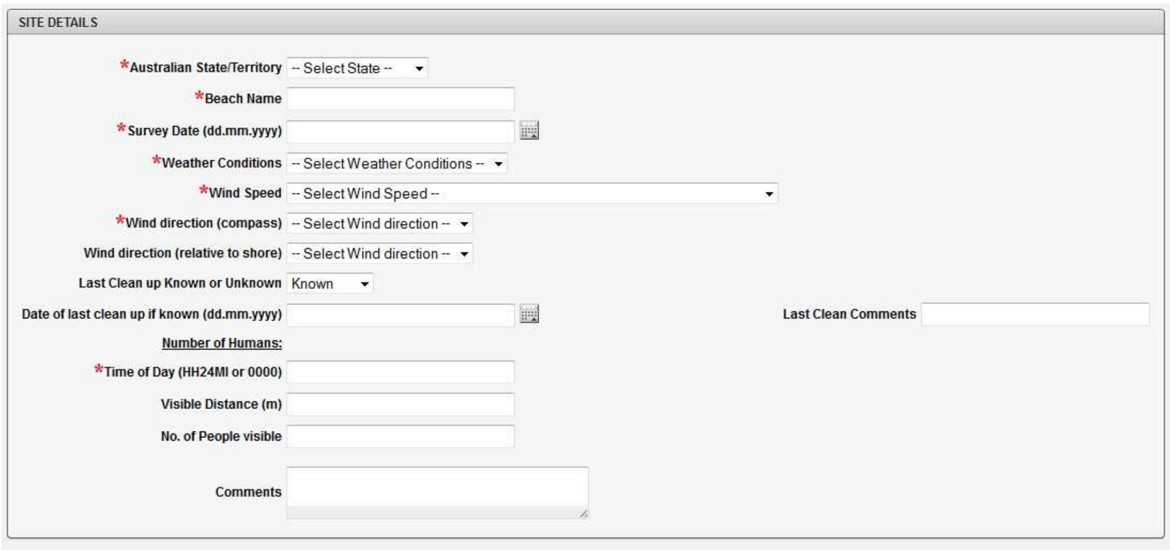
2) Click on the "Emu Parade Survey" button.



3) Enter in the 'surveyor details', these are the same details as can be found on your "Marine Debris Beach Survey" data sheets. NOTE: The "latitude (Decimal Degrees) must be negative (e.g. -35.12546).



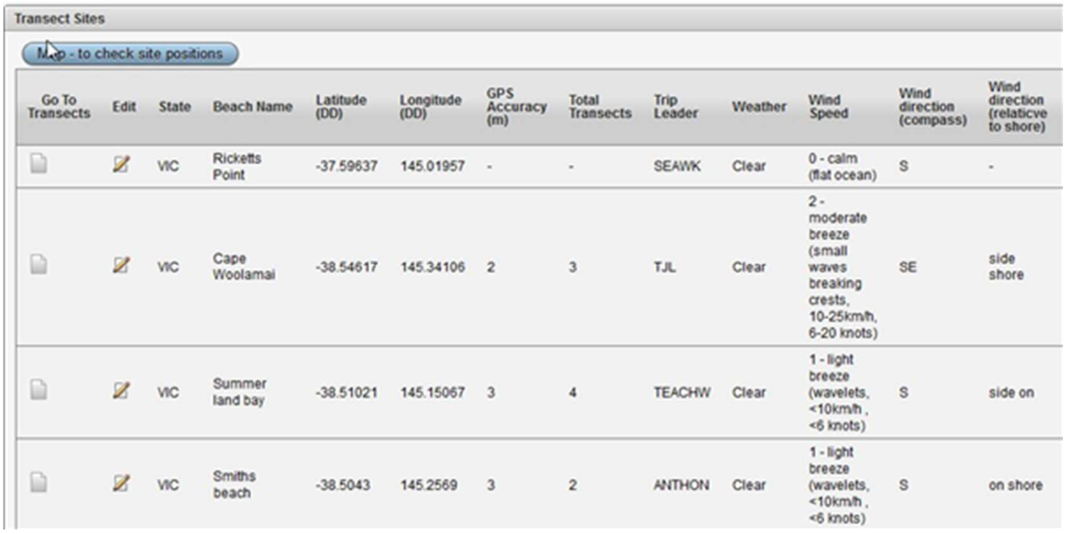
4) Enter in the 'site details' as required, these are the same details as can be found on your "Marine Debris Beach Survey" data sheets.



5) Click either the "save" or "save and load photos" button –

a. If you clicked the “save and load photos” button, enter in a description such as ‘beach looking north’ then navigate to where your photo is stored, click on it then press the “upload” button. The screen will come up with an “action processed” box and you will then need to press the “cancel” button to get back to your site to enter transect details.

6) Clicking “save” will take you back to the front screen where you can now enter your transect data.

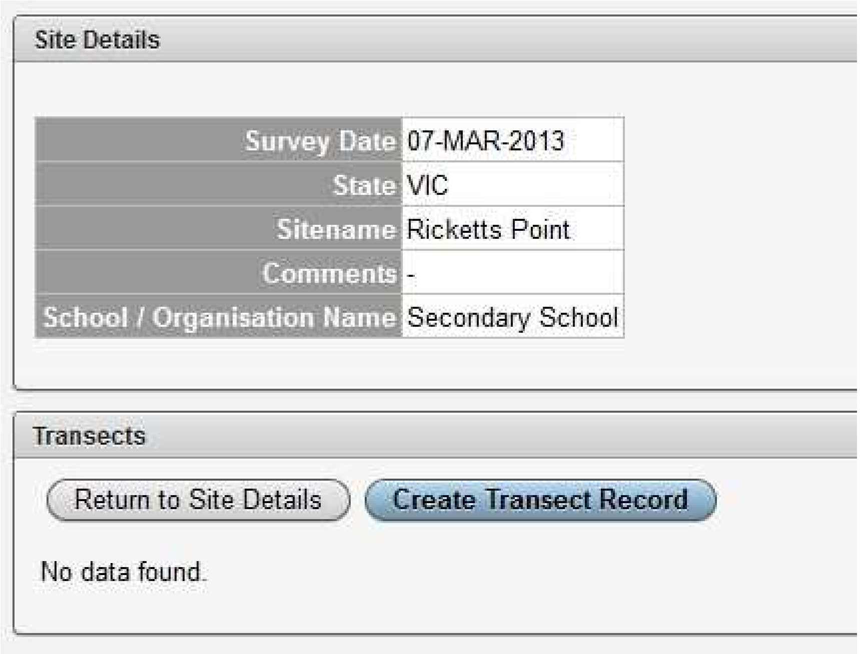


Transect Sites

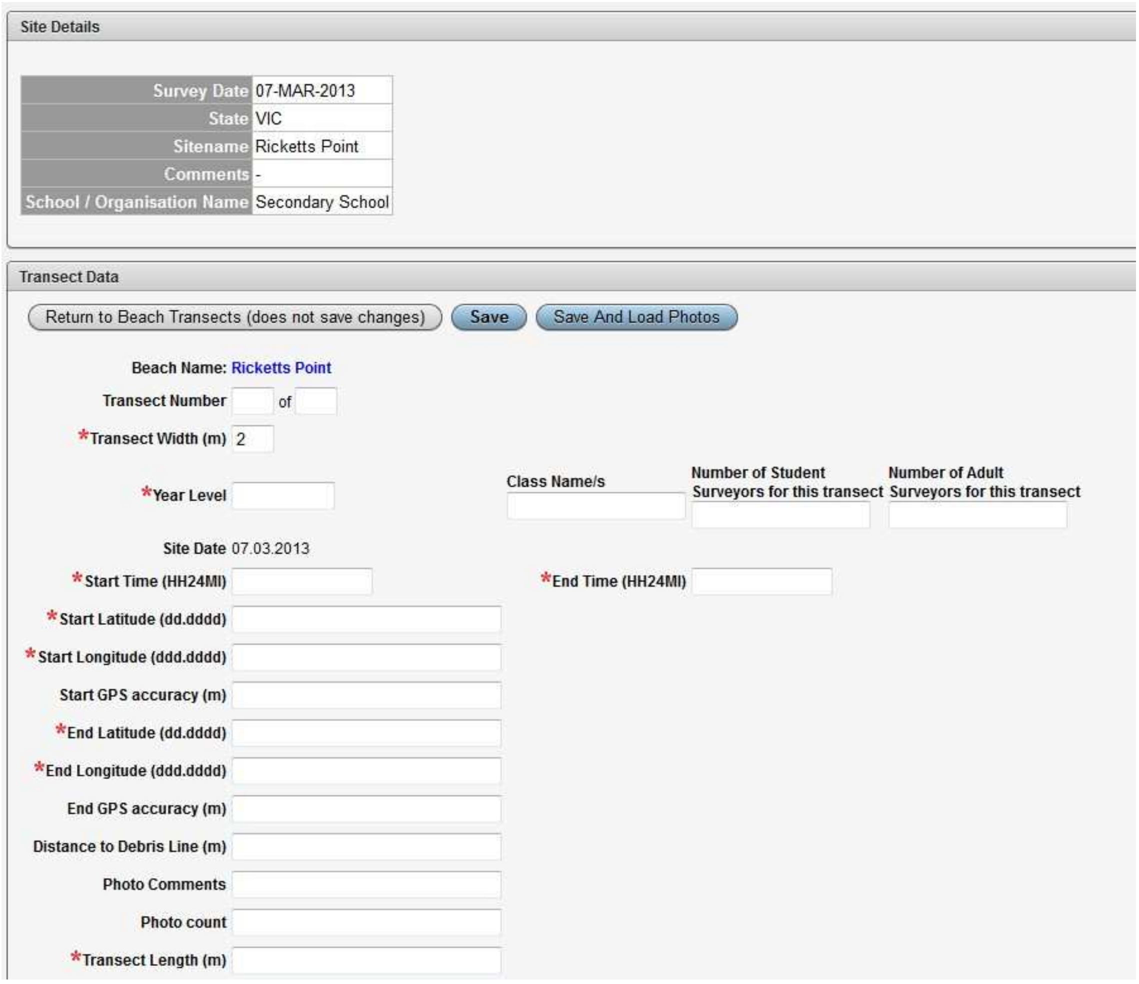
Map - to check site positions

Go To Transects	Edit	State	Beach Name	Latitude (DD)	Longitude (DD)	GPS Accuracy (m)	Total Transects	Trip Leader	Weather	Wind Speed	Wind direction (compass)	Wind direction (relaticve to shore)
		VIC	Ricketts Point	-37.59637	145.01957	-	-	SEAWK	Clear	0 - calm (flat ocean)	S	-
		VIC	Cape Woolamai	-38.54617	145.34106	2	3	TJL	Clear	2 - moderate breeze (small waves breaking crests, 10-25km/h, 6-20 knots)	SE	side shore
		VIC	Summer land bay	-38.51021	145.15067	3	4	TEACHW	Clear	1 - light breeze (wavelets, <10km/h , <6 knots)	S	side on
		VIC	Smiths beach	-38.5043	145.2569	3	2	ANTHON	Clear	1 - light breeze (wavelets, <10km/h , <6 knots)	S	on shore

7) To enter transect data, click on the  icon under ‘go to transects’, and then click on the “create Transect Record” button.


Site Details
Survey Date 07-MAR-2013
State VIC
Sitename Ricketts Point
Comments -
School / Organisation Name Secondary School
Transects
Return to Site Details
Create Transect Record
No data found.

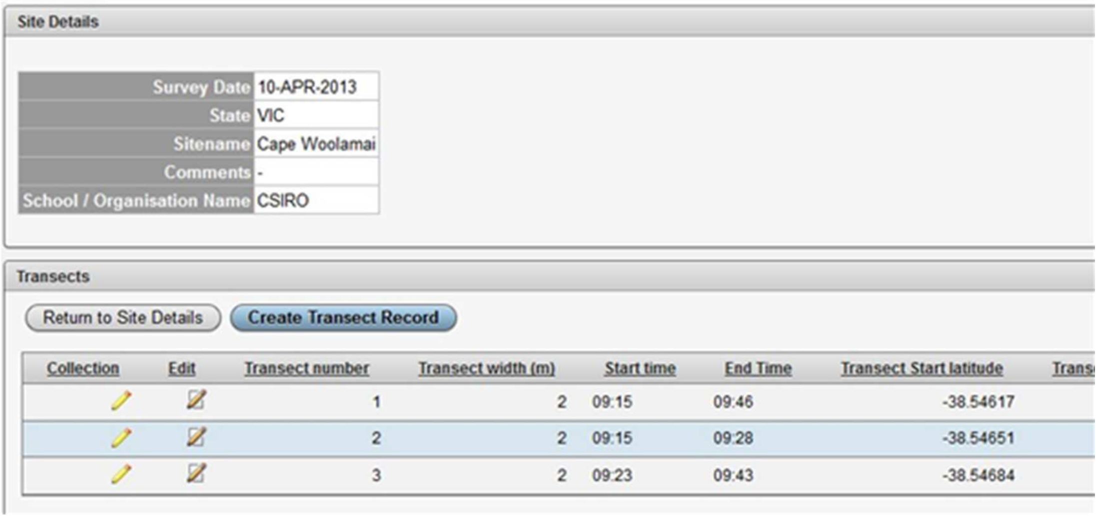
8) Enter in all the 'transect details' noting that these are the same details on your "Transect Data" data sheet. NOTE: Again the "latitude (Decimal Degrees) must be negative (e.g. -35.12546).



9) Click either the "save" or "save and load photos" button –

   a. If you clicked the "save and load photos" button, do the same steps as you did previously.

   b. Clicking "save" will take you back to the transect data screen where you can enter your collection data.



Site Details

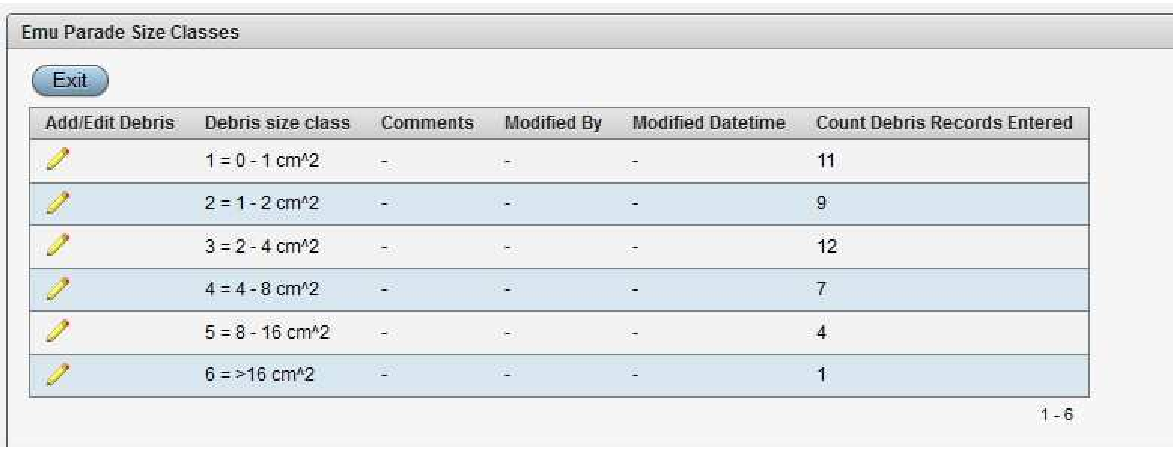
Survey Date	10-APR-2013
State	VIC
Sitename	Cape Woolamai
Comments	-
School / Organisation Name	CSIRO

Transects

Return to Site Details | Create Transect Record

Collection	Edit	Transect number	Transect width (m)	Start time	End Time	Transect Start latitude	Trans
		1	2	09:15	09:46	-38.54617	
		2	2	09:15	09:28	-38.54651	
		3	2	09:23	09:43	-38.54684	

10) To enter your collection data, click on the  icon under 'emu parade', then click on the same icon next to the size category you want to enter.



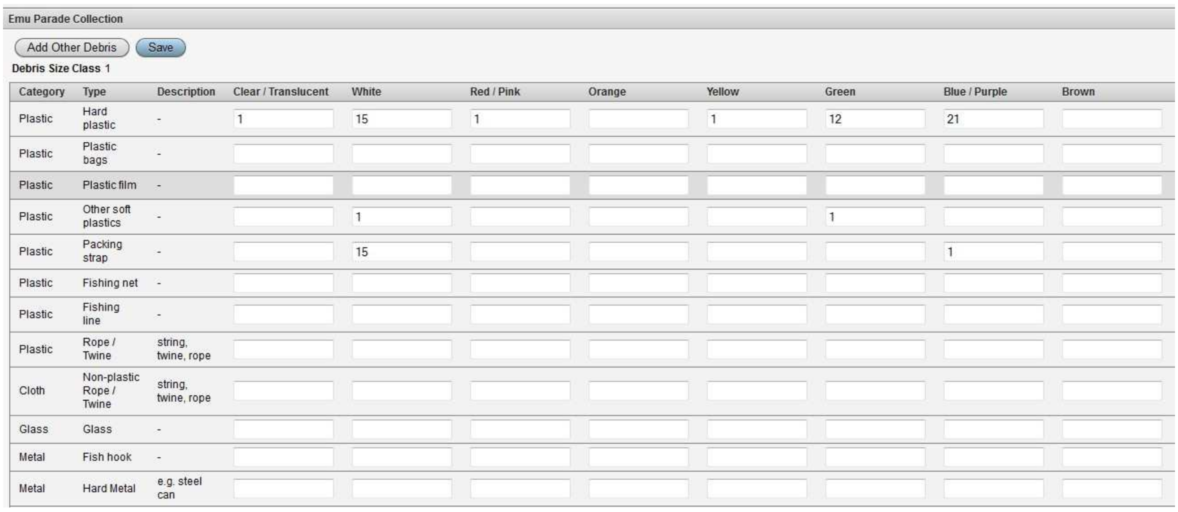
Emu Parade Size Classes

Exit

Add/Edit Debris	Debris size class	Comments	Modified By	Modified Datetime	Count Debris Records Entered
	1 = 0 - 1 cm^2	-	-	-	11
	2 = 1 - 2 cm^2	-	-	-	9
	3 = 2 - 4 cm^2	-	-	-	12
	4 = 4 - 8 cm^2	-	-	-	7
	5 = 8 - 16 cm^2	-	-	-	4
	6 = >16 cm^2	-	-	-	1

1 - 6

11) Simply enter the number of items you collected in that size category for that type/color of debris.



Emu Parade Collection

Add Other Debris | Save

Debris Size Class 1

Category	Type	Description	Clear / Translucent	White	Red / Pink	Orange	Yellow	Green	Blue / Purple	Brown
Plastic	Hard plastic	-	1	15	1		1	12	21	
Plastic	Plastic bags	-								
Plastic	Plastic film	-								
Plastic	Other soft plastics	-		1				1		
Plastic	Packing strap	-		15					1	
Plastic	Fishing net	-								
Plastic	Fishing line	-								
Plastic	Rope / Twine	string, twine, rope								
Cloth	Non-plastic Rope / Twine	string, twine, rope								
Glass	Glass	-								
Metal	Fish hook	-								
Metal	Hard Metal	e.g. steel can								

12) Repeat steps 6 to 10 for each emu parade.

Appendix G. Marine Plastic Pollution in waters around Australia: Characteristics, Concentrations, and Pathways, PLOS One 2013

OPEN ACCESS Freely available online PLOS | ONE

Marine Plastic Pollution in Waters around Australia: Characteristics, Concentrations, and Pathways

Julia Reisser[1,2,3*], Jeremy Shaw[4], Chris Wilcox[3,5], Britta Denise Hardesty[3,5], Maira Proietti[6], Michele Thums[1,2,7], Charitha Pattiaratchi[1,2]

1 School of Environmental Systems Engineering, University of Western Australia, Perth, Western Australia, Australia, **2** Oceans Institute, University of Western Australia, Perth, Western Australia, Australia, **3** Wealth from Oceans Flagship, Commonwealth Scientific and Industrial Research Organisation, Floreat, Western Australia, Australia, **4** Centre for Microscopy, Characterisation and Analysis, University of Western Australia, Perth, Western Australia, Australia, **5** Marine and Atmospheric Research, Commonwealth Scientific and Industrial Research Organisation, Hobart, Tasmania, Australia, **6** Instituto de Oceanografia, Universidade Federal do Rio Grande, Rio Grande, Rio Grande do Sul, Brazil, **7** Australian Institute of Marine Science, Perth, Western Australia, Australia

Abstract

Plastics represent the vast majority of human-made debris present in the oceans. However, their characteristics, accumulation zones, and transport pathways remain poorly assessed. We characterised and estimated the concentration of marine plastics in waters around Australia using surface net tows, and inferred their potential pathways using particle-tracking models and real drifter trajectories. The 839 marine plastics recorded were predominantly small fragments ("microplastics", median length = 2.8 mm, mean length = 4.9 mm) resulting from the breakdown of larger objects made of polyethylene and polypropylene (e.g. packaging and fishing items). Mean sea surface plastic concentration was 4256.4 pieces km^{-2}, and after incorporating the effect of vertical wind mixing, this value increased to 8966.3 pieces km^{-2}. These plastics appear to be associated with a wide range of ocean currents that connect the sampled sites to their international and domestic sources, including populated areas of Australia's east coast. This study shows that plastic contamination levels in surface waters of Australia are similar to those in the Caribbean Sea and Gulf of Maine, but considerably lower than those found in the subtropical gyres and Mediterranean Sea. Microplastics such as the ones described here have the potential to affect organisms ranging from megafauna to small fish and zooplankton.

Citation: Reisser J, Shaw J, Wilcox C, Hardesty BD, Proietti M, et al. (2013) Marine Plastic Pollution in Waters around Australia: Characteristics, Concentrations, and Pathways. PLoS ONE 8(11): e80466. doi:10.1371/journal.pone.0080466

Editor: Graeme Clive Hays, University of Wales Swansea, United Kingdom

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Competing Interests: The authors have the following interests. This study was partly funded by Austral Fisheries and the Shell social investment program. There are no patents, products in development or marketed products to declare. This does not alter their adherence to all the PLOS ONE policies on sharing data and materials, as detailed online in the guide for authors.

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Introduction

Plastics are a diverse group of materials derived from petrochemicals [1]. Their global production has grown exponentially from 1,700,000 tonnes in 1950 to 280,000,000 tonnes in 2011 [2]. The disposability of plastics, together with their low recycling rates, has contributed to a significant rise in the amount of waste produced globally [3]. For instance, in Australia, 1,433,046 tonnes of plastics were used in 2010–2011, of which only 20% was recycled. Moreover, around 37% of this plastic was for the manufacturing of single-use disposable packaging [4]. Plastics are transported from populated areas to the marine environment by rivers, wind, tides, rainwater, storm drains, sewage disposal, and even flood events. It can also reach the sea from vessels (e.g. fishing gear) and offshore installations [5]. Once in the oceans, they will either float at the ocean surface, or sink to the seafloor if made from polymers denser than seawater [6]. Buoyant plastics may be cast ashore by inshore currents or winds [7], or may enter the open ocean, where they tend to accumulate in convergence zones such as the ones formed by the five large-scale gyres (South and North Pacific, South and North Atlantic, and Indian [8–10]).

Marine plastics are known to undergo fragmentation into increasingly smaller pieces by photochemical, mechanical and biological processes [6,11]. Plastics are also directly manufactured in small sizes (<5mm), which may find their way into the oceans. These include virgin plastic pellets (pelletwatch.org; [12]), synthetic fibers from clothes [13], micro beads from cosmetics [14], and synthetic 'sandblasting' media [6]. There is increasing awareness that these small plastic particles (often called microplastics when smaller than 5 mm [6]) represent a significant proportion of the human-made debris present in the oceans. However, their at-sea spatial and temporal dynamics remain poorly assessed, mostly due to a lack of data on their characteristics and at-sea occurrence [15,16]. In Australia, the only published information on microplastics comes from a global study that recorded their occurrence in the sediments of Busselton beach (Western Australia) and Port Douglas (Queensland) [13]. Apart from this, our current knowledge on plastic contamination in the Australian marine environment is restricted to (1) beach litter cleanups that record mainly the occurrence of relatively large objects (e.g. [17–19]), (2) land-based surveys of marine megafauna impacted by marine debris (e.g. [17,20–22]), and (3) inferences based on plastic pollution reports from New Zealand (e.g. [23]).

The impacts of plastics on marine vertebrates, such as turtles, mammals and birds, have been well recognized since the 80's [24,25]. However, only recently has concern about the effects of small plastic particles on food webs and marine ecosystems been raised. More than half of modern plastics contain at least one hazardous ingredient [26] and those that end up in aquatic systems can become increasingly toxic by adsorbing persistent organic pollutants on their surface [27]. These concentrated toxins might then be delivered to animals via plastic ingestion and/or endocytosis [28,29] and transferred up their food webs [30–32]. This bio-magnification process is more likely to happen when plastics are small enough to be ingested by organisms that are close to the bottom of the ocean food web, such as planktivorous fish [33] and zooplankton [34]. For instance, it was inferred that small plastic particles found in the stomach contents of Southern Bluefin tuna captured close to Tasmania [35] were coming from the guts of their prey: myctophid fish [36]. In this scenario, plastic contaminants can be transferred to the affected organism and then biomagnified up the food chain. If this process is taking place, plastics can affect the health of food webs, which include humans as an apex predator.

Australia's acknowledgement of plastic threats to marine ecosystems is mostly limited to impacts from relatively large debris (e.g. abandoned fishing nets, plastic bags) on marine megafauna (e.g. turtles, mammals, birds) [37]. A first step towards a better understanding of the extent of marine plastic hazards to Australian organisms and environments is a better assessment of the occurrence and characteristics of plastic debris at-sea. To this end, we characterized (size, type, color, polymer) and estimated concentration (pieces km^{-2}) of plastics in waters around Australia using surface net tows. Additionally, potential pathways taken by the collected plastics were inferred using outputs of a dispersal model and trajectories of satellite-tracked drifting buoys.

Materials and Methods

Ethics Statement

Permits to conduct this field research were obtained from the Great Barrier Reef Marine Park Authority (GBRMPA: permit G11/34378.1). No other special permitting was required because sampling was limited to the collection of marine debris.

During seven transit voyages aboard Australian vessels (Figure 1), we undertook three consecutive 15-minute net tows (mean ± standard deviation tow length = 1.3±0.50 km) at 57 locations (hereafter called "net stations"), while the ship was travelling at a speed of 2 – 4 knots. These net tows sampled the air-sea interface, using a Neuston net (1.2×0.6 m mouth, 335 µm mesh) or a Manta net (1×0.17 m mouth, 333 µm mesh). After each net tow, the collected material was transferred to a container filled with seawater and examined for floating plastic pieces for at least an hour by a trained observer (J.R.). Each plastic piece was picked up with forceps and placed in a graduated dish to be counted, measured (length), photographed and classified into type (hard, soft, line, expanded polystyrene, pellet), and color. A random sample of 200 plastic pieces was selected for polymer composition analysis by Fourier transform infrared spectrometry (FT-IR; range = 500 – 4000 cm^{-1}). Polymer type was determined by comparing sample FT-IR spectra against known spectra from a database (Perkin-Elmer ATR of Polymers Library).

To estimate sea surface plastic concentrations (Cs, pieces km^{-2}), we first divided the number of plastic pieces found in the cod-end of each net tow by its towed area, which was estimated by multiplying net mouth width by tow length (determined from GPS position data). Mean Cs was then estimated for each of the 57 net stations by averaging the Cs of its three net tows. To our knowledge, this is the first study to take net tow replicates for marine plastic sampling. Apart from providing us measurements of Cs variability, our approach (i.e. execution of 3 short net tows instead of 1 long trawl) also avoided net clogging by gelatinous zooplankton.

Since buoyant plastics are vertically distributed due to wind-driven mixing, we also estimated depth-integrated plastic concentrations (Ci, pieces km^{-2}) by applying a one-dimensional column model [15]:

$$C_i = \frac{C_s}{1 - e^{-d w_b A_O^{-1}}}$$

Where:

d = immersion depth of the surface-towed net; equal to 0.17 m for the Manta net tows (full immersion of the net frame) and 0.3 m for the Neuston net tows (half of the frame immersed).

w_b = buoyant rise velocity of marine plastics; equal to 0.02 m s^{-1}. Preliminary experiments indicate that it ranges from 0.005 – 0.035 m s^{-1} [15].

A_o = near-surface turbulent (eddy) exchange coefficient, which was estimated by:

$$A_O = 1.5 u_{*w} k H_s$$

Where:

k = von Karman constant; equal to 0.4.

H_s = significant wave height (m).

u_{*w} = frictional velocity of water (m s^{-1}).

Both H_s and u_{*w} were taken from the ERA-Interim model [38]. There was a considerable similarity between wind fields of the ERA-Interim forecast model (U_{10}) and the wind speed measured by an anemometer (w) on five of our seven voyages (U_{10} = 0.85+1.04w, r^2 = 0.79, N = 39 net stations), indicating that the use of the model outputs is adequate.

To infer potential pathways taken by the collected plastics, we used two approaches: (1) application of the Australian Connectivity Interface Connie2 (csiro.au/connie2), and (2) trajectories of satellite-tracked buoys from the Global Drifter Program (aoml.-noaa.gov/phod/dac). In our first approach, an area of 0.1° latitude by 0.1° longitude was created around each net station and particle-tracking models were run backwards in time. Particles were released within these areas over a 30-day period (25 particles per day), and subsequently tracked for a dispersal time equal to 45 days. These models were forced by averaged ocean current fields (2002 – 2006) of the month when the net station was sampled. Details of the particle tracking model, and the eddy-resolving/data-assimilating ocean general circulation model can be found in [39] and [40], respectively. In our second approach, an area of 4° latitude by 4° longitude was centered on each net station and drifters (drogued and un-drogued) that reached these regions were selected. The tracks starting from the drifter release point until they entered one of the net station areas were then plotted onto maps.

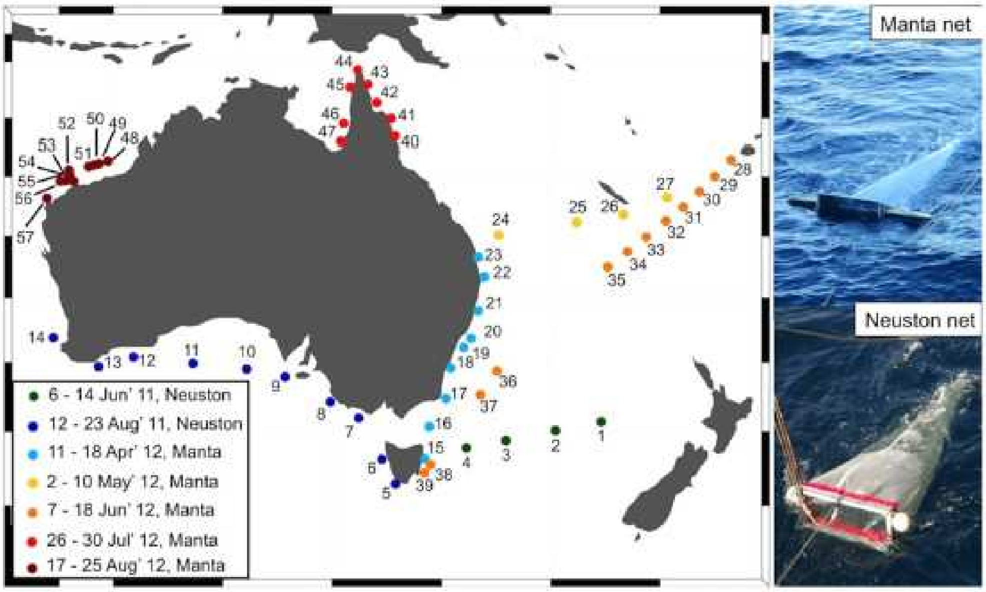

Figure 1. Location of the 57 net stations sampled during this study. Dot colors indicate the voyage when the net station was sampled and numbers follow the chronological order of sampling. Pictures of the two types of net used are shown in the right panel.
doi:10.1371/journal.pone.0080466.g001

Results

We recorded 839 pieces of plastic, ranging in length from 0.4 to 82.6 mm (median = 2.8 mm, mean ± standard error = 4.9±0.27 mm, Figure 2). The majority of these plastic pieces had low circularity in their shape when compared to manufactured plastic particles (e.g. pellets and microbeads from cosmetics), suggesting they mostly resulted from the breakdown of larger items. The main plastic type was hard plastic (N = 633, median length = 2.4 mm, range = 0.7 – 57.0 mm) followed by soft plastic (N = 142, median length = 5.0 mm, range = 0.5 – 73.0 mm), plastic line (N = 54, median length = 10.3 mm, range = 2.0 – 82.6 mm), expanded polystyrene (N = 8, median length = 2.9 mm, range = 1.3 – 24.3 mm), and pellet (N = 2, both 4 mm). Most plastics were white/transparent (84.7%), but blue (8.3%) and other colors (7%) were also present. Of the 200 pieces subjected to FT-IR, 67.5% were made of polyethylene, 31% of polypropylene, 1% of expanded polystyrene, and 0.5% of ethylene vinyl acetate (Figure 3).

Approximately 80% of our net tows (136 out of 171), and 93% of our net stations (53 out of 57), had at least one piece of plastic (range: 0 – 68, median = 2, mean ± standard error = 4.9±0.63 pieces per net tow). Estimated sea surface plastic concentrations (C_s) for each net tow ranged from 0 to 48895.6 pieces km^{-2} (median = 1932.1 pieces km^{-2}, mean ± standard error = 4256.4±757.79 pieces km^{-2}) and the mean C_s of net stations varied between 0 and 23610.7 pieces km^{-2} (Figure 4, Table S1).

Relatively high mean C_s (>15500 pieces km^{-2}) were estimated only at low wind speeds (<7 m s^{-1}, Figure 5a). There was an inverse relationship between C_s and wind forcing ($b = -0.77$ in $C_s = a(u_{*w})^b$), which was relatively consistent with the biophysical model applied here (Figure 5b). When taking into account the effect of wind-mixing, net tow plastic concentrations increased by a mean factor of 2.8 (range: 1.04 – 10.0, median = 1.9). Hence, the amount of plastics collected by our net tows (C_s) represents anywhere between 10.0% and 96.1% (median = 52.7%, mean ± standard deviation = 50.0±24.47%) of the estimated total amount of plastic present in the water column (C_i, Figure 6).

Depth-integrated plastic concentration estimates (C_i) for each net tow ranged from 0 to 105438.6 pieces km^{-2} (median = 4363.7 pieces km^{-2}, mean ± standard error = 8966.3±1330.75 pieces km^{-2}) and the mean C_i of net stations ranged from 0 to 43194.5 pieces km^{-2} (Figure 7). In this scenario, plastic concentrations higher than 15500 pieces km^{-2} (red dots) were quite common, and those higher than 31500 pieces km^{-2} (dark red dots) were found close to populated areas (Brisbane and Fiji) as well as in some remote coastal regions (southwest Tasmania) and oceanic areas (Figure 7).

A wide range of pathways was taken by the virtual particles arriving at the net stations (Figure 8 and Maps S1). The routes taken by real drifters, from their release points to the net stations, showed similar patterns but covered larger areas due to their longer drifting time and wider range of release date (Figure 9 and Maps S2).

Discussion

We found that the surface waters around Australia are contaminated with small plastics that are mostly a by-product of the degradation of larger objects made of polyethylene and polypropylene. The high prevalence of plastic fragments smaller than 5 mm in Australian waters is consistent with other regions of the world's oceans, where microplastics were found to be the most abundant type of debris in all types of marine environment [8–10,13,41,42]. Plastic pollution levels were moderate when compared to concentrations in other marine areas [8–10,43,44]. Higher amounts of plastic were found close to cities on Australia's

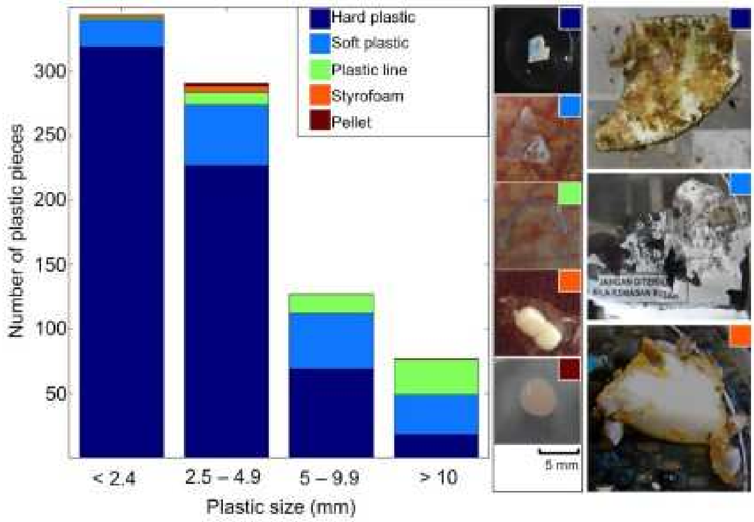

Figure 2. Size and types of marine plastics collected around Australia. Bars indicate the number of plastic pieces within each size category (<2.5, 2.5 – 4.9, 5 – 10, >10 mm) and colors show the amount of each plastic type within size categories. Examples of the types of plastic we collected are shown in the photos, including our biggest fragment of hard plastic (length = 57 mm, net station 32), soft plastic (length = 73 mm, net station 57, note the Indonesian words), and expanded polystyrene (Styrofoam cup fragment, length = 24.3 mm, net station 28).
doi:10.1371/journal.pone.0080466.g002

east coast, as well as in remote locations (west Tasmania and North West Shelf). Recent studies reported toxicological effects of these small and contaminated plastics on a host of organisms, including large marine vertebrates [45] and fish [30–32,46]. As such, small plastics are a type of harmful marine debris, implying

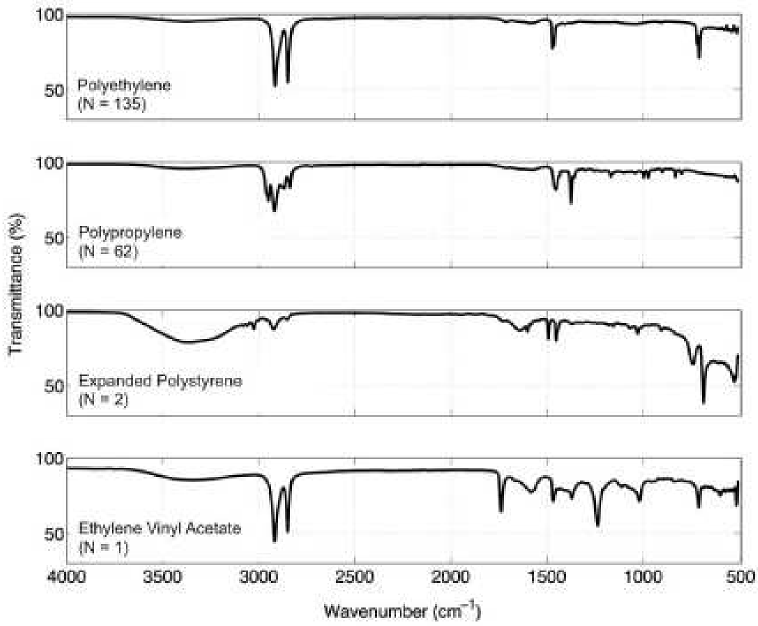

Figure 3. Mean infrared spectra of the plastic pieces within each polymer type.
doi:10.1371/journal.pone.0080466.g003

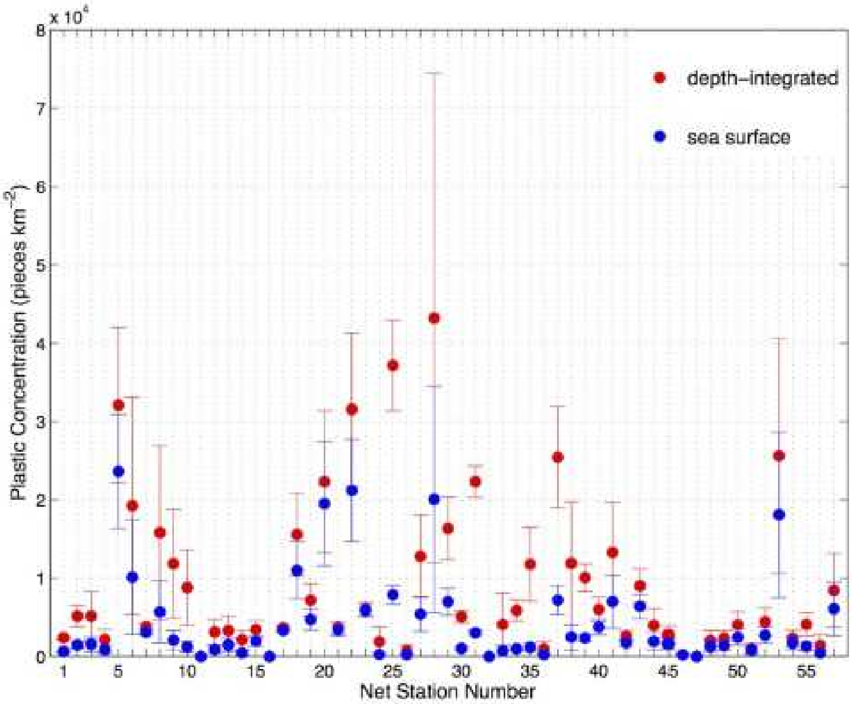

Figure 6. Mean and standard error of sea surface (*Cs*) and depth-integrated (*Ci*) plastic concentrations. Blue represents mean and standard error of *Cs* and red represents mean and standard error of *Ci*.
doi:10.1371/journal.pone.0080466.g006

plastic particles (micro and nanoparticles). In addition, post processing techniques for sorting particles are also likely to miss small fragments [47]. An example of a new method with the potential to eliminate this limitation is the application of molecular mapping by reflectance micro-FT-IR spectroscopy, which does

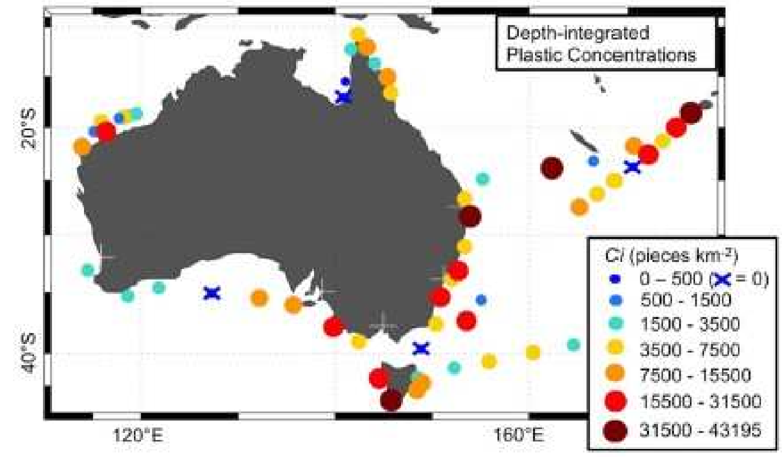

Figure 7. Mean depth-integrated plastic concentration (*Ci*) at the 57 net stations. White crosses indicate location of major Australian cities (population >1 million). From west to east: Perth, Adelaide, Melbourne, Sydney, and Brisbane.
doi:10.1371/journal.pone.0080466.g007

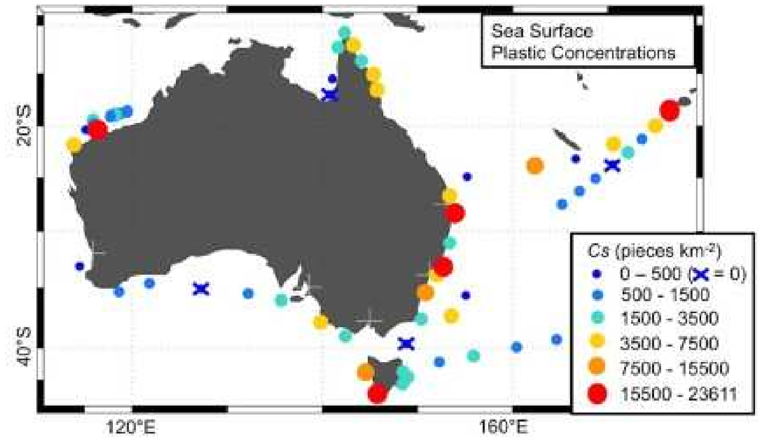

Figure 4. Mean sea surface plastic concentration (*Cs*) at the 57 net stations. White crosses indicate location of major Australian cities (population >1 million). From west to east: Perth, Adelaide, Melbourne, Sydney, and Brisbane.
doi:10.1371/journal.pone.0080466.g004

that plastic hazards to Australian species and ecological communities are likely to be broader than those officially recognized.

Characteristics of marine plastics

Captured plastic particles ranged in size from 0.4 – 82.6 mm. The frequency distribution of different sized plastics, which was skewed towards smaller particles, provides evidence for the existence of smaller plastics. Current methods for assessing plastic pollution at the ocean surface rely on the use of nets, which omits plastic particles outside the collectible range of their mesh [47]. It will be critical for future investigations to develop efficient and reproducible techniques capable of detecting smaller buoyant

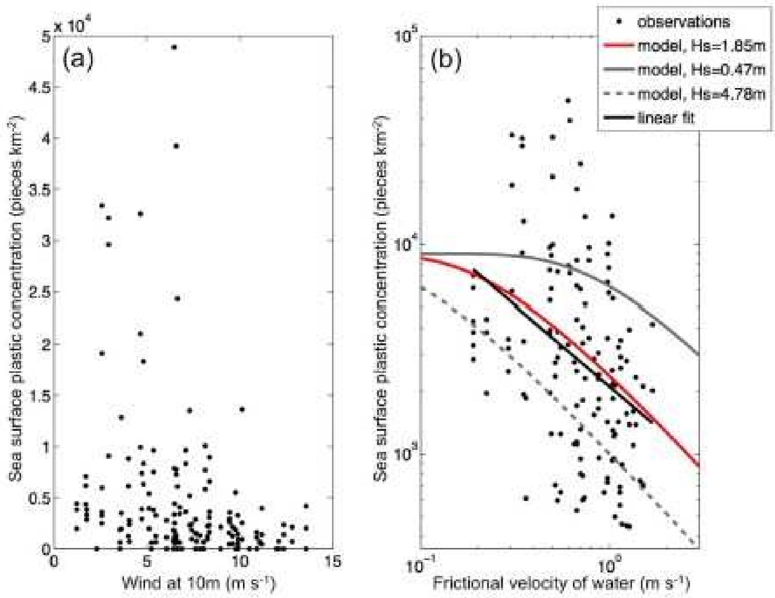

Figure 5. Sea surface plastic concentration (*Cs*) versus a) wind speed (U_{10}) and b) water friction velocity (u_{*w}). In (b) we also show the linear fit ($Cs = a\,(u_{*w})^{b}$) and theoretical model estimates for *Cs*, when depth-integrated plastic concentration (C_i) is equal to 8966 (mean *Ci* of the 171 net tows) and significant wave height (*Hs*) is equal to the mean (1.85 m), maximum (4.78 m) and minimum (0.47 m) values estimated for the 57 net stations.
doi:10.1371/journal.pone.0080466.g005

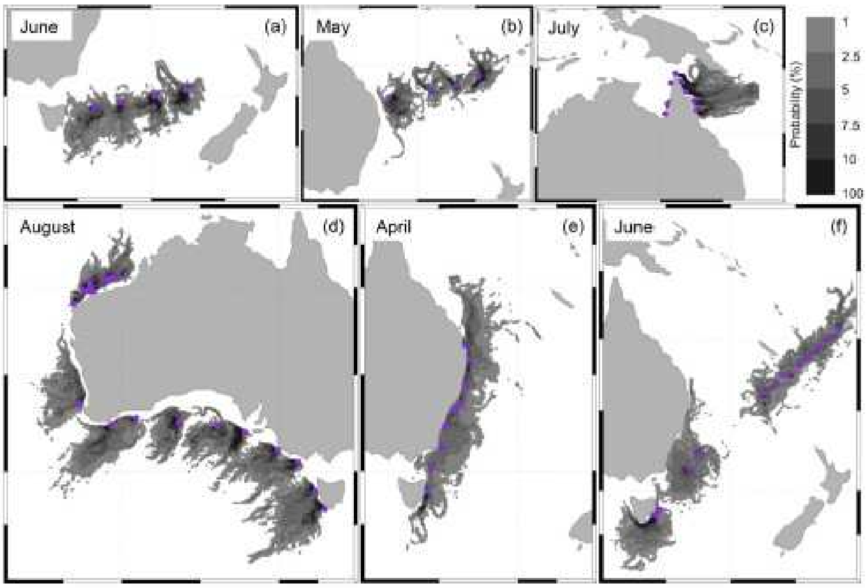

Figure 8. Cumulative probability distribution of virtual particles arriving at the 57 net stations. The month when the virtual particles (25 per day) were released is indicated in each panel. Backtracking dispersal time was equal to 45 days and arriving destinations (net stations) are marked with purple dots. See also Maps S1.
doi:10.1371/journal.pone.0080466.g008

not rely on visual selection of plastic particles for characterization [48].

Hard plastics were by far the most common plastic type found (75.4%), but soft plastics (e.g. fragments of plastic wrappers) and lines (mostly fishing lines) were also relatively common (16.5% and 6.4%, respectively). It is interesting to note that soft plastics were more abundant in the larger size class (>2.4 mm). Our findings are consistent with recent studies documenting plastic pollution at the ocean surface, although explanations for variations in hard/soft plastic trends are not given [8,10,49]. Plastics gradually lose buoyancy in seawater as a result of biofilm formation [50]. We suggest that negative buoyancy due to biofouling occurs more quickly in soft/thin than in hard/thicker plastic fragments, resulting in a decline in the occurrence of soft plastics at the ocean surface, as they become smaller/older and begin to sink. Indirect evidence for this is that the proportion of soft plastics found in our coastal net stations was higher than that reported in open ocean settings further away from potential sources [49]. While a small number of experimental studies have confirmed that biofilms decrease the buoyancy of plastic items [50,51], none of them report the magnitude or speed of this process across different types of small fragments.

The plastics reported here were mostly white/transparent (84.7%) or blue (8.3%), which is consistent with reports from other investigations on buoyant marine plastics [49,52]. Depending on the feeding ecology of the affected animal, ingested plastic color proportions can differ from what is available in the environment [22]. For instance, ingested plastic color proportions in Australian shearwaters (*Ardenna pacifica* and *Ardenna tenuirostris*) are different from those reported by this study [20,21]. As these birds are known to use color vision to select their food [21,53], color can play a role in the ingestion risk associated with a certain plastic item. In contrast, the color proportion of plastics found in scats of fur seals (*Arctocephalus* spp.) at Macquarie Island (Australia) reflected what was available as flotsam in this environment [36]. These plastics are likely to be coming from the stomach contents of their main prey: the myctophid *Electrona subaspera*, which are pelagic small fish known to feed at night, selecting their food based on size rather than color [36].

The vast majority (98.5%) of the plastics detected were made of polyolefins (polyethylene and polypropylene), which is in agreement with what has been found for this size range of plastics in other marine regions around the world [47,49]. Polyethylene and polypropylene account for most of our global plastic production (38% and 24%, respectively [6]) and they are typically applied in the manufacturing of single-use disposable packaging. In addition to packaging, which reaches the oceans primarily from coastal areas, fishing equipment made of these polyolefins (e.g. fish crates, nets, ropes, fishing lines [17]) are also likely sources of the plastic particles registered here. Other types of polymers found in this study include two pieces of expanded polystyrene (Styrofoam), a type of plastic also used in packaging and fishing gear, and one fragment of ethylene vinyl acetate, which has several applications such as the making of shoe soles and foam mats.

Concentrations and sources

Our overall mean sea surface plastic concentration (Cs) was 4256.4 pieces km^{-2}, which is similar to mean values reported for other regions outside subtropical gyres, such the Caribbean Sea (mean $Cs = 1414$ pieces km^{-2}) and Gulf of Maine (mean $Cs = 1534$ pieces km^{-2}) [9]. Within subtropical gyres, Cs values tend to be higher but within the same order of magnitude: 20328 pieces km^{-2} in the North Atlantic Gyre [9], and 26898 pieces km^{-2} in the South Pacific Gyre [8]. The exception

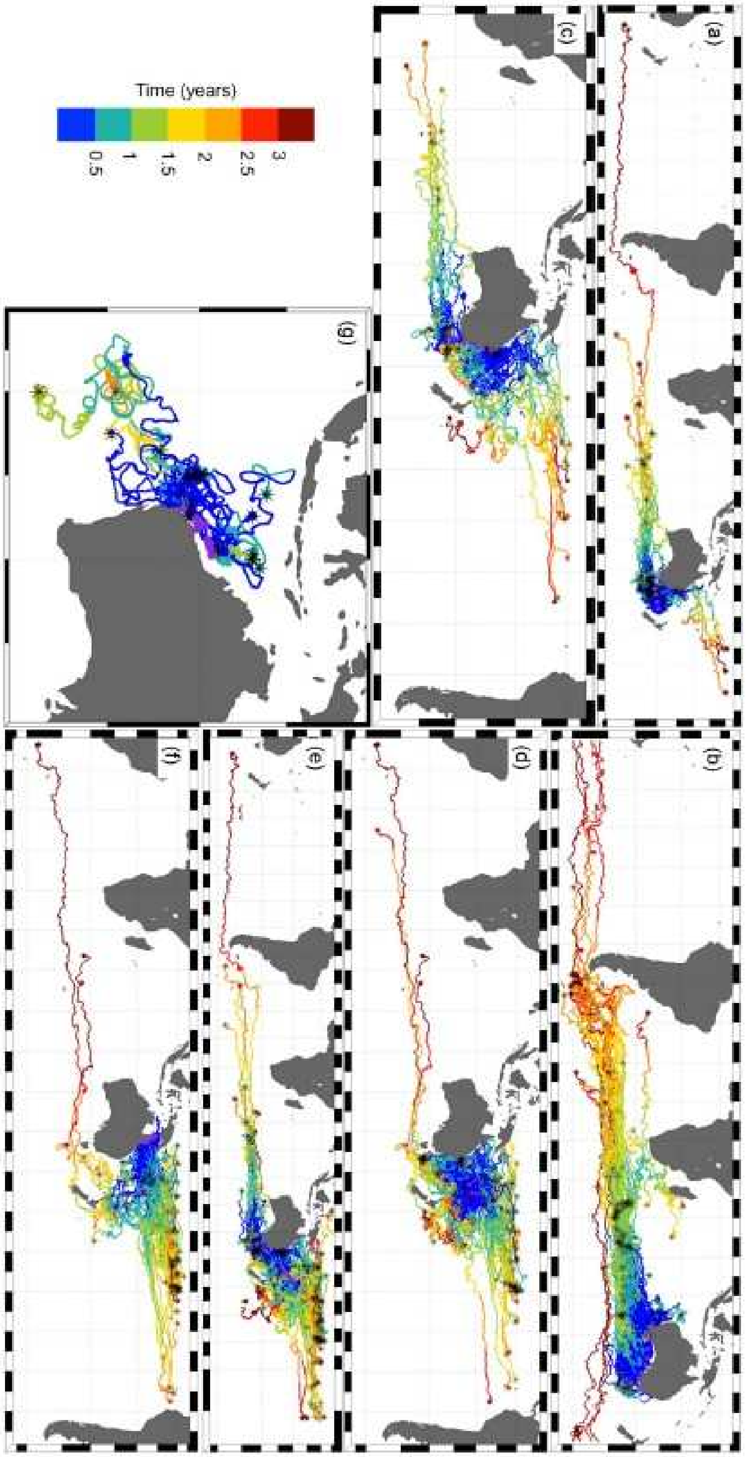
Time (years)
0.5
1
1.5
2
2.5
3
(a)
(b)
(c)
(d)
(e)
(f)
(g)

Figure 9. Real drifter pathways arriving at the 57 net stations. Purple dots indicate net station locations and asterisks indicate drifter release areas. See also Maps S2.
doi:10.1371/journal.pone.0080466.g009

seems to be the subtropical waters of the North Pacific and Mediterranean, which present mean *Cs* values that are an order of magnitude higher than those reported here: 116000 pieces km^{-2} in the Mediterranean [43], 174000 pieces km^{-2} in Northwest Pacific [44], and 334271 pieces km^{-2} in Northeast Pacific [10]. The latter is also known as the "Great Pacific Garbage Patch" [10], which is the largest aggregator of floating marine particles [54].

Our findings show that the distribution of marine plastics is quite widespread (93% of our net stations had at least one plastic piece), patchy (i.e. high variability within and between net stations' *Ct*) and dynamic (*Cs* ranged from 10% to 91% of *Ct*). Therefore, better spatio-temporal data coverage is required in order to identify plastic pollution hotspots within Australian waters. However, our data already indicate some spatial patterns: we observed high plastic concentrations close to Sydney and Brisbane cities. This suggests that plastics along Australia's east coast are mostly associated with domestic inputs. Since high quantities of plastic were also found close to Viti Levu (Fiji), we hypothesize that part of the plastics coming from coastal areas remain in the vicinity of their sources for a long time, while fragmenting into smaller pieces. This suggestion of local retention of plastic debris is in agreement with findings of recent studies (e.g.[7]) and could be tested by developing high-resolution models able to simulate plastic transport in coastal environments.

While the relatively high concentrations of plastic found close to the East Australian coast (net stations 18–20, 22, 37) seem to originate from local sources of plastics, those found in southwest Tasmania/eastern South Australia (net stations 5, 6, 8), and the North West Shelf (net station 54) could be associated with international sources and/or maritime operations. The presence of internationally-based plastics is suggested by (1) a fragment with Indonesian words that was collected in North West Shelf (see Figure 2) and (2) beach surveys, which registered in South Australia plastic debris from South Africa and South America [19]. High plastic concentrations in the southern tip of Tasmania (net station 5) might be caused by convergence effects of the encounter of the East Australian and Zeehan coastal currents [19], whereas those found off the east coast (e.g. net station 37) could be associated with meso-scale eddies of the East Australian current [55].

Aside from this study and the one that developed the biophysical model we applied here [15], we are not aware of any investigation that quantitatively considers the effect of vertical mixing processes on plastic concentrations. This effect needs to be taken into account in future studies assessing at-sea plastic pollution to allow better comparisons between data collected under different sea states. An important step towards improved simulations of plastic distribution along the water column is to better quantify the buoyant rise velocity (w_b) of plastic particles from different oceanic and coastal surface waters. This variable has a considerable impact on the output of the model applied here. Furthermore, other environmental variables that were not taken into account in our one-dimensional column model (e.g. Langmuir circulation, breaking waves, mixed layer depth) could to be incorporated in this type of modeling.

Potential pathways

The model outputs and routes taken by real drifters showed that plastics we found could have moved via a wide range of routes. This is because our net stations are within regions that experience different hydrodynamics (e.g. North West Shelf, Great Australian Bright, Coral Sea, Tasman Sea) [40]. Plastics have the potential to reach the sampled sites by travelling with a range of currents, including: (1) Antarctic Circumpolar current [56], which can carry plastics from a wide area to several of our net stations, particularly those along the coast of Tasmania, south coast of Australia, and Tasman Sea (net stations 1–15, 38 and 39); (2) South Equatorial current in the Pacific Ocean [56,57], which can bring international plastics to the east coast of Australia (net stations 16–24, 40–45, 36, 37) and areas close to Fiji and New Caledonia (net stations 25–35); (3) East Australian current [55,56], which can carry plastics from domestic highly populated regions (e.g. Brisbane and Sydney) to the net stations along the coast of Tasmania (net station 5, 15, 38, 39), east coast of Australia (net stations 16–24, 36, 37) and the Tasman Sea (net stations 1–4); (4) Holloway, Leeuwin, South Australian, and Zeehan coastal current systems [58–61], which can bring plastics from international areas connected to the Indonesian Throughflow and Indian Gyre (e.g. Southeast Asia/Indonesia [16]), as well as from domestic populated areas, to the net stations of the North West Shelf (net stations 48–57), off Perth (net station 14), and along the south coast of Australia, Bass Strait, Tasman Sea, and coast of Tasmania (net stations 1–13, 15–17, 37–39); and (5) West Australia current [61], which could transport international marine plastics that accumulated in the Indian Gyre to the net stations in the North West Shelf (net stations 48–57) and off Perth (net station 14).

It is important to note that running models backwards and using drifter trajectories arriving at sampled locations can only provide an indication of the directions that the collected plastics could have taken. To precisely estimate plastic pathways is quite challenging, mostly because plastic source locations and quantities are still largely unknown. Moreover, there are still no methods to estimate the "age" (drifting time) of a certain plastic particle. For instance, only plastics with long drifting times (years) could have matched the long tracks of drifters. Another limitation of the real drifter approach is that the resulting pathway formed by all drifter tracks arriving at a certain region is not only dependent on the ocean current systems, but also on the locations where most of the drifters were released. For instance, sampled sites in the North West Shelf (net stations 48–57) had only a few drifters arriving at them. This is mostly due to the non-existence of drifters in the shallow waters of the Indonesian archipelago. The creation of a shallow-water drifter (e.g. [62]) release program in this area could bring crucial information to help inform marine plastic pathways and sources.

Final remarks

This investigation shows that the abundant and widespread small marine plastics around Australia are likely coming from a variety of domestic and international, land- and ocean-based sources. Even though marine plastic pollution is a global environmental issue, mostly caused by our massive production of plastic single-use disposable items, there are still no attempts to regulate plastic disposal on land at an international level [26]. Additionally, dumping of plastics into the oceans remains a significant issue owing the difficulties with regulation and enforcement [17,63]. We suggest further at-sea studies on the characterization, spatial distribution, and pathways of marine plastics in coastal and oceanic regions around Australia, as well as on marine plastic toxin loads and interactions between small plastic particles and organisms at all trophic levels of the food web. This would improve our current knowledge on the effects of plastic on the marine ecosystem as a whole.

Supporting Information

Table S1 Net tow data (N = 171). Columns indicate net station number, sampling date (day.month.year), location (degrees minutes), and sea surface plastic concentration (C_t; pieces per km^{-2}).
(PDF)

Maps S1 Cumulative probability distribution of virtual particles arriving at the 57 net stations. The month when the virtual particles (25 per day) were released is indicated in each panel. Backtracking dispersal time was equal to 45 days and arriving destinations (net stations) are marked with red dots.
(PDF)

Maps S2 Real drifter pathways arriving at the 57 net stations. Purple dots indicate net station locations and asterisks indicate drifter release areas.
(PDF)

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Author Contributions

Conceived and designed the experiments: JR JS CW BDH MP MT CP. Performed the experiments: JR JS CW. Analyzed the data: JR CP. Contributed reagents/materials/analysis tools: JR JS CW BDH CP. Wrote the paper: JR JS MP MT.

References

1. Thompson RC, Swan SH, Moore CJ, vom Saal FS (2009) Our plastic age. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 1973–1976.
2. PlasticsEurope (2012) Plastics - the Facts 2012. An analysis of European plastics production, demand and waste data for 2011. 38 p.
3. Hoornweg D, Bhada-Tata P (2012) What a waste: a global review of solid waste management. 98 p.
4. PACIA (2011) National plastics recycling survey (2010-11 financial year). 53 p.
5. Ryan PG, Moore CJ, van Franeker JA, Moloney CL (2009) Monitoring the abundance of plastic debris in the marine environment. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 1999–2012.
6. Andrady AL (2011) Microplastics in the marine environment. Marine Pollution Bulletin 62: 1596–1605.
7. Thiel M, Hinojosa I, Miranda L, Pantoja J, Rivadeneira M, et al. (2013) Anthropogenic marine debris in the coastal environment: A multi-year comparison between coastal waters and local shores. Marine Pollution Bulletin 71: 307–316.
8. Eriksen M, Maximenko N, Thiel M, Cummins A, Lattin G, et al. (2013) Plastic pollution in the South Pacific subtropical gyre. Marine Pollution Bulletin 68: 71–76.
9. Law KL, Morét-Ferguson S, Maximenko NA, Proskurowski G, Peacock EE, et al. (2010) Plastic accumulation in the North Atlantic subtropical gyre. Science 329: 1185–1188.
10. Moore CJ, Moore SL, Leecaster MK, Weisberg SB (2001) A comparison of plastic and plankton in the North Pacific central gyre. Marine Pollution Bulletin 42: 1297–1300.
11. Davidson TM (2012) Boring crustaceans damage polystyrene floats under docks polluting marine waters with microplastic. Marine Pollution Bulletin 64: 1821–1828.
12. Mato Y, Isobe T, Takada H, Kanehiro H, Ohtake C, et al. (2001) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environmental Science & Technology 35: 318–324.
13. Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, et al. (2011) Accumulation of microplastic on shorelines woldwide: sources and sinks. Environmental Science & Technology 45: 9175–9179.
14. Fendall LS, Sewell MA (2009) Contributing to marine pollution by washing your face: microplastics in facial cleansers. Marine Pollution Bulletin 58: 1225–1228.
15. Kukulka T, Proskurowski G, Morét-Ferguson S, Meyer D, Law K (2012) The effect of wind mixing on the vertical distribution of buoyant plastic debris. Geophysical Research Letters 39: 1–6.
16. Lebreton LM, Greer S, Borrero J (2012) Numerical modelling of floating debris in the world's oceans. Marine Pollution Bulletin 64: 653–661.
17. Jones MM (1995) Fishing debris in the Australian marine environment. Marine Pollution Bulletin 30: 25–33.
18. Frost A, Cullen M (1997) Marine debris on northern New South Wales beaches (Australia): sources and the role of beach usage. Marine Pollution Bulletin 34: 348–352.
19. Edyvane K, Dalgetty A, Hone P, Higham J, Wace N (2004) Long-term marine litter monitoring in the remote Great Australian Bight, South Australia. Marine Pollution Bulletin 48: 1060–1075.
20. Carey MJ (2011) Intergenerational transfer of plastic debris by Short-tailed Shearwaters (*Ardenna tenuirostris*). Emu 111: 229–234.
21. Verlis K, Campbell M, Wilson S (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.
22. Schuyler Q, Hardesty BD, Wilcox C, Townsend K (2012) To eat or not to eat? Debris selectivity by marine turtles. PloS one 7: e40884.
23. Gregory MR (2009) Environmental implications of plastic debris in marine settings—entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 2013–2025.
24. Carr A (1987) Impact of nondegradable marine debris on the ecology and survival outlook of sea turtles. Marine Pollution Bulletin 18: 352–356.
25. de Stephanis R, Giménez J, Carpinelli E, Gutierrez-Exposito C, Cañadas A (2013) As main meal for sperm whales: plastics debris. Marine Pollution Bulletin 69: 206–214.
26. Rochman CM, Browne MA, Halpern BS, Hentschel BT, Hoh E, et al. (2013) Policy: classify plastic waste as hazardous. Nature 494: 169–171.
27. Rochman CM, Hoh E, Hentschel BT, Kaye S (2013) Long-Term field measurement of sorption of organic contaminants to five types of plastic pellets: implications for plastic marine debris. Environmental Science & Technology 47: 1646–1654.
28. von Moos N, Burkhardt-Holm P, Kohler A (2012) Uptake and effects of microplastics on cells and tissue of the blue mussel Mytilus edulis L. after an experimental exposure. Environmental Science & Technology 46: 11327–11335.
29. Teuten EL, Saquing JM, Knappe DR, Barlaz MA, Jonsson S, et al. (2009) Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 2027–2045.
30. Basheer C, Lee HK, Tan KS (2004) Endocrine disrupting alkylphenols and bisphenol-A in coastal waters and supermarket seafood from Singapore. Marine Pollution Bulletin 48: 1161–1167.
31. Choy CA, Drazen JC (2013) Plastic for dinner? Observations of frequent debris ingestion by pelagic predatory fishes from the central North Pacific. Marine Ecology Progress Series 485: 155–163.
32. Gassel M, Harwani S, Park J-S, Jahn A (2013) Detection of nonylphenol and persistent organic pollutants in fish from the North Pacific Central Gyre. Marine Pollution Bulletin 64: 2374–2379.
33. Boerger CM, Lattin GL, Moore SL, Moore CJ (2010) Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Marine Pollution Bulletin 60: 2275–2278.
34. Cole M, Lindeque P, Fileman E, Halsband C, Goodhead RM, et al. (2013) Microplastic ingestion by zooplankton. Environmental Science & Technology 47: 6646–6655.
35. Young JW, Lamb TD, Le D, Bradford RW, Whitelaw AW (1997) Feeding ecology and interannual variations in diet of southern bluefin tuna, *Thunnus maccoyii*, in relation to coastal and oceanic waters off eastern Tasmania, Australia. Environmental Biology of Fishes 50: 275–291.
36. Eriksson C, Burton H (2003) Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. AMBIO 32: 380–384.

37. Commonwealth of Australia (2009) Background paper for the threat abatement plan for the impacts of marine debris on vertebrate marine life. Available: http://www.environment.gov.au/biodiversity/threatened/publications/tap/marine-debris.html Accessed 2013 Jul 16.
38. Dee D, Uppala S, Simmons A, Berrisford P, Poli P, et al. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society 137: 553–597.
39. Condie SA, Waring J, Mansbridge JV, Cahill ML (2005) Marine connectivity patterns around the Australian continent. Environmental Modelling & Software 20: 1149–1157.
40. Schiller A, Oke PR, Brassington G, Entel M, Fiedler R, et al. (2008) Eddy-resolving ocean circulation in the Asian–Australian region inferred from an ocean reanalysis effort. Progress in Oceanography 76: 334–365.
41. Browne MA, Galloway TS, Thompson RC (2010) Spatial patterns of plastic debris along estuarine shorelines. Environmental Science & Technology 44: 3404–3409.
42. Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, et al. (2004) Lost at sea: where is all the plastic? Science 304: 838–838.
43. Collignon A, Hecq J-H, Glagani F, Voisin P, Collard F, et al. (2012) Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Marine Pollution Bulletin 64: 861–864.
44. Yamashita R, Tanimura A (2007) Floating plastic in the Kuroshio current area, western North Pacific Ocean. Marine Pollution Bulletin 54: 485–488.
45. Fossi MC, Panti C, Guerranti C, Coppola D, Giannetti M, et al. (2012) Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (*Balaenoptera physalus*). Marine Pollution Bulletin 64: 2374–2379.
46. Wright SL, Thompson RC, Galloway TS (2013) The physical impacts of microplastics on marine organisms: A review. Environmental Pollution 178: 483–492.
47. Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for identification and quantification. Environmental Science & Technology 46: 3060–3075.
48. Harrison JP, Ojeda JJ, Romero-González ME (2012) The applicability of reflectance micro-Fourier-transform infrared spectroscopy for the detection of synthetic microplastics in marine sediments. Science of the Total Environment 416: 455–463.
49. Morét-Ferguson S, Law KL, Proskurowski G, Murphy EK, Peacock EE, et al. (2010) The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Marine Pollution Bulletin 60: 1873–1878.
50. Ye S, Andrady AL (1991) Fouling of floating plastic debris under Biscayne Bay exposure conditions. Marine Pollution Bulletin 22: 608–613.
51. Lobelle D, Cunliffe M (2011) Early microbial biofilm formation on marine plastic debris. Marine Pollution Bulletin 62: 197–200.
52. Carpenter EJ, Smith K (1972) Plastics on the Sargasso Sea Surface. Science 175: 1240–1241.
53. Bowmaker J (1980) Colour vision in birds and the role of oil droplets. Trends in Neurosciences 3: 196–199.
54. van Sebille E, England MH, Froyland G (2012) Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environmental Research Letters 7: 044040.
55. Ridgway K, Dunn J (2003) Mesoscale structure of the mean East Australian Current System and its relationship with topography. Progress in Oceanography 56: 189–222.
56. Talley LD, Pickard GL, Emery WJ, Swift JH (2011) Descriptive physical oceanography: an introduction: Elsevier. 555 p.
57. Webb DJ (2000) Evidence for shallow zonal jets in the South Equatorial Current region of the southwest Pacific. Journal of Physical Oceanography 30: 706–720.
58. Ridgway K, Condie S (2004) The 5500-km-long boundary flow off western and southern Australia. Journal of Geophysical Research 109: 1–18.
59. Condie S, Andrewartha J (2008) Circulation and connectivity on the Australian North West Shelf. Continental Shelf Research 28: 1724–1739.
60. Sandery PA, Kämpf J (2007) Transport timescales for identifying seasonal variation in Bass Strait, south-eastern Australia. Estuarine, Coastal and Shelf Science 74: 684–696.
61. Pattiaratchi C, Woo M (2009) The mean state of the Leeuwin current system between North West Cape and Cape Leeuwin. Journal of the Royal Society of Western Australia 92: 221–241.
62. Ohlmann JC, White PF, Sybrandy AL, Niiler PP (2005) GPS-cellular drifter technology for coastal ocean observing systems. Journal of Atmospheric and Oceanic Technology 22: 1381–1388.
63. Rakestraw A (2012) Open oceans and marine debris: solutions for the ineffective enforcement of MARPOL Annex V. Hastings International and Comparative Law Review 35: 383–451.

Appendix H. Millimeter-Sized Marine Plastics: A New Pelagic Habitat for Micro-organisms and Invertebrates, PLOS One 2014

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Millimeter-Sized Marine Plastics: A New Pelagic Habitat for Microorganisms and Invertebrates

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Abstract

Millimeter-sized plastics are abundant in most marine surface waters, and known to carry fouling organisms that potentially play key roles in the fate and ecological impacts of plastic pollution. In this study we used scanning electron microscopy to characterize biodiversity of organisms on the surface of 68 small floating plastics (length range = 1.7–24.3 mm, median = 3.2 mm) from Australia-wide coastal and oceanic, tropical to temperate sample collections. Diatoms were the most diverse group of plastic colonizers, represented by 14 genera. We also recorded 'epiplastic' coccolithophores (7 genera), bryozoans, barnacles (*Lepas* spp.), a dinoflagellate (*Ceratium*), an isopod (Asellota), a marine worm, marine insect eggs (*Halobates* sp.), as well as rounded, elongated, and spiral cells putatively identified as bacteria, cyanobacteria, and fungi. Furthermore, we observed a variety of plastic surface microtextures, including pits and grooves conforming to the shape of microorganisms, suggesting that biota may play an important role in plastic degradation. This study highlights how anthropogenic millimeter-sized polymers have created a new pelagic habitat for microorganisms and invertebrates. The ecological ramifications of this phenomenon for marine organism dispersal, ocean productivity, and biotransfer of plastic-associated pollutants, remains to be elucidated.

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Introduction

Millimeter-sized plastics resulting from the disintegration of synthetic products (known as 'microplastics' if smaller than 5 mm) are abundant and widespread at the sea surface [1–7]. These small marine plastics are a toxic hazard to food webs since they can contain harmful compounds from the manufacturing process (e.g. Bisphenol A), as well as contaminants adsorbed from the surrounding water (e.g. polychlorinated biphenyls) [8–11]. These substances can be carried across marine regions and transferred from plastics to a wide range of organisms, from zooplankton and small fish to whales [8,12–19]. Furthermore, they can physically damage suspension- and deposit-feeding fauna (e.g. internal abrasions and blockages after ingestion) [20], and alter pelagic and sediment-dwelling biota by modifying physical properties of their habitats [21]. Finally, these small marine plastics can transport rafting species [22–27], potentially changing their natural ranges to become non-native species and even invasive pests.

Apart from providing long-lasting buoyant substrata that allow many organisms to widely disperse [28–38], marine plastics may also supply energy for microbiota capable of biodegrading polymers and/or associated compounds [27,39–43], and perhaps for invertebrates capable of grazing upon plastic inhabitants. The hydrophobic nature of plastic surfaces stimulates rapid formation of biofilm, which drives succession of other micro- and macro-organisms. This 'epiplastic' community appears to influence the fate of marine plastic pollution by affecting the degradation rate [27,44], buoyancy [3,45,46], and toxicity level [43] of plastics. Moreover, epiplastic microbiota could have impacts on the microflora of its consumers, and infectious organisms may reach their hosts through plastic ingestion [27,43,47].

Although epiplastic organisms may play an important role in determining the fate and ecological impacts of plastic pollution, little research has been directed to such study, particularly on the inhabitants of the widely dispersed and abundant millimeter-sized marine plastics [43]. In 1972, two papers first reported the occurrence of organisms (diatoms, hydroids, and bacteria) on small

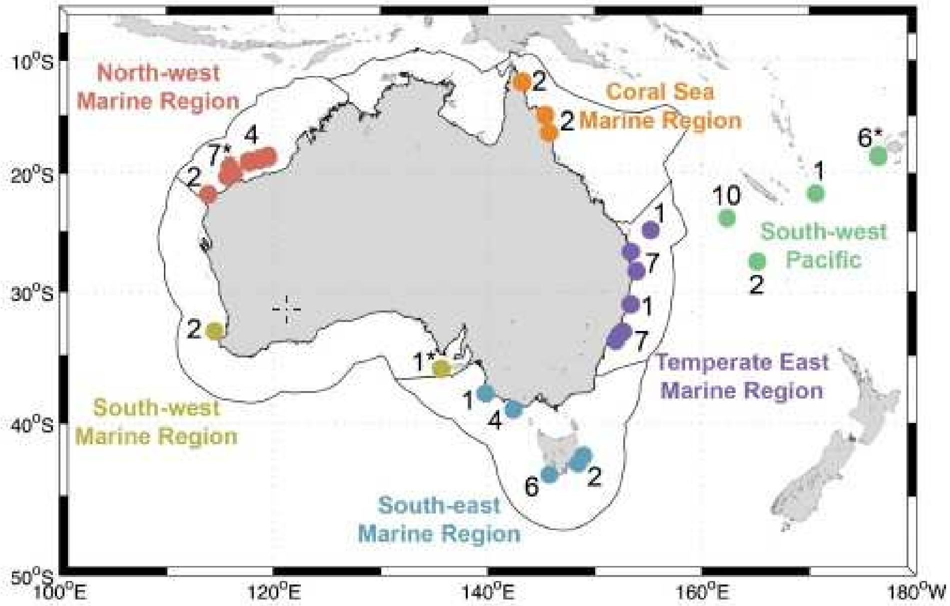

Figure 1. Sampling locations of the 68 plastics analyzed in this study. Black lines delimit marine regions of Australia (environment.gov.au/topics/marine/marine-bioregional-plans); dots indicate areas where the analyzed plastics were collected; numbers represent how many plastics were taken for scanning electron microscopy analyses at these locations. Samples collected were fragments of hard plastic (N = 65), except at locations marked with an asterisk: one piece of Styrofoam cup in Fijian waters, one pellet in South Australia, and one piece of soft plastic in the Australia's North-west marine region.
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plastics (0.1–5 mm long) collected by plankton nets [22,23]. Further at-sea studies focusing on microplastic fouling biota only emerged in the 2000's [21,27,48]. Zettler et al. (2013) conducted the first comprehensive characterisation of epiplastic microbial communities, which they coined the "Plastisphere" [27]. These authors used scanning electron microscopy (SEM) and next-generation sequencing to analyze three polyethylene and three polypropylene plastic pieces (approx. 2–20 mm long) from offshore waters of the North Atlantic. This pioneer study revealed a unique, diverse, and complex microbial community that included diatoms, ciliates, and bacteria.

Here, we used SEM to examine types of organisms inhabiting the surface of 68 small marine plastics (length range = 1.7–24.3 mm, median = 3.2 mm) from inshore and offshore waters from around the Australian continent (Figure 1). We contributed many new records of taxa associated with millimeter-sized marine plastics and imaged a variety of marine plastic shapes and surface textures resulting from the interaction of polymers with environments and organisms.

Materials and Methods

Ethics Statement: Permits to conduct field research within the Great Barrier Reef area were obtained from the Great Barrier Reef Marine Park Authority (GBRMPA: permit G11/34378.1). No other special permit was required since sampling was limited to marine debris.

Buoyant plastics were collected using surface net tows in waters around Australia (see details in [4,49]) and preserved in 2.5% glutaraldehyde buffered in filtered seawater. Prior to analysis with a scanning electron microscope, plastics were dehydrated through a series of increasing ethanol concentrations (up to 100%), critical-point dried using CO_2, mounted on aluminum stubs with carbon tape, and sputter coated with a 20–30 nm layer of gold. We used a Zeiss 1555 VP-FESEM scanning electron microscope operated at 10–20 kV, 11–39 mm working distance, and 10–30 μm aperture. We randomly selected 65 hard plastics among those small enough to fit onto SEM stubs (<10 mm) and large enough to be easily handled (>1 mm). For comparison, a piece of (1) soft plastic, (2) industrial plastic pellet, and (3) expanded polystyrene (Styrofoam) were also examined, totaling 68 plastic pieces examined with SEM. These plastics were collected from offshore waters of the South-west Pacific (N = 19) and from different Australian marine regions (environment.gov.au/topics/marine/marine-bioregional-plans): North-west (N = 13), South-west (N = 3), South-east (N = 13), Temperate East (N = 16), and Coral Sea (N = 4; Figure 1).

The different types of organisms detected on each plastic piece were imaged, measured using ImageJ (length and width, http://rsb.info.nih.gov/ij/), classified into taxonomic/morphological groups, and the frequency of occurrence (FO) for each type was calculated. We used online resources (e.g. marinespecies.org, westerndiatoms.colorado.edu), primary taxonomic literature (e.g [50–54]), and expert consultation (see acknowledgments section) to identify the organisms at the lowest possible taxonomic level. Long filaments were very common but were excluded from the analysis due to difficulty in determining if they were organisms or mucilage.

For each plastic piece observed, an image of the entire piece was taken at 50×magnification. These images were uploaded to ImageJ to measure plastic particles' size parameters (length, area, perimeter, aspect ratio) and shape parameters (circularity and solidity indexes [55,56]). Surface fractures, pits and grooves [57,58] were also observed, recorded, and imaged while examining the entire surface of the plastics at magnifications of 100–

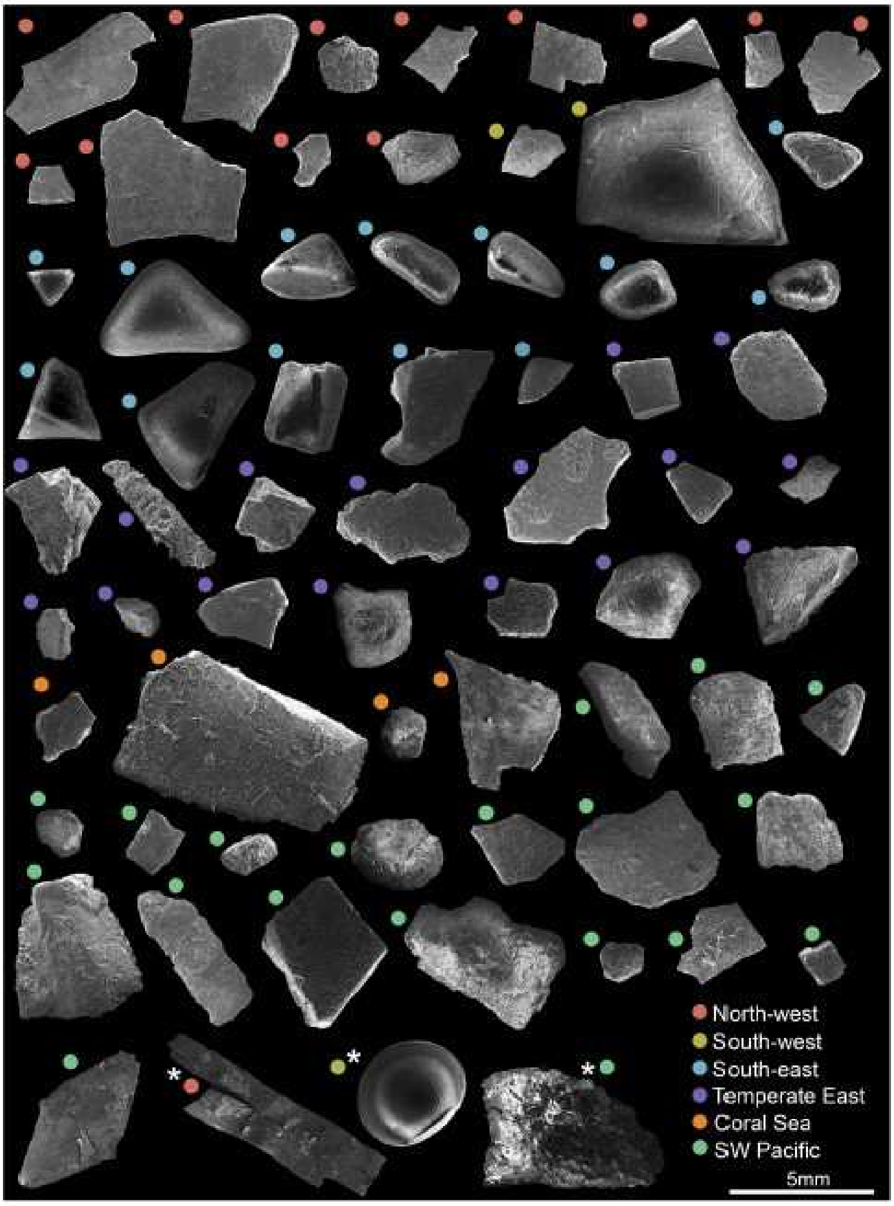

Figure 2. Overall appearance of marine plastics, as shown by scanning electron micrographs. Dot color indicates the marine region where the piece was sampled (see legend and Figure 1). Pieces are hard plastic fragments, with the exception of the soft plastic fragment (red dot), pellet (yellow dot), and Styrofoam fragment (green dot) shown at the bottom of the diagram and marked with a white asterisk. All images are at the same magnification (see scale bar at lower right).
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500×. Other peculiar microtextures observed at higher magnifications, such as those suggesting interactions with biota, were also recorded and imaged. After SEM analyses, plastics were washed with distilled water and submitted to Fourier Transform Infrared spectrometry (FT-IR) for polymer identification. Two plastic pieces were destroyed while being cleaned for FT-IR; as such, we identified the polymer of 66 out of the 68 plastics examined using SEM.

Results

We examined 65 hard plastic fragments with lengths ranging from 1.7 to 8.9 mm (median = 3.2 mm), one 4 mm-wide plastic pellet, one 8.7 mm portion of a 15 mm long soft plastic fragment, and one 7 mm piece of a 24.3 mm Styrofoam cup fragment. Apart from the Styrofoam cup fragment (expanded polystyrene), plastics were made of polyethylene (N = 54) and polypropylene (N = 11).

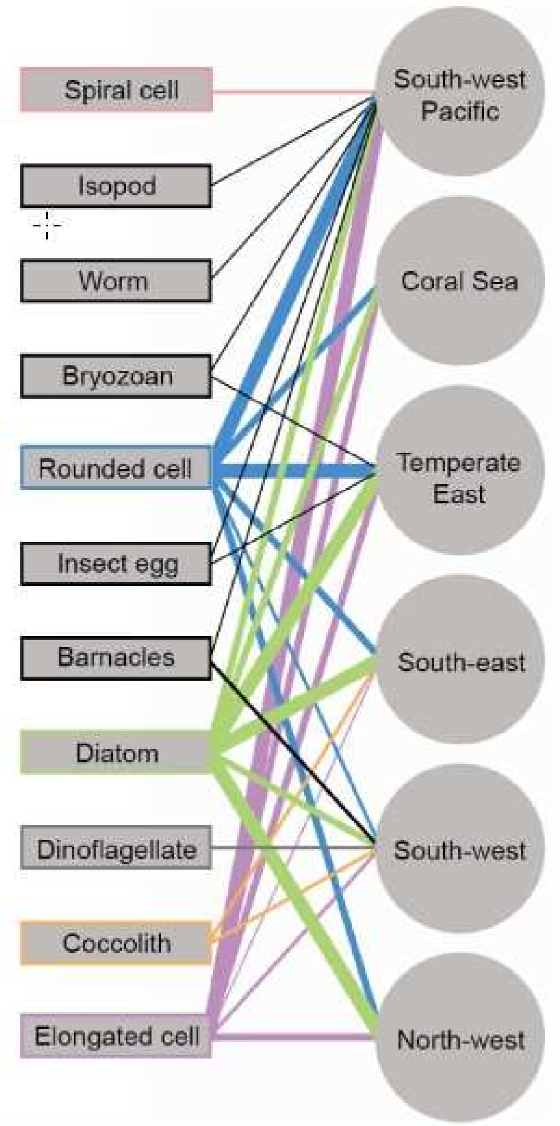

Figure 3. Types of epiplastic organisms detected at each of the marine regions sampled in this study (see Figure 1). Lines connect types of organisms (squares) to the marine regions (circles) where they were observed. Line color indicates type of organism, with black lines representing invertebrates. Line thickness is proportional to the organism's frequency of occurrence (FO = <25%, 25–50%, 50–75%, >75%).
doi:10.1371/journal.pone.0100289.g003

Hard plastics had a diverse range of shapes (solidity index = 0.87–0.98, circularity index = 0.28–0.83; Figure 2) and types of surface microtextures, including linear fractures, pits, and scraping marks (Figure S1). Diatoms and bacteria (rounded, and elongated cells) were by far the most frequently observed organisms, being detected in all sampled marine regions (Figure 3). Plastics' FT-IR spectra, 1143 SEM micrographs, and a matrix containing information from collection sites, plastics characteristics, and organism/microtexture presence-absence data are available in [59].

Diatoms were the most abundant, widespread, and diverse group of plastic colonizers (Figures 3 and 4). These organisms were frequently observed (FO = 78%, N = 68 plastics) and included symmetrical biraphids/naviculoids (*Navicula* subgroup lineatae, *Mastogloia* sp., *Haslea* sp.; Figure 4a–c), Nitzschioids (*Nitzschia* spp., *Nitzschia longissima*; Figure 4d–f), monoraphids (*Cocconeis* spp., *Achnanthes* sp.; Figure 4g–i), centrics (*Minidiscus trioculatus*, *Thalassiosira* sp.; Figure 4j), araphids (*Thalassionema nitzschioides* var. *parva*, *Microtabella* spp., *Licmophora* spp., *Grammatophora* sp.; Figure 4k,l,o), and asymmetrical biraphids (*Amphora* spp., *Cymbella* sp.; Figure 4m,n). Most diatoms were growing flat on the surface (adnate and motile diatoms), but some were erect, attached to plastics by mucous pads or stalks/peduncles. The genus *Nitzschia* was the most frequent diatom (FO = 42.6%), followed by *Amphora* (13.2%), *Licmophora* (11.8%), *Navicula* (8.8%), *Microtabella* (5.9%), *Cocconeis* (4.4%), *Thalassionema* (2.9%), and *Minidiscus* (2.9%). The other six genera were only detected on a single plastic piece (FO = 1.5%). These frequencies of occurrence are likely to be underestimated, as many diatoms could not be identified from girdle-view positions (FO unidentified diatoms = 45.6%).

Calcareous coccolithophores were observed only on plastics from southern Australia (South-east and South-west marine regions; FO = 37.5%, N = 16 plastics; Figure 3, Figure 5a–h). The species identified included *Calcidiscus leptoporus* (Figure 5a), *Emiliania huxleyi* (Figure 5b,c), *Gephyrocapsa oceanica* (Figure 5d), *Umbellosphaera tenuis* (Figure 5e), *Umbilicosphaera hulburtiana* (Figure 5f), *Coccolithus pelagicus* (Figure 5g), and *Calciosolenia* sp. (Figure 5h). Many of these observations related to detached coccolith scales held in place by mucilage and chitin filaments resembling those produced by diatoms (e.g. *Thalassiosira*; Figure 5b,f). However, intact coccospheres were also present (Figure 5c,d,f). Additionally, one specimen of the dinoflagellate *Ceratium* cf. *macroceros* was present on a 8.2 mm plastic from South-west Australia (Figure 3, Figure 5i).

We found several unidentified organisms of various morphotypes and sizes, mostly resembling bacterial, cyanobacterial, and fungal cells (Figure 6). After diatoms, rounded/oval cells (length-width ratio <1.5; Figure 6a–c,i–m) were the most frequently observed morphotype (FO = 72%, N = 68 plastics; Figure 3). Rounded/oval cells with widths <1 µm and ≥1 µm had an overall FO of 38.2% and 54.4%, respectively. Elongated cells (length-width ratio ≥1.5; Figure 6e–h) were also frequently observed, being detected on 59% of the plastics examined (Figure 3). Those with widths <1 µm and ≥1 µm had an overall FO of 51.5% and 11.7%, respectively. Spiral cells (Figure 6d) had similar appearances (resembling spirochaete bacteria) and sizes (0.2–0.3 µm width), and were only observed in the South-west Pacific region (FO = 31.6%, N = 19; Figure 3). Several plastic pits and grooves contained bacteria-like cells closely resembling their shape (Figure 6i–m). They were particularly common on plastics covered by large rounded cells (Figure 6k).

A few invertebrates were observed on the millimeter-sized plastics (FO = 16.2%, N = 68 plastics; Figures 3 and 7). Colonies of encrusting bryozoans were the most common epiplastic animal (FO = 8.8%; Figure 7a–d). They occurred on two fragments from the Temperate East marine region and on four fragments from oceanic waters of the South-west Pacific (plastic length = 3.2–5.4 mm). Four of these bryozoan colonies were hosting abundant diatom assemblages dominated by *Licmophora* sp., *Nitzschia longissima* (Figure 7a), *Amphora* sp. (Figure 7c), and *Nitzschia* sp. (Figure 7d). Additionally, lepadomorph barnacles (*Lepas* spp.; Figure 7e,f) were attached to the 24.3 mm Styrofoam cup

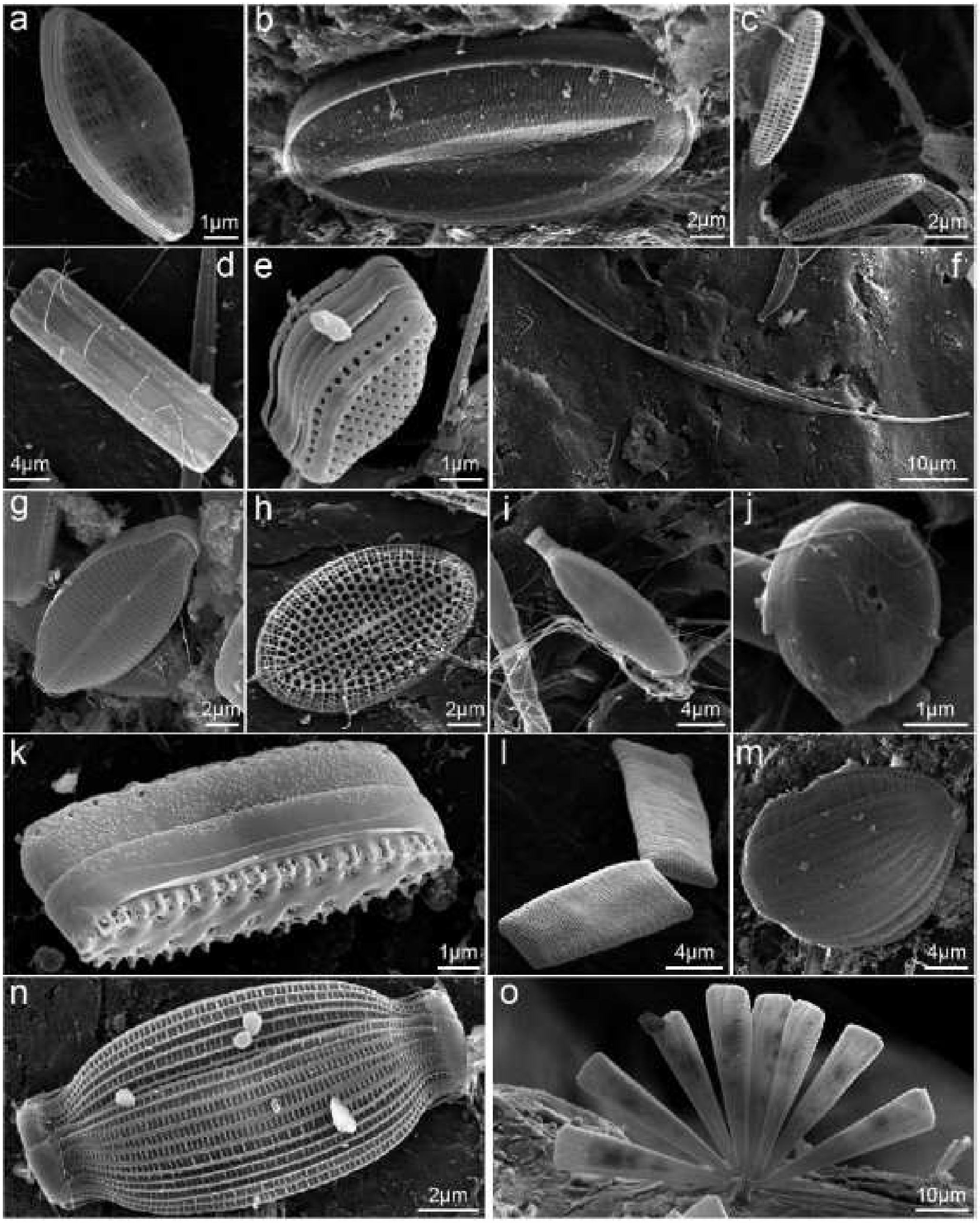

Figure 4. Examples of epiplastic diatoms. a: *Navicula* sp.; b: *Mastogloia* sp.; c: small naviculoids; d: *Nitzschia* sp.; e: *Nitzschia* sp.; f: *Nitzschia longissima*.; g: *Cocconeis* sp.; h: *Cocconeis* sp.; i: *Achnanthes* sp.; j: *Thalassiosira* sp.; k: *Thalassionema nitzschioides*; l: *Microtabella* sp.; m: *Amphora* sp.; n: *Amphora* sp.; o: *Licmophora* sp.
doi:10.1371/journal.pone.0100289.g004

fragment and to a 8.2 mm-long hard plastic; an Asellote isopod (Figure 7g) was found on the Styrofoam cup fragment; eggs of the marine insect *Halobates* sp. (Figure 7h) were observed on two plastics (4.6 and 5.5 mm long); and a unidentified marine worm (Figure 7i,j) was found on a 6 mm hard plastic fragment.

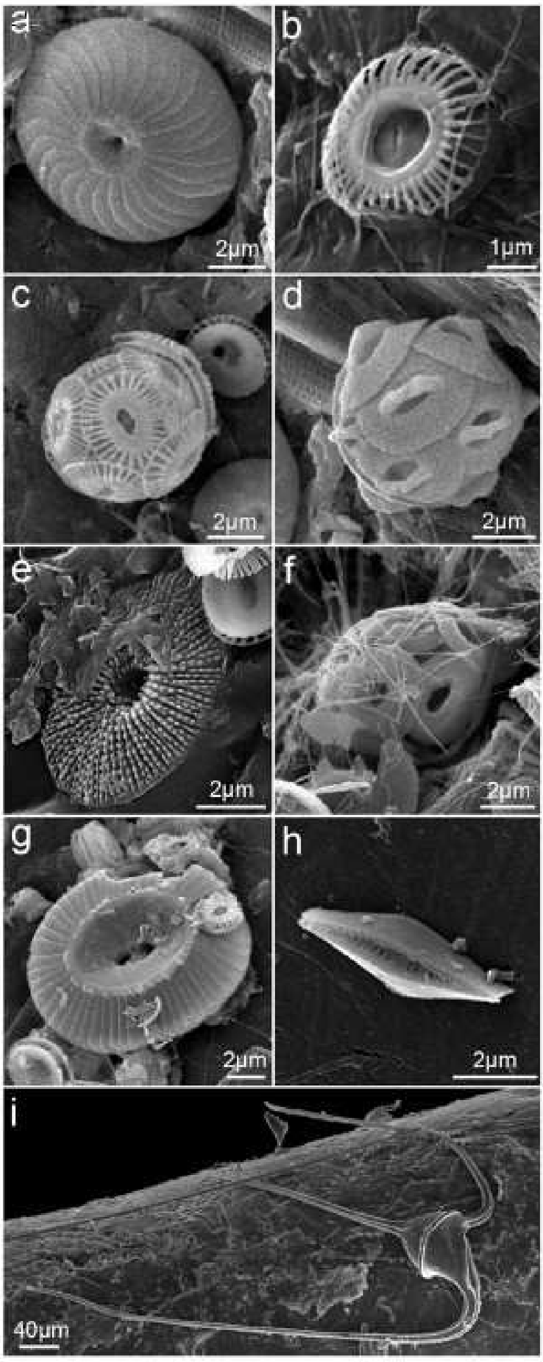

Figure 5. Examples of epiplastic coccoliths and dinoflagellate. a: Calcidiscus leptoporus; b, c: Emiliania huxleyi; d: Gephyrocapsa oceanica; e: Umbellosphaera tenuis; f: Umbilicosphaera hulburtiana; g: Coccolithus pelagicus; h: Calciosolenia sp.; i: Ceratium cf. macroceros dinoflagellate.
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Discussion

There now exists a large body of evidence that millimeter-sized plastics are abundant and widespread in marine environments [1–6,22,23] and our study significantly adds to this by conclusively demonstrating that they are colonized by a wide range of biota, particularly diatom and bacteria species (Table 1, [3,22,24–27]). We more than doubled the number of known diatom genera inhabiting millimeter-sized marine plastics and provide the first identifications of coccolithophore genera attached to these floating plastic particles. We also recorded a few invertebrate species living on these small plastics. As such, our findings provide further evidence that not only large debris [28–38] serve as vehicles for organism dispersal. Abundant 'microplastics' are equally providing a new pelagic habitat to many microorganism and a few invertebrate taxa.

We observed fouling diatoms to be diverse and widespread on marine plastics. These diatoms seemed to firmly attach to the plastic, resisting water turbulence and wave action. All the identified diatom genera are well known to form biofilms on estuarine and marine sediments and rocks (epilithic), vegetation (epiphytic), and animals (epizoic) [60–65]; marine plastics thus create a novel, long-lasting and abundant floating habitat for 'benthic' diatoms, in a light and nutrient-filled environment that is stable and beneficial to these organisms. Future epiplastic diatom research should focus on the quantitative contribution of these organisms to enhancing primary and secondary productivity of different marine regions, such as within subtropical gyres where productivity tends to be low but plastic pollution level high [1–3,66]. Because of their rapid growth and production of extracellular substances [67], epiplastic diatoms may provide an important food source for invertebrate grazers. As plastic debris can contain harmful substances [8,10–12,19], it remains unclear if such grazer-plastic relationships would have a positive or negative impact on the populations involved in this new type of food web.

A significant number of coccolithophore species were present on millimeter-sized marine plastics. These planktonic organisms are not commonly recognized as fouling or rafting organisms [36], although their occasional occurrence on marine plastics was briefly mentioned in recent studies [26,27]. Some of our observations were of clusters of mixed coccolith species, resembling zooplankton fecal pellets, and of solitary coccoliths, likely detached from living coccospheres and stuck to clingy parts of the plastic biofilm. However, entire coccolithophores were also seen attached to plastics, suggesting that these organisms could be using ocean plastics as 'floating devices'. We only observed coccoliths on plastics from southern Australia; as such, additional studies in these temperate waters may help better understand this potential coccolith-plastic relationship. Another atypical organism detected was the planktonic dinoflagellate *Ceratium* cf. *macroceros*. Recent studies have found plastics heavily fouled by dinoflagellates, including individuals and cysts of the potentially harmful species *Ostreopsis* sp., *Coolia* sp., and *Alexandrium* spp. [27,31], but here we only detected a single specimen of this group.

Several unidentified organisms (rounded, oval, elongated, and spiral) resembling bacterial cells were flourishing on millimeter-sized marine plastics. This supports previous studies that describe well established bacterial populations growing on plastic fragments [26,27]. Many of these unidentified cells were apparently interacting with the plastic surface by forming pits and grooves. Within this group of "pit-formers", colonies of rounded cells (around 5 micron in diameter) covered large areas of the plastic surface. They were similar to some previously unidentified epiplastic organisms from the North Atlantic [27]. These SEM

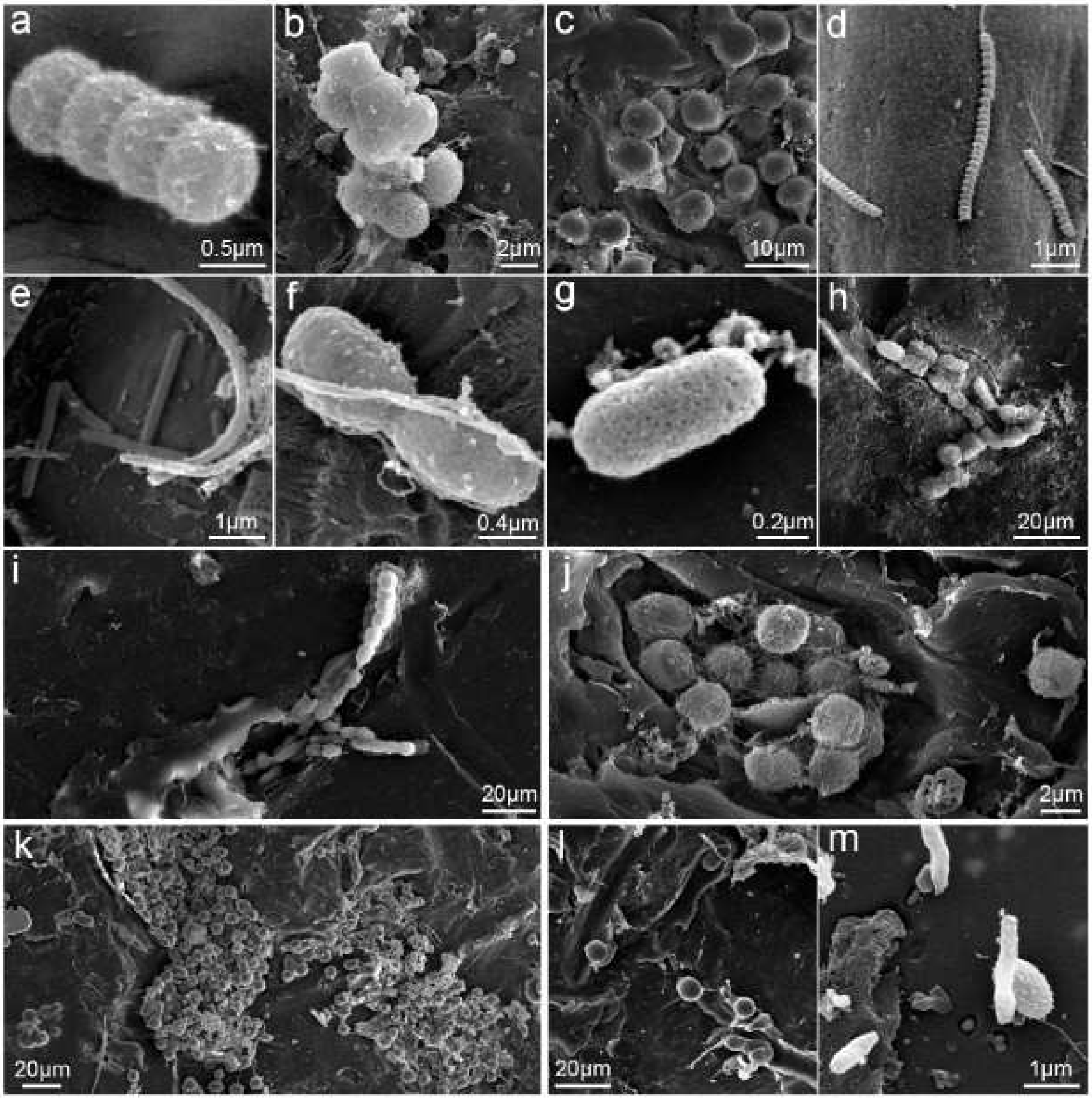

Figure 6. Examples of epiplastic rounded, elongated and spiral cells. a, b, c: rounded cells; d: spiral "spirochaete" cell; e, f, g, h: elongated cells.; i, j, k, l, m: pits and grooves on plastics with rounded cells.
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observations, along with detections of hydrocarbon-degrading bacteria genes on marine plastics [27] and experiments demonstrating that marine bacteria can biodegrade polymers [27,39–43], strongly suggest that plastic biodegradation is occurring at the sea surface. Such process could partially explain why quantities of millimeter-sized marine plastics are not increasing as much as expected [2,7]. Studies of the "Plastisphere" from different marine regions worldwide will prove invaluable for extending our knowledge on epiplastic marine microbial communities, and may support the development of biotechnological solutions for better plastic waste disposal practices [68–70].

A number of invertebrates inhabited the small plastics examined here: bryozoans, barnacles *Lepas* spp., an Asellota isopod, a marine worm, and eggs of the marine insect *Halobates* sp. Even though microplastic-associated animals are rare and less diverse when compared to those associated with macroplastics [28–38], ecological implications of this phenomenon may be significant (e.g. [48]), given the large quantities and wide distribution ranges of millimeter-sized plastics in the marine environment [1–6,22,23]. Among the effects plastic associates may have is to shape 'epiplastic' microbiota by hosting unique epizoic assemblages on their bodies. For instance, the bryozoan colonies examined here covered a large proportion of their plastic-host, with some of them

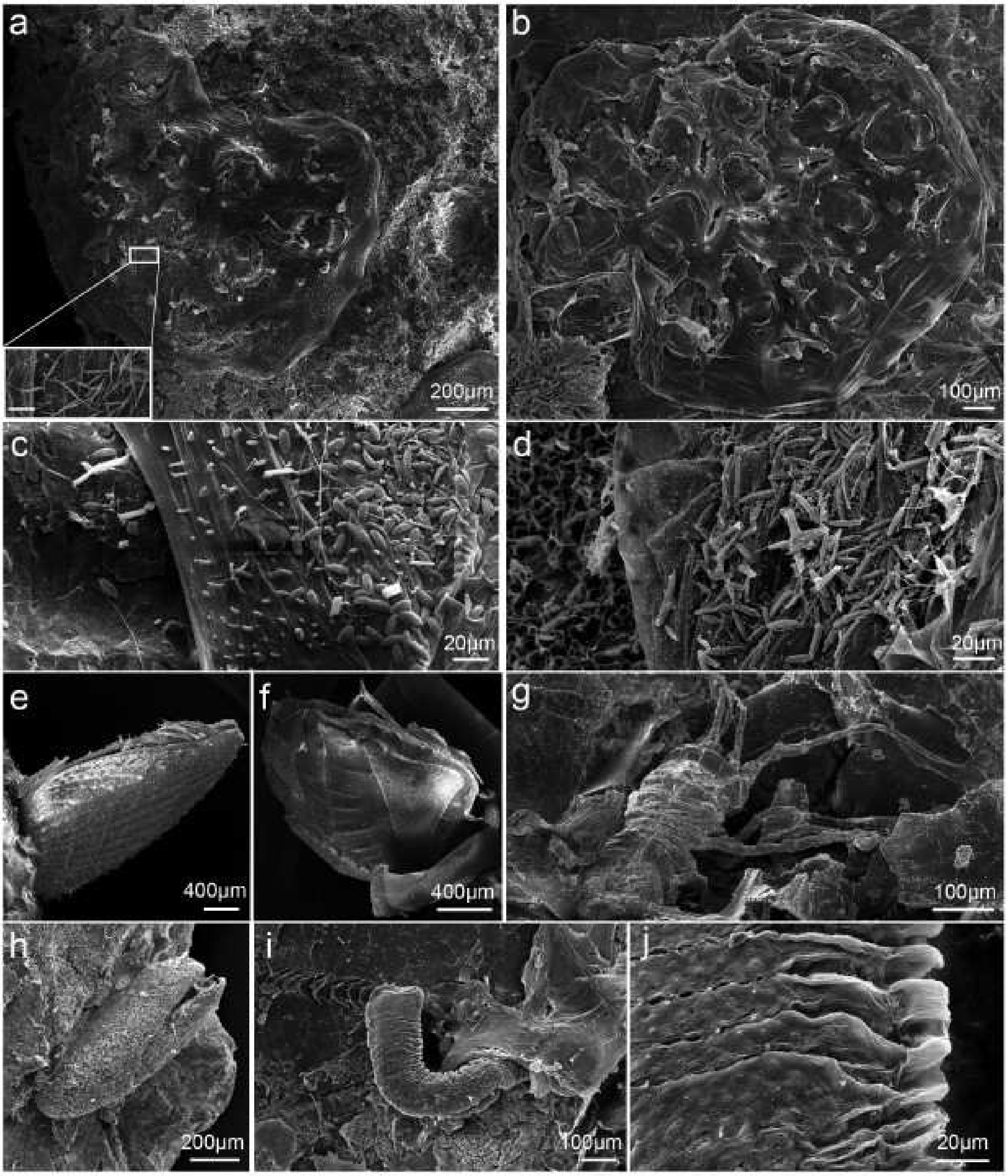

Figure 7. Examples of epiplastic invertebrates. a: Bryozoan colony harboring an abundant assemblage of *Nitzschia longissima* (zoomed image shows part of this assemblage, scale bar = 20 µm); b: bryozoan colony relatively free of fouling; c: bryozoan-plastic interface displaying an abundant epizoic assemblage of *Amphora* sp.; d: bryozoan-plastic interface displaying an abundant epizoic assemblage of *Nitzschia* sp.; e, f: barnacles (*Lepas* spp.); g: Asellota isopod; h: egg of the marine insect *Halobates* sp.; i: marine worm; j: zoom on the surface of the unidentified marine worm.
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harboring unique diatom-dominated assemblages. Previous studies have shown that bryozoans do not represent neutral surfaces for microbial colonizers [71,72], with some species offering a favorable habitat for diatoms when compared to the surrounding

Table 1. List of known genera occurring on millimeter-sized pelagic plastics.

Group	Abundance/FO	Genera
Bacteria[a,b,c,d,j]	[d]1833 per mm^{-2}	*Acinetobacter*[b], *Albidovulum*[b], *Alteromonas*[b], *Amoebophilus*[b], *Bacteriovorax*[b], *Bdellovibrio*[b], *Blastopirellula*[b], *Devosia*[b], *Erythrobacter*[b], *Filomicrobium*[b], *Fulvivirga*[b], *Haliscomenobacter*[b], *Hellea*[b], *Henriciella*[b], *Hyphomonas*[b], *Idiomarina*[b], *Labrenzia*[b], *Lewinella*[b], *Marinosdllum*[b], *Microscilla*[b], *Muricauda*[b], *Nitratireductor*[b], *Oceaniserpentilla*[b], *Parvularcula*[b], *Pelagibacter*[b], *Phycisphaera*[b], *Phormidium*[b], *Pleurocapsa*[b], *Prochlorococcus*[b], *Pseudoalteromonas*[b], *Pseudomonas*[b], *Psychrobacter*[b], *Rhodovulum*[b], *Rivularia*[b], *Roseovarius*[b], *Rubrimonas*[b], *Sediminibacterium*[b], *Synechococcus*[b], *Thalassobius*[b], *Thiobios*[b], *Tenacibaculum*[b], *Thalassobius*[b], *Vibrio*[b]
Diatoms[a,b,c,d,f]	[a]77.9%[d] 1188 per mm^{-2}	***Amphora***[a], ***Achananthes***[a], *Chaetoceros*[b], ***Cocconeis***[a], *Cyclotella*[c], ***Cymbella***[a], ***Grammatophora***[a], ***Haslea***[a], ***Licmophora***[a], *Mastogloia*[a,c], ***Microtabella***[a], ***Minidiscus***[a], *Navicula*[b], *Nitzschia*[a,b], *Pleurosigma*[c], *Sellaphora*[b], *Stauroneis*[b], ***Thalassionema***[a], ***Thalassiosira***[a]
Coccoliths[a,d,b]	[a]8.8%	***Calcidiscus***[a], ***Emiliania***[a], ***Gephyrocapsa***[a], ***Umbellosphaera***[a], ***Umbilicosphaera***[a], ***Coccolithus***[a], ***Caldosolenia***[a]
Bryozoa[a,e,f]	[a]8.8%	*Membranipora*[f], *Jellyella*[e], *Bowerbankia*[e], *Filicrisia*[e]
Hydroids[c,e]	–	*Clytia*[f], *Gonothyraea*[f], *Obelia*[e]
Polychaete[g]	–	*Spirorbis*[g], *Hydroides*[g]
Dinoflagellates[a,b,d]	[a]1.5%	*Alexandrium*[a], *Ceratium*[d]
Insect eggs[a,h,i]	[a]2.9%	*Halobates*[a,h,i]
Barnacles[a]	[a]2.9%	***Lepas***[a]
Rhodophyta[b,g]	–	*Fosliella*[g]
Foraminifera[g]	–	*Discorbis*[g]
Radiolaria[b,d]	–	*Circorrhegma*[d]
Ciliate[b]	–	*Ephelota*[b]

Organism groups (first column), their abundance and/or frequency of occurrence (when available; second column), and genera (third column). References are indicated by superscript letters and given at the bottom of the table, along with approximate length range of plastics examined. Genera in bold indicate those first detected in this study.
[a]This study (1.7–24.3 mm),
[b]Zettler et al. 2013 (2–20 mm) [27],
[c]Carpenter and Smith 1972 (2.5–5 mm) [22],
[d]Carson et al. 2013 (1–10 mm) [26],
[e]Goldstein et al. 2014 (4–5 mm) [38],
[f]Gregory 1978 (2–5 mm) [24],
[g]Gregory 1983 (1–5 mm) [25],
[h]Majer et al. 2012 (2–5 mm) [74],
[i]Goldstein et al. 2012 (1.2–6.5 mm) [48],
[j]Carpenter et al. 1972 (0.1–2 mm) [23].
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substratum (e.g. by protecting against predators and supplying nutrients through flow generated by polypids [73]). Further studies focusing on both epiplastic microorganisms and invertebrates have the potential to further elucidate symbiotic and/or competitive relationships between inhabitants of this new type of pelagic habitat.

In summary, this study showed that millimeter-sized marine plastics are providing a new niche for several types of microorganisms and some invertebrates. This phenomenon has considerable ecological ramifications and deserves further research. As discussed here, additional observational and experimental studies on the inhabitants of these small plastic fragments may better elucidate several key plastic pollution processes that remain poorly assessed, such as at-sea polymer degradation and mineralisation, impacts of epiplastic communities on their consumers, and changes in the distributional range of species by plastic rafting.

Supporting Information

Figure S1 Examples of marine plastics' surface textures. a, d: polypropylene plastics with linear fractures and pits; b, c: higher magnification of the plastic surface shown in 'a' (note very similar pits – one empty and one with a cell conforming its shape); e: higher magnification of the plastic surface shown in 'd' (note three equally spaced deep pits); f: polyethylene soft plastic with linear fractures, producing squared microplastics; g: higher magnification of the plastic surface shown in 'f' (note shallow pits likely formed by *Cocconeis* sp.); h: rounded scrape mark similar to the ones found close to the worm-like animal (see Figure 6i); i,k: sub-parallel scrape marks; j: large plastic pit likely formed by an egg of *Halobates* sp.
(TIF)

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Conceived and designed the experiments: JR JS GH MP DKAB MT CW BDH CP. Performed the experiments: JR JS GH MP DKAB CW. Analyzed the data: JR JS GH MP DKAB. Contributed reagents/materials/analysis tools: JR JS MP MT CW BDH CP. Wrote the paper: JR JS GH MP DKAB.

References

1. Eriksen M, Maximenko N, Thiel M, Cummins A, Lattin G, et al. (2013) Plastic pollution in the South Pacific subtropical gyre. Marine Pollution Bulletin 68: 71–76.
2. Law KL, Morét-Ferguson S, Maximenko NA, Proskurowski G, Peacock EE, et al. (2010) Plastic accumulation in the North Atlantic subtropical gyre. Science 329: 1185–1188.
3. Moore CJ, Moore SL, Leecaster MK, Weisberg SB (2001) A comparison of plastic and plankton in the North Pacific central gyre. Marine Pollution Bulletin 42: 1297–1300.
4. Reisser J, Shaw J, Wilcox C, Hardesty BD, Proietti M, et al. (2013) Marine plastic pollution in waters around Australia: characteristics, concentrations, and pathways. PLOS ONE 8(11): e80466.
5. Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for identification and quantification. Environmental Science & Technology 46: 3060–3075.
6. Morét-Ferguson S, Law KL, Proskurowski G, Murphy EK, Peacock EE, et al. (2010) The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Marine Pollution Bulletin 60: 1873–1878.
7. Law KL, Moret-Ferguson S, Goodwin DS, Zettler ER, DeForce E, et al. (2014) Distribution of surface plastic debris in the eastern Pacific Ocean from an 11-year dataset. Environmental Science & Technology 48: 4732–4738.
8. Teuten EL, Saquing JM, Knappe DR, Barlaz MA, Jonsson S, et al. (2009) Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 2027–2045.
9. Rochman CM, Browne MA, Halpern BS, Hentschel BT, Hoh E, et al. (2013) Policy: Classify plastic waste as hazardous. Nature 494: 169–171.
10. Mato Y, Isobe T, Takada H, Kanehiro H, Ohtake C, et al. (2001) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environmental Science & Technology 35: 318–324.
11. Rios LM, Moore C, Jones PR (2007) Persistent organic pollutants carried by synthetic polymers in the ocean environment. Marine Pollution Bulletin 54: 1230–1237.
12. Gassel M, Harwani S, Park J-S, Jahn A (2013) Detection of nonylphenol and persistent organic pollutants in fish from the North Pacific Central Gyre. Marine Pollution Bulletin 64: 2374–2379.
13. Basheer C, Lee HK, Tan KS (2004) Endocrine disrupting alkylphenols and bisphenol-A in coastal waters and supermarket seafood from Singapore. Marine Pollution Bulletin 48: 1161–1167.
14. Boerger CM, Lattin GL, Moore SL, Moore CJ (2010) Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Marine Pollution Bulletin 60: 2275–2278.
15. Choy CA, Drazen JC (2013) Plastic for dinner? Observations of frequent debris ingestion by pelagic predatory fishes from the central North Pacific. Marine Ecology Progress Series 485: 155–163.
16. Cole M, Lindeque P, Fileman E, Halsband C, Goodhead RM, et al. (2013) Microplastic ingestion by zooplankton. Environmental Science & Technology 47: 6646-6655.
17. Fossi MC, Panti C, Guerranti C, Coppola D, Giannetti M, et al. (2012) Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (Balaenoptera physalus). Marine Pollution Bulletin 64: 2374–2379.
18. von Moos N, Burkhardt-Holm P, Köhler A (2012) Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure. Environmental Science & Technology 46: 11327–11335.
19. Rochman CM, Hoh E, Kurobe T, Teh S (2013) Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Nature 3: 3263.
20. Wright SL, Thompson RC, Galloway TS (2013) The physical impacts of microplastics on marine organisms: A review. Environmental Pollution 178: 483–492.
21. Carson HS, Colbert SL, Kaylor MJ, McDermid KJ (2011) Small plastic debris changes water movement and heat transfer through beach sediments. Marine Pollution Bulletin 62: 1708–1713.
22. Carpenter EJ, Smith K (1972) Plastics on the Sargasso Sea Surface. Science 175: 1240–1241.
23. Carpenter EJ, Anderson SJ, Harvey GR, Miklas HP, Peck BB (1972) Polystyrene spherules in coastal waters. Science 178: 749–750.
24. Gregory MR (1978) Accumulation and distribution of virgin plastic granules on New Zealand beaches. New Zealand Journal of Marine and Freshwater Research 12: 399-414.
25. Gregory MR (1983) Virgin plastic granules on some beaches of eastern Canada and Bermuda. Marine Environmental Research 10: 73–92.
26. Carson HS, Nerheim MS, Carroll KA, Eriksen M (2013) The plastic-associated microorganisms of the North Pacific Gyre. Marine Pollution Bulletin 75: 126–132.
27. Zettler ER, Mincer TJ, Amaral-Zettler LA (2013) Life in the 'Plastisphere': Microbial communities on plastic marine debris. Environmental Science & Technology 47: 7137–7146.
28. Winston JE (1982) Drift plastic–An expanding niche for a marine invertebrate? Marine Pollution Bulletin 13: 348–351.
29. Jokiel PL (1990) Long-distance dispersal by rafting: reemergence of an old hypothesis. Endeavour 14: 66–73.
30. Barnes DK (2002) Biodiversity: invasions by marine life on plastic debris. Nature 416: 808–809.
31. Masó M, Garcés E, Pagès F, Camp J (2003) Drifting plastic debris as a potential vector for dispersing Harmful Algal Bloom (HAB) species. Scientia Marina 67: 107–111.
32. Barnes DK, Fraser KP (2003) Rafting by five phyla on man-made flotsam in the Southern Ocean. Marine Ecology Progress Series 262: 289-291.
33. Barnes D (2004) Natural and plastic flotsam stranding in the Indian Ocean. The Effects of Human Transport on Ecosystems: Cars and Planes, Boats and Trains Davenport, D & Davenport, J(Eds) Royal Irish Academy, Dublin: 193–205.
34. Gregory MR (2009) Environmental implications of plastic debris in marine settings–entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 2013–2025.
35. Fortuño J, Masó M, Sáez R, De Juan S, Demestre M (2010) SEM microphotographs of biofouling organisms on floating and benthic plastic debris. Rapp Comm int Mer Médit 39: 358.
36. Thiel M, Gutow L (2005) The ecology of rafting in the marine environment. II. The rafting organisms and community. Oceanography and Marine Biology: An Annual Review 43: 279–418.
37. Aliani S, Molcard A (2003) Hitch-hiking on floating marine debris: macrobenthic species in the Western Mediterranean Sea. Migrations and Dispersal of Marine Organisms: Springer. 59-67.
38. Goldstein MC, Carson HS, Eriksen M (2014) Relationship of diversity and habitat area in North Pacific plastic-associated rafting communities. Marine Biology 161: 1441–1453.
39. Balasubramanian V, Natarajan K, Hemambika B, Ramesh N, Sumathi C, et al. (2010) High-density polyethylene (HDPE)-degrading potential bacteria from marine ecosystem of Gulf of Mannar, India. Letters in Applied Microbiology 51: 205–211.
40. Artham T, Doble M (2009) Fouling and degradation of polycarbonate in seawater: field and lab studies. Journal of Polymers and the Environment 17: 170–180.
41. Sudhakar M, Trishul A, Doble M, Suresh Kumar K, Syed Jahan S, et al. (2007) Biofouling and biodegradation of polyolefins in ocean waters. Polymer Degradation and Stability 92: 1743–1752.
42. Harshvardhan K, Jha B (2013) Biodegradation of low-density polyethylene by marine bacteria from pelagic waters, Arabian Sea, India. Marine Pollution Bulletin 77: 100–106.
43. Harrison JP, Sapp M, Schratzberger M, Osborn AM (2011) Interactions between microorganisms and marine microplastics: a call for research. Marine Technology Society Journal 45: 12–20.
44. Andrady AL (2011) Microplastics in the marine environment. Marine Pollution Bulletin 62: 1596–1605.
45. Lobelle D, Cunliffe M (2011) Early microbial biofilm formation on marine plastic debris. Marine Pollution Bulletin 62: 197–200.
46. Ye S, Andrady AL (1991) Fouling of floating plastic debris under Biscayne Bay exposure conditions. Marine Pollution Bulletin 22: 608–613.
47. Pham P, Jung J, Lumsden J, Dixon B, Bols N (2012) The potential of waste items in aquatic environments to act as fomites for viral haemorrhagic septicaemia virus. Journal of Fish Diseases 35: 73–77.
48. Goldstein MC, Rosenberg M, Cheng L (2012) Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biology Letters 8: 817–820.
49. Reisser J, Shaw J, Wilcox C, Hardesty BD, Proietti M, et al. (2013) Data from: Marine Plastic Pollution in waters around Australia: characteristics, concentrations, and pathways. Figshare.
50. Cheng L (1976) Marine Insects. University of California: 581p.
51. Hallegraeff GM, Bolch C, Hill D, Jameson I, LeRoi J, et al. (2010) Algae of Australia: phytoplankton of temperate coastal waters. Australia. 421 p.
52. Kensley B (1994) Redescription of *Ischiosargata* Sivertsen & Holthuis, 1980 from the South Atlantic Ocean (Crustacea: Isopoda: Asellota). Proceedings of the Biological Society of Washington 107: 274–282.

53. Magalhães W, Bailey-Brock J (2012) Capitellidae Grube, 1862 (Annelida: Polychaeta) from the Hawaiian Islands with description of two new species. Zootaxa 3581: 1–52.
54. Weise W, Rheinheimer G (1977) Scanning electron microscopy and epifluorescence investigation of bacterial colonization of marine sand sediments. Microbial Ecology 4: 175–188.
55. Ferreira T, Rasband W (2012) ImageJ User Guide. 198.
56. Paulrud S, Mattsson JE, Nilsson C (2002) Particle and handling characteristics of wood fuel powder: effects of different mills. Fuel Processing Technology 76: 23–39.
57. Cooper DA, Corcoran PL (2010) Effects of mechanical and chemical processes on the degradation of plastic beach debris on the island of Kauai, Hawaii. Marine Pollution Bulletin 60: 650–654.
58. Corcoran PL, Biesinger MC, Grifi M (2009) Plastics and beaches: A degrading relationship. Marine Pollution Bulletin 58: 80–84.
59. Reisser J, Shaw J, Hallegraeff G, Proietti M, Barnes D, et al. (2014) Data from: Millimeter-sized Marine Plastics: A New Pelagic Habitat for Microorganisms and Invertebrates. Figshare.
60. Congestri R, Albertano P (2011) Benthic Diatoms in Biofilm Culture. The Diatom World: Springer. 227–243.
61. Tiffany MA (2011) Epizoic and Epiphytic Diatoms. The Diatom World: Springer. 195–209.
62. Carpenter EJ (1970) Diatoms attached to floating *Sargassum* in the western Sargasso Sea 1. Phycologia 9: 269–274.
63. Reisser J, Proietti M, Sazima I (2010) First record of the silver porgy (*Diplodus argenteus*) cleaning green turtles (*Chelonia mydas*) in the south-west Atlantic. Marine Biodiversity Records 3: e75.
64. Romagnoli T, Totti C, Accoroni S, De Stefano M, Pennesi C (2014) SEM analysis of the epibenthic diatoms on *Eudendrium racemosum* (Hydrozoa) from the Mediterranean Sea. Turkish Journal of Botany 38.
65. Totti C, Poulin M, Romagnoli T, Perrone C, Pennesi C, et al. (2009) Epiphytic diatom communities on intertidal seaweeds from Iceland. Polar Biology 32: 1681–1691.
66. Polovina JJ, Howell EA, Abecassis M (2008) Ocean's least productive waters are expanding. Geophysical Research Letters 35.
67. Kawamura T, Saido T, Takami H, Yamashita Y (1995) Dietary value of benthic diatoms for the growth of post-larval abalone *Haliotis discus hannai*. Journal of Experimental Marine Biology and Ecology 194: 189–199.
68. Sangale M, Shahnawaz M, Ade A (2012) A review on biodegradation of polythene: the microbial approach. J Bioremed Biodeg 3.
69. Sivan A (2011) New perspectives in plastic biodegradation. Current Opinion in Biotechnology 22: 422–426.
70. Webb HK, Arnott J, Crawford RJ, Ivanova EP (2012) Plastic degradation and its environmental implications with special reference to poly (ethylene terephthalate). Polymers 5: 1–18.
71. Scholz J, Hillmer G (1995) Reef-bryozoans and bryozoan-microreefs: control factor evidence from the Philippines and other regions. Facies 32: 109–143.
72. Kittelmann S, Harder T (2005) Species-and site-specific bacterial communities associated with four encrusting bryozoans from the North Sea, Germany. Journal of Experimental Marine Biology and Ecology 327: 201–209.
73. Wuchter C, Marquardt J, Krumbein WE (2003) The epizoic diatom community on four bryozoan species from Helgoland (German Bight, North Sea). Helgoland Marine Research 57: 13–19.
74. Majer A, Vedolin M, Turra A (2012) Plastic pellets as oviposition site and means of dispersal for the ocean-skater insect *Halobates*. Marine Pollution Bulletin 64: 1143–1147.

Appendix I. Global research priorities to mitigate plastic pollution impacts on marine wildlife. Endangered Species Research 2014 in press.

Global research priorities to mitigate plastic pollution impacts on marine wildlife

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Abstract

Marine wildlife faces a growing number of threats across the globe, and the survival of many species and populations are dependent on conservation action. One threat in particular that has emerged over the last four decades is the pollution of oceanic and coastal habitats with plastic debris. The increased occurrence of plastics in marine ecosystems mirrors the increased prevalence of plastics in society, and reflects the high durability and persistence of plastics in the environment. In an effort to guide future research and assist mitigation approaches to marine conservation, we have generated a list of 17 priority research questions based on the expert opinions of 26 researchers from around the world, whose research expertise spans several disciplines, and covers each of the world's oceans and the taxa most at risk from plastic pollution. This paper highlights a growing concern related to threats posed to marine wildlife from microplastics and fragmented debris, the need for data at scales relevant to management, and the urgent need to develop interdisciplinary research and management partnerships to limit the release of plastics into the environment and curb future impacts of plastic pollution.

Key words - Marine wildlife, plastic, pollution, priority, global

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Introduction

As a material, plastic has existed for just over a century (Gorman 1993) and mass production began in earnest in the 1950s (Beall 2009). By 1988, 30 million tons of plastic products were produced annually (O'Hara et al. 1988), reaching 265 million tons by 2010 (PEMRG 2011) and accounting for eight percent of global oil production (Thompson et al. 2009). Most plastic products are lightweight, inexpensive, and durable. These defining characteristics make plastics a convenient material for the manufacture of everyday products. However, these same attributes make plastics a threat to ecosystems due to their persistence in terrestrial, aquatic and marine environments. Marine litter, plastic pollution in particular, is ubiquitous and in fact the proportion (in terms of mass) of ocean debris that is plastic increases with distance from the source (Gregory & Ryan 1997). Plastic pollution is now recognized worldwide as an important stressor for many species of marine wildlife and their habitats (Moore 2008).

Marine wildlife is impacted by plastic pollution through entanglement, ingestion, bioaccumulation, and changes to the integrity and functioning of their habitats. While macroplastic debris is the main contributor to entanglement, both micro and macro debris are ingested across a wide range of marine species. The impacts to marine wildlife are now well established for many taxa, including mammals (Laist 1987, 1997, Page et al. 2004), seabirds (Laist 1997, van Franeker et al. 2011), sea turtles (Beck & Barros 1991, Tomas et al. 2002, Wabnitz & Nichols 2010, Guebert-Bartholo et al. 2011, Lazar & Gračan 2011, Shuyler et al. 2013), fish (Boerger et al. 2010, Possatto et al. 2011, Ramos et al. 2012, Dantas et al. 2013, Choy & Drazen 2013), and a range of invertebrates (Chiappone et al. 2005). Over 170 marine species have been recorded to ingest man-made polymers that could cause life-threatening complications such as gut impaction and perforation, reduced food intake and transfer of toxic compounds (Müller et al. 2012). Although marine debris affects many species (Laist 1997, Convention on Biological Diversity 2012), there are limited data from which to evaluate the collective impact at community and population levels, even for a single species.

Until recently, the vast expanse of the ocean coupled with the perceived abundance of marine life led resource managers to dismiss the proliferation of plastic debris as a potential hazard and to overlook this significant threat (Derraik 2002). Researchers began studying the occurrence and consequences of macro categories of plastic debris in coastal and marine environments during the 1970s. However, once in the marine environment, plastics degrade and fragment into smaller pieces. Scientists are now increasingly aware that these fragments of plastic or small virgin plastic pellets pose a substantial threat to marine biota (Carpenter & Smith 1972, Derraik 2002, Barnes et al. 2009, Ivar do Sul & Costa 2013). Since the discovery of microplastics in the North Atlantic (Carpenter & Smith 1972, Carpenter et al. 1972) and through subsequent research on the continued accumulation of plastic in all ocean basins (e.g. Moore et al. 2001, Law et al. 2010, Titmus & Hyrenbach 2011, Eriksen et al. 2013), the significance of plastic pollution as a threat to marine wildlife has been increasingly recognized at international (e.g. UNEP 2009) and national (e.g. Australia's Marine Debris Threat Abatement Plan and the U.S. NOAA Marine Debris Task Force) scales. However, despite increased scientific and public awareness, gaps in our knowledge of the prevalence and impacts of plastic pollution persist, and it remains challenging to both better understand and mitigate the effects of this type of material on marine species and ecosystems.

Given ongoing plastic production and the related problem of increasing amounts of plastic debris in oceans, it is timely to identify key areas in which we need to further our understanding of plastic pollution to enable effective mitigation of the impacts of plastic debris on marine wildlife. In a similar fashion to Hamann et al. (2010), Donlan et al. (2010), Sutherland et al. (2011) and Lewison et al. (2012), we develop a list of priority research questions that could aid the control and mitigation of impacts from plastic pollution on marine wildlife and habitats. Our study differs from previous priority setting studies because this is the first study that brings together leading marine pollution and marine wildlife experts from around the world to address knowledge gaps for an important threatening process impacting on marine habitats and many species of marine wildlife.

Methods

To quantify the global research effort on the topic of plastic pollution in the marine environment, we searched the Scopus literature database (up to December 2013) for publications related to plastic pollution in the marine environment using combinations of the search terms 'MARINE + PLASTIC POLLUTION', 'MARINE + LITTER and 'MARINE DEBRIS'. We repeated the search adding terms to allow quantification of research effort on air breathing marine wildlife "MARINE TURTLES" or "SEA BIRDS" or "MARINE MAMMALS". From the literature output on marine wildlife we compiled a list of 46 authors with either more than one peer-reviewed paper on plastic pollution published between 2007 to 2012, or one or more publications cited more than five times by others. The 46 authors were invited to suggest up to 10 priority research questions to assist the mitigation of plastic pollution impacts on marine wildlife and associated ecosystems.

A total of 26 (13 male and 13 female) marine scientists contributed 196 initial research questions. These scientists were based in nine countries and represented working experience from all oceans where plastic pollution is known to affect marine fauna and their habitats, specifically: Eastern Pacific (16% of authors), Central Pacific (10%), Western Pacific (16%), Western Atlantic (10%), Central Atlantic (6%), Eastern Atlantic and Mediterranean (9%), Indian Ocean (16%), Southern Ocean (10%), South Atlantic (6%). Questions were then compiled and sorted to reduce redundancy and to create overarching categorical questions as per Hamann et al. (2010) and Lewison et al. (2012). Based on these responses, we assembled a final list of 16 priority research questions, which are presented in no particular order of importance (see Table 1). Following each question, we include a summary of information related to the question topic and suggestions for further research.

Results

Literature search

Our literature search identified 561 publications from 192 scientific journals on various aspects of marine plastic pollution (Fig. 1). Approximately half (47%) were published in Marine Pollution Bulletin. The first publications of plastic pollution appeared in the scientific literature in the 1960s, and by the mid-1980s marine ecologists were starting to acknowledge that plastic debris in the ocean would have significant long-term impacts on marine ecology (see Shomura and Yoshida 1985 and the special edition of Marine Pollution Bulletin 1987, volume 18, 6B). Of the 561 publications, 143 were related to interactions of marine plastic pollution with air-breathing marine species. In addition, the Proceedings of the First International Marine Debris Conference included 11 abstracts documenting marine plastic pollution interactions with marine wildlife (Shomura & Yoshida 1985). Some of these were likely published in subsequent peer-reviewed literature. The earliest paper on the impacts of plastic pollution on wildlife reported a gannet (*Sula bassana*) with a yellow ring of plastic coated wire around its leg (Anon 1955), however, from the account provided it is not possible to determine whether it was a case of entanglement or a deliberate banding. We found the earliest accounts of ingestion were published in 1969, documenting seabirds consuming plastic (Kenyon & Kridler 1969). In the early 1970s, the first accounts of microplastics at sea emerged in the Atlantic Ocean (Carpenter et al. 1972, Carpenter & Smith 1972, Gochfeld 1973, Rothstein 1973, Hays & Cormons 1974) and the first interactions between microplastics and marine mammals and sea turtles were published in 1978 (Waldichuk 1978) and 1987 (Carr 1987) respectively, although records with marine turtles were reported in the first marine debris symposium (Balazs 1985). It is possible that we missed some of the early literature or literature contained in journals that are not indexed by online databases. However, it is evident that since the 1970s, and particularly since year 2000, there has been an increasing trend in the number of publications on plastic pollution and its relationship to marine ecosystems (Fig. 1).

Table 1. Summary table of priority research questions

Global research priorities to mitigate plastic pollution impacts on marine wildlife
1. What are the impacts of plastic pollution on the physical condition of key marine habitats?
2. What are the impacts of plastic pollution on trophic linkages?
3. How does plastic pollution contribute to the transfer of non-native species?
4. What are the species-level impacts of plastic pollution, and can they be quantified?
5. What are the population-level impacts of plastic pollution, and can they be quantified?
6. What are the impacts of wildlife entanglement?
7. How will climate change influence the impacts of plastic pollution?
8. What, and where, are the main sources of plastic pollution entering the marine environment?
9. What factors drive the transport and deposition of plastic pollution in the marine environment, and where have these factors created high concentrations of accumulated plastic?
10. What are the chemical and physical properties of plastics that enable their persistence in the marine environment?
11. What are some standard approaches for the quantification of plastic pollution in marine and coastal habitats?
12. What are the barriers to, and opportunities for, delivering effective education and awareness strategies regarding plastic pollution?
13. What are the economic and social effects of plastic pollution in marine and coastal habitats?
14. What are the costs and benefits of mitigating plastic pollution, and how do we determine viable mitigation options?
15. How can we improve data integration to evaluate and refine management of plastic pollution?
16. What are the alternatives to plastic?

Priority research questions

1. What are the impacts of plastic pollution on the physical condition of key marine habitats?

Plastic pollution now impacts all marine and coastal habitats to varying degrees. In particular, there are substantial empirical data identifying, and in some cases quantifying, the impacts of plastic and other debris in oceanic waters, on the sea floor, on sandy beaches and in other coastal environments (Fig 2). It is also clear that effects on habitat condition are not uniform, and depend on the ecological, economic and social value attributed to the habitat, the physical environment, and the type, size, accumulation and/or degradation rates of plastic. In addition, there is substantial spatial and temporal variation in accumulation patterns, polymer type and source of plastics (e.g. Willoughby et al. 1997, Ribic et al. 2010, Eriksen et al. 2013).

Quantifying the impact of plastic pollution on the physical condition of habitats has received little attention (but see Votier et al. 2011, Bond and Lavers 2013, Lavers et al. 2013, Lavers et al. 2014) relative to impacts of plastic pollution on organisms (e.g. Derraik 2002, Gregory 2009). However, in intertidal habitats, accumulation of plastic debris has been shown to alter key physico-chemical processes such as light and oxygen availability (Goldberg 1997) and temperature and water movement (Carson et al. 2011). This leads to alterations in macro- and meiobenthic communities (Uneputty & Evans 1997) and interruption of foraging patterns of key species (Aloy et al. 2011). On sandy beaches, the occurrence of microplastics may change permeability and temperature of sediments with consequences for animals with temperature-dependent sex-determination, such as some reptiles (Carson et al. 2011). In addition, heavy fouling can lead to loss of important biogenic habitat, which may have considerable flow-on effects to broader ecosystem processes (Smith 2012). Large plastic debris may change the biodiversity of habitats locally by altering the availability of refugia and providing hard surfaces for taxa that would otherwise be unable to settle in such habitats (Katsanevakis et al. 2007). Similar observations have been made in subtidal habitats, including the deep sea (Watters et al. 2010, Schlining et al. 2013).

In tropical and subtropical shallow-water coral reef habitats decline in the condition of corals has been attributed to progressive fouling caused by entangled fishing line, as well as direct suffocation, abrasion and shading of fouled colonies caused by nets (Yoshikawa & Asoh 2004, Richards & Beger 2011). This may contribute to ecological phase-shifts at heavily affected sites (Asoh et al. 2004, Yoshikawa & Asoh 2004, Richards & Beger 2011). Taxa with branching morphologies (e.g. gorgonians, sponges, milleporid and scleractinian corals, macroalgae and seagrass) are most likely to be affected by entanglement. While some taxa may be able to overgrow entangling debris, it is unclear how this may affect their integrity, longevity, and resilience to change (Chiappone et al. 2005, Smith & Hattori 2008).

Overall there is a general bias toward studies reporting on impacts of plastic pollution on the condition of sandy beaches and urban coastlines, and less knowledge on the condition of other habitats (e.g. estuaries, mangroves, benthic habitats, deep sea zones), especially those in remote areas with limited human access. Hence, advancing knowledge about how plastic pollution impacts the condition of diverse marine habitats remains a priority. Useful starting points would be 1) field based experimental research that either documents change in condition/ function of habitats or establishes thresholds of concern that can be then used as indicators for monitoring and 2) Design and testing of survey techniques to determine baseline condition and/or changes to condition in remote or difficult to access habitats. These could include the application of rapid assessment techniques, remote sensing or citizen science. Fulfilling these knowledge gaps is important because information on habitat condition can assist management agencies in quantifying the degree of impact, setting priorities, and implementing mitigation.

2. What are the impacts of plastic pollution on trophic linkages?

Ingestion of microplastic has been reported in almost every level of the marine food web, from filter-feeding marine invertebrates (Wright et al. 2013), to fishes (Choy & Drazen 2013, Boerger et al. 2010), seabirds, sea turtles and marine mammals (Fig 3, see Q4, and 5). Plankton and plastic particles <333 µm in size co-occur in marine systems and smaller (<100 µm) diameter polymer fibers have been identified in sediments suggesting that plastics exposure is occurring at the base of the food web (Thompson et al. 2004, Browne et al. 2011). Recent studies have identified impacts to marine invertebrates associated with foraging on nano- and microparticles of polystyrene (Wegner et al. 2012, Besseling et al. 2013) and laboratory studies have demonstrated and examined plastic ingestion by zooplankton (e.g. De Mott 1988, Bern 1990, Cole et al. 2013). There is also recent evidence that ingested microplastics can bridge trophic levels into crustaceans and other secondary consumers (Farrell & Nelson 2013). Furthermore, recent research has detected plastic-derived compounds in the tissues of seabirds that had consumed plastics (Lavers et al. 2013, Tanaka et al. 2013, Lavers et al. 2014; see Q4,5).

When taken in conjunction, it is clear that plastic pollution is impacting food webs through ingestion and bioaccumulation of particles and toxic chemicals and thus is likely to be influencing ecosystem processes in ways that have yet to be elucidated. In particular, there is a need to better understand the influence of nano- and microplastics on zooplankton and planktivorous species (especially in a natural setting), the role(s) of plastic ingestion at several trophic levels in the transfer of organic pollutants along the food chain, and the influence of plastic pollution on epipelagic ecosystems (e.g. Ryan & Branch 2012, Setälä et al. 2014). Fulfilling these knowledge gaps will require developments in both field and laboratory science. From a laboratory research perspective useful starting points would be improving knowledge of plastic chemistry and the fate of chemicals in biological systems as well as thresholds of concern. From a field science perspective more knowledge is needed about rates and patterns of accumulation; a starting point could be the development of biological indicators, such as investigating the use of "plastic in fish-gut treatments" (e.g. on large factory trawlers) that have low-labor inputs but sample large numbers of planktivorous fish with acceptable precision and measurable variance.

3. How does plastic pollution contribute to the transfer of non-native species?

A number of transport mechanisms exist for the transfer of marine species to non-native environments, such as hull fouling, ballast water, aquaculture, dry ballast, rafting, and the aquarium trade (Orensanz et al. 2002, Hewitt et al. 2004a,b, Haydar 2012). However, relatively little is known about species rafting (as biofouling) on plastic debris or non-native bacterial biofouling of plastics (i.e. biofilms) (yet see Winston et al. 1997, Lobelle & Cunliffe 2011). Introduced species have a higher propensity to foul man-made substrates, such as plastics (Whitehead et al. 2011), than native species (Wyatt et al. 2005, Glasby et al. 2007, Tamburri et al. 2008). Couple this propensity with the durability and persistence of plastics, and the likelihood of plastics transporting non-native species increases substantially. Consequently, species that have a propensity to foul plastic will have a greater likelihood of dispersing further by rafting or hitchhiking on debris.

A wide range of species is known to foul debris, and the level and composition of fouling of debris varies spatially and temporally (e.g. Ye & Andrady 1991, Artham et al. 2009) with the type of substrate and the distance from source areas (and hence residence time at sea). For example, Whitehead et al. (2011) determined that of stranded debris in South Africa, kelp and plastics were the most frequently colonized (33% and 29%, respectively). In contrast, Widmer and Hennemann (2010) reported that only 5% of marine debris was biofouled in southern Brazil (27°S), of which 98% of items were plastic (Widmer & Hennemann 2010).

To date, relatively few published articles have focused on rafting of introduced species on plastic debris. Although the biomass of fouling species carried by plastic debris is far less than that carried on the hulls of ships (Lewis et al. 2005), debris represents a large amount of surface area available for colonization. A key starting point would be to quantify the potential and actual contribution of rafting on plastic debris for the primary introduction of a species into a new region and then the secondary spread within that region. Another key area that warrants further investigation is to better understand the transport of non native biofilms, molecular science could offer a useful starting point (Barnes & Milner 2005, Lewis et al. 2005, Goldstein et al. 2012).

4. What are the species-level impacts of plastic pollution, and can they be quantified?

Plastic pollution affects marine species of all trophic levels, ranging from zooplankton to whales (Laist 1987, Passow & Alldredge 1999, Jacobsen et al. 2010). Both macro and micro plastic debris can affect individual species either through ingestion or entanglement (including entrapment) (Day et al. 1985, Laist 1987, Moore 2008, Ceccarelli 2009, Schuyler et al. 2012, Kaplan-Dau et al. 2009) (see Q6). Large plastic debris items, such as rope, cargo straps, fishing line, fishing pots and traps, and net, are the main contributors to entanglement, while both whole and fragmented micro and macro plastic debris is ingested across at least 170 marine vertebrate and invertebrate species (Carr 1987, Laist 1987, Bjorndal et al. 1994, Derraik 2002, Ceccarelli 2009, Boerger et al. 2010, Jacobsen et al. 2010, Baulch & Perry 2012, Fossi et al. 2012, Schuyler et al. 2012, Besseling et al. 2013). In general, the size of ingested plastic items is related to body size (e.g. Furness 1985, Ryan 1987) and ontogenetic phase (Ramos et al. 2012, Dantas et al. 2013). The degree of impact is likely related to the size, shape, and quantity of the ingested items and a range of physiological, behavioral, and geographical factors.

Ingestion effects include gut perforation, gut impaction, dietary dilution, toxin introduction, and interference with development (Ryan 1988a, Bjorndal et al. 1994, McCauley & Bjorndal 1999, Mader 2006, Teuten et al. 2009, van Franeker et al. 2011, Gray et al. 2012, Tanaka et al. 2013). Importantly, swallowed plastic does not need to be large in quantity to cause serious injury to an animal (Bjorndal et al. 1994). Gastrointestinal perforation caused by swallowed hooks and hard plastic can cause chronic infection, septicaemia, peritonitis, gastrointestinal motility disorders, and eventual death (Day et al. 1985, Jungling et al. 1994, McCauley & Bjorndal 1999, Cadee 2002, Guebert-Bartholo et al. 2011). Impaction of the gastrointestinal tract affects many species; the offending blockage can paralyze the gastrointestinal tract, inhibit the digestive process, and result in symptoms such as bloating, pain, necrosis, and mechanical abrasion or blockage of absorptive surfaces in the digestive tract (Mader 2006). Nutrient dilution is the result of a reduction of nutritious food intake due to ingestion of non-nutritive and space-occupying plastic reducing fitness and affecting both adult and juvenile animals (Day et al. 1985, Ryan 1988a, Bjorndal et al. 1994, Auman et al. 2004, McCauley & Bjorndal 1999, van Franeker et al. 2011, Gray et al. 2012).

Some species are more susceptible than others to the ingestion of marine debris. For example, sea turtles are particularly susceptible due to their feeding strategies (i.e. some specialize on jellyfish for which floating debris may be mistaken), as well as downward facing papillae on their esophageal mucosa that have evolved to allow efficient ingestion of food but that inhibit the ability of sea turtles to regurgitate,(Wyneken 2001). Seabirds, especially those that feed in oceanic convergence zones, consume plastic debris directly, but also feed it to their chicks (Ryan 1988ab, Cadee 2002, Moore 2008, Ryan 2008, van Franeker et al. 2011, Kuhn & van Franeker 2012, Verlis et al. 2013). Species that are adapted to regurgitating indigestible dietary items like squid beaks may off-load ingested debris, but species that lack these adaptations are more vulnerable to the effects of cumulative ingestion (Ryan 1988b). A useful starting point for managing species-plastic interactions could be a review that quantifies the risk each species faces within a global setting. A proxy for this review could be the mean load size of ingested plastic as a proportion of body mass or identification of long-term trends (e.g. Schuyler et al. 2013).

Causes of ingestion and entanglement need to be better understood across most marine species impacted by plastic pollution. Many studies on plastic consumption have shown species-based preferences for different colors, tastes, types, and sizes of debris, but evidence remains largely speculative (Day et al. 1985, De Mott 1988, Ryan 1987, Bjorndal et al. 1994, Bugoni et al. 2001, Cliff et al. 2002, Colabuono et al. 2009, Mrosovsky et al. 2009, Boerger et al. 2010, Denuncio et al. 2011, Gray et al. 2012, Schuyler et al. 2012, Lavers et al. 2014). Current hypotheses for why animals consume marine debris include mistaken identity (mimicking natural prey items), curiosity/play and failure of distinction (plastic debris mixed with normal dietary items) (Balazs 1985, Eriksson & Burton 2003, Schuyler et al. 2012). These hypotheses need more testing across a wide range of species and would constitute a useful starting point for future field and laboratory research. Furthermore, because the size categories and definitions for macro and micro debris vary in the literature a review (with recommendations) of ecologically relevant size classes for plastic items, in light of research findings such as overlap with plankton size ranges, would be useful (Eriksson & Burton 2003, Cole et al. 2011).

5. What are the population-level impacts of plastic pollution, and can they be quantified?

Details of long-term survivorship impacts from marine debris are poorly known, and the links between plastics and their harmful effects at the population level are not clear. Notably, survival and reproductive rates of Laysan albatrosses (*Diomedea immutabilis*) from the early 1960s on Midway are virtually identical to rates today, despite increases in the rates of plastic ingestion (Fisher 1975, van der Werf & Young 2011). For most species it is challenging to identify even the proportion of individuals impacted, let alone the population mortality rate attributable to plastic ingestion. Furthermore, most studies look at lethal impacts, as sub-lethal impacts to populations are likely to be harder to identify (Baulch & Perry 2012).

A further area of concern is the potential toxicological effect of plastic on growth rates, survivorship and reproduction, all of which are important areas for population stability. Plastic marine debris contains not only potentially harmful plasticizers incorporated at manufacture (Meeker et al. 2009), but plastics can adsorb and accumulate additional toxic chemicals such as PCBs and heavy metals from seawater (Mato et al. 2001, Ashton et al. 2010, Holmes et al. 2012, Rochman et al. 2014 and see Q15, 16). Tagatz et al. (1986) showed that high concentrations of dibutyl phthalate, a commonly used plasticizer, significantly affected the composition and diversity of macrobenthic communities. While chemicals can leach into the tissues of wildlife that ingest plastic(Teuten et al. 2009, Tanaka et al. 2013, Lavers et al. 2014) quantification of population scale effects warrants further research. Animals exposed to compounds such as phthalates and BPA showed adverse impacts on reproductive functionality, particularly during developmental stages (Talsness et al. 2009), and exposure to chemicals in ingested plastic has led to hepatic stress in fish (Rochman et al. 2013a). Adsorbed chemicals from ingested plastics such as DDTs, PCBs, and other chlorinated hydrocarbons may decrease steroid levels and lead to delayed ovulation (Azzarello & VanVleet 1987). The potential function of plasticizers as endocrine disruptors has been hypothesized to have resulted in a disproportionately high level of mortality in female fulmars (*Fulmarus glacialis*) during a 2004 stranding event (van Franeker et al. 2011, Bouland et al. 2012). However, the links between plastic ingestion and population drivers such as reproductive timing and female survivorship have yet to be shown conclusively.

To understand the long-term, population-scale impacts of plastic pollution, it is critical to assess plastic impacts on life history traits such as fecundity, reproductive success, mortality rates, and even potential behavioral changes which might influence courtship, migration, and other reproductive activities. Useful starting points for research would be quantifying baseline levels of chronic and acute exposure and the degree of both direct and indirect impact. Doing this will require both field and laboratory based physiology and ecology and the design of monitoring programs to ensure that relevant tissue samples and environmental information are collected. Furthermore, quantifying the magnitude of impacts on different populations and life stages (e.g. entanglement vs. ingestion; physical blockages vs. perforations vs. toxicological effects, and how the magnitude of these impacts compares with other stressors) would improve efficacy of various management approaches.

6. What are the impacts of wildlife entanglement?

Marine debris entanglement is now an internationally recognized threat to marine taxa (Shomura & Yoshida 1985, Kaplan-Dau et al. 2009, Gilardi et al. 2010, Allen et al. 2012) with at least 135 species recorded as ensnared in marine debris including sea snakes, turtles, seabirds, pinnipeds, cetaceans and sirenians (Laist 1997, Possatto et al. 2011, Udyawer et al. 2013). Wildlife become entangled in everything from monofilament line and rope to packing straps, hair bands, discarded hats, and lines from crab pots. Entanglement effects include abrasions, lesions, constriction, scoliosis (Wegner & Cartamil 2012), or loss of limbs, as well as increased drag, which may result in decreased foraging efficiency (Feldkamp 1985, Feldkamp et al. 1989) and reduced ability to avoid predators (Gregory 1991, 2009). To date, there are scant data overall to provide a global estimate of the number of animals affected by entanglement, mostly because reports are either restricted to opportunistic observations of animals or are from heavily visited coastal regions. Given that we likely observe only a small fraction of entangled or injured wildlife (e.g. scarring, BDH pers. obs.), actual or total rates of wildlife entanglement are not known.

Entanglement is a key factor threatening survival and persistence of some species (see Q1, Henderson 2001, Boland & Donohue 2003, Karamanlidis et al. 2008), including the northern fur seal (*Callorhinus ursinus*; Fowler

1987) and endangered species such as Hawaiian and Mediterranean monk seals (*Monachus* sp.) (Votier et al. 2011). Among marine mammals there are important age-class drivers of entanglement rates; for example, in pinnipeds, younger animals (e.g. seal pups and juveniles) may be more likely to become entangled in nets, whereas subadults and adults are more likely to become entangled in line (Henderson 2001). In general, younger, immature animals are more often reported as entangled, at least in pinniped studies for which age class is reported (Fowler 1987, Hanni & Pyle 2000, Henderson 2001). Ghost nets also ensnare cetaceans, turtles, sharks, crocodiles, crabs, lobsters, and numerous other species (Poon 2005, Gunn et al. 2010, Wilcox et al. 2013).

Overall, we lack sufficient information to determine whether injury and mortality from incidental entanglement has population-level effects on many marine species (Gilman et al. 2006). A priority research avenue is to investigate whether most entanglement occurs when wildlife encounters lost, abandoned, or derelict fishing gear, or 'ghost nets', and if there are spatial and temporal links to species entanglement in derelict fishing gear and other forms of plastic debris. If so these could have implications for fisheries management as the amount of fishing gear lost to the ocean is estimated to be 640,000 tons per year (Macfayden et al. 2009) and retrieval of nets has considerable financial, environmental and safety implications (Gilardi et al. 2010).

7. How will climate change influence the impacts of plastic pollution?

Changes to sea level, atmospheric and sea surface temperatures, ocean pH and rainfall patterns are each associated with global climate change. These factors will alter biophysical processes that in turn will influence the source, transport and degradation of plastic debris in the ocean. Coastal cities and towns represent one of the main sources of plastic pollution, serving as point sources for the flow of plastic into the sea via urban and natural drainage systems (e.g. Faris & Hart 1994). Changes to precipitation patterns could alter the rate and periodicity of plastic pollution transport into the sea and/or change the functionality of storm water filters and trash guards, reducing the ability of these systems to remove solid debris before it enters the ocean. Additionally, sea level rise and the increased frequency and duration of severe weather events may inundate waste disposal sites and landfills. Storms and rising sea levels also release litter buried in beaches and dune systems. These factors could lead to larger amounts of plastic debris deposited into the marine ecosystem through runoff, and may introduce toxic materials into the marine environment (Derraik 2002). Thiel and Haye (2006) discuss the importance of extreme weather events, such as intense hurricanes/cyclones, for transporting organisms and pollutants into and through oceanic systems. Overall, the pattern of extreme weather events is expected to change, potentially affecting the transfer of plastic pollution, and possibly, non-native, invasive species (see Q3).

Ocean currents and gyres play a significant role in the distribution and concentration of floating marine plastics (Lebreton et al. 2012). Alterations in sea surface temperatures, precipitation, salinity, terrestrial runoff, and wind are likely to influence the speed, direction, and upwelling or downwelling patterns of many ocean currents. This could, in turn, influence areas of plastic accumulation and spread plastics to previously less affected regions, altering exposure rates of marine wildlife. For example, changes to the currents interacting with the Southern Ocean may lead to the transport, establishment and spread of plastics and/or invasive species into areas such as Antarctica (Ivar do Sul et al. 2011). In addition, changes to ocean circulation could cause further damage to benthic environments through increased deposition of plastic onto the sea floor, altering the composition of normal ecosystems and causing anoxic or hypoxic conditions (Goldberg 1997).

It is clear that the impacts of climate change will vary temporally and spatially, and will affect the environment in a variety of ways. The interaction of climate change and other ecosystem stressors is an important area of research, but how climate change affects plastic pollution has yet to be investigated.

8. What, and where, are the main sources of plastic pollution entering the marine environment?

Sources of plastic pollution are extensive and are generally categorized as being either ocean- or land-based (Sheavly & Register 2007), with land-based debris recognized as the most prevalent (Gregory 1991, UNESCO 1994, Nollkaemper 1994). Land-based debris generally originates from urban and industrial waste sites, sewage and storm water outfalls, and terrestrial litter that is transported by river systems or left by beach users (Wilber 1987, Pruter 1987, Karua 1992, Williams & Simmons 1997, Santos et al. 2005, Corcoran et al. 2009, Ryan et al. 2009, Campbell 2012, O'Shea et al. 2014). Consequently, large urban coastal populations are the main source of debris (Cunningham & Wilson 2003) entering the marine environment and advected elsewhere by ocean currents (Martinez et al. 2009). Ocean-based marine debris is material either intentionally or unintentionally dumped or lost overboard from vessels (including offshore oil and gas platforms) and includes fishing gear, shipping containers, tools, and equipment (Jones 1995, Santos et al. 2005). Specific fishing-related debris includes plastic rope, nets (responsible for 'ghost fishing', Cottingham 1988), monofilament line, floats, and packaging bands on bait boxes (Jones 1995, Ivar do Sul et al. 2011).

Currently we lack sufficient understanding of the sources of plastic pollution at management-relevant scales, such as catchments, municipal areas or coastal areas. If it were possible for managers to identify the step(s) along the product disposal chain where plastic is being lost to the environment, targeted mitigation approaches could be implemented. This would likely enable cost-efficient and successful management. A key starting point for research could include; research and development of new technologies for processing waste, design and evaluation of alternate packaging types or strategies, infrastructure to prevent waste from entering the environment, techniques to remove plastic from the environment, improving the ability to recycle waste. Especially in developing nations and/or remote towns and communities or the development of rapid assessment techniques to identify polymer types (see Q11,12,13). In addition, in areas with predictable rainfall patterns (i.e. locations with distinct wet seasons), research and monitoring could focus on understanding and mitigating impacts of urban storm-water and riverine loads entering the marine environment during the "first flush".

9. What factors drive the transport and deposition of plastic pollution in the marine environment, and where have these factors created high concentrations of accumulated plastic?

In the mid-1980s, Archie Carr described the convergence zones in the Atlantic as white lines of expanded polystyrene and likened the plastic debris littering the Tortuguero Beach in Costa Rica to hailstones (Carr 1986, 1987). It is now clear that plastics are distributed throughout the world's oceans, deposited on most coastlines, and found in very remote areas including the deep sea (e.g. Convey et al. 2002, Eriksson & Burton 2003, Barnes et al. 2009, see Q8). The diverse physical and chemical nature of plastic polymers affects buoyancy, and thus influences transport and distribution of plastics in the marine water column. Transport mechanisms and the location of sources and sinks have been a research area of interest for some time. Indeed, a one-day workshop focusing on this topic was held at the 5th International Marine Debris Conference in Hawaii (Law & Maximenko 2011). Recent approaches to understanding the transport of debris have used combinations of ocean circulation models including Lagrangian particle tracking (Lebreton et al. 2012, Maximenko et al. 2012, Potemra 2012, Van Sebille et al. 2012, Carson et al. 2013) and direct tracking (e.g. using aircraft or satellites) of ghost nets (Wilcox et al. 2013, Pichel et al. 2012) and debris from the 2011 Japanese tsunami (Lebreton & Borrero 2013). Central to these recent approaches has been the rapid improvement of computing power, as well as GIS and remote sensing technology (Hamann et al. 2011).

To date, most models have been developed at large scales (global, ocean or basin): there is now a need for researchers to develop localized models to better understand near-shore transport mechanisms at scales relevant to management, such as state or national levels (e.g. Potemra 2012, Carson et al. 2013, O'Shea et al. 2014). Furthermore, the identification of sinks, not only for pollution within the water column, but also for benthic debris (Schlining et al. 2013), especially in relation to key habitat areas for marine wildlife (such as foraging areas, migration pathways and breeding sites) is needed. First steps could be the refinement of existing high-resolution hydrodynamic models and combining these models with satellite or aerial imagery, in order to understand river input, wave and wind drag influence on transport, beaching and washing of debris back into the water. This could include testing the influence of wind drag on plastic with different degrees of buoyancy and the use of 3D hydrodynamic models to improve modeling of the movement of less buoyant plastics.

10. What are the chemical and physical properties of plastics that enable their persistence in the marine environment?

Plastics absorb ultraviolet (UV) radiation and undergo photolytic, photo-oxidative, and thermo-oxidative reactions that result in degradation of their constituent polymers (Gugumus 1993, Andrady et al. 1998). The rate and process of various types of degradation of synthetic polymers is likely to depend upon a number of factors, including the bonds present within the material and the amount of light, heat, ozone, mechanical stress, or number of microorganisms present. Overall, the structure of a polymer determines its surface area, degree of crystallinity, polymer orientation, material components, accessibility to enzymes, presence of additives and degree of persistence in the environment. The polymer structure is thus critical in determining degree of the material's biodegradability (Palmisano & Pettigrew 1992). However, there are limited data to make conclusions about biodegradability for most polymer types. Additionally, little is known about how physical properties such as weight and shape determine whether or not plastics will float or be air-driven, and how long they will persist as surface pollution before sinking.

Environmental factors affecting the persistence of plastics in the environment include physical and chemical factors such as wind and wave exposure, pH, temperature, sediment structure, oxidation potential, moisture, nutrients, oxygen, and the presence of inhibitors. Microbiological factors are also likely to affect the biodegradability of plastics and these will be influenced by the distribution, abundance, diversity, activity, and adaptation of microorganisms (Palmisano & Pettigrew 1992). Additionally, activities of macrofauna, such as maceration of plastics by insects or rodents, and potentially fish, may influence the rate of biodegradation by increasing the surface area available for colonization by microorganisms.

Research has also demonstrated that plastic pellets can adsorb hydrophobic compounds such as persistent organic pollutants (POPs) from the water (Mato et al. 2001, Teuten et al. 2007, Karapanagioti et al. 2011, Holmes et al. 2012). The degree to which plastics adsorb organic pollutants from the water is likely to depend on the underlying chemical structureThis also underpins the resilience and durability of the plastic once in the environment, and when it breaks down, its degree of buoyancy (Cooper & Corcoran 2010). There are likely strong links between the chemical and physical properties of the plastic and its persistence in the marine environment, yet for most polymers, these links remain to be quantified.

Research is needed to better understand the effects of different degradation products from plastic polymers on marine wildlife. There is a need for further information on the interactions between molecular structure and physical form of plastics (including biodegradable plastics), methods of microbial attack, and environmental factors influencing degradation. A key area to start would be to understand which of the polymer types have the greatest impact on marine wildlife, and then to determine the physicochemical factors that influence the polymer degradation in order to identify steps in the manufacturing process that might be altered to reduce the generation of these polymer types. Such an understanding is critical when conducting life cycle assessments for products and common types of waste and in developing risk or threat abatement strategies. Hence this remains a key knowledge gap with substantial scope for future research.

11. What are some standard approaches for the quantification of plastic pollution in marine and coastal habitats?

Understanding rates and patterns of dispersal, accumulation and abundance of plastic in the environment is an important step toward understanding habitat and species vulnerability. However, comparisons among regions (and among studies in the same region) are handicapped by a lack of uniformity in approach to quantification (Ryan et al. 2009). A particularly common problem is the failure to standardize, or even report, the lower size range of litter items sampled, with drastic implications for resultant density estimates (Ryan 2013).

One established method of following changes in marine plastic abundance is by regular shoreline (strand-line) surveying (Cheshire et al. 2009). Although commonly employed, the technique has many challenges (Ribic & Ganio 1996, Velander & Mocogni 1999). The first is that the human propensity to stroll along beaches and pick up litter is both common and laudable. More challenging factors affecting beach surveys are the local processes that affect beach debris deposition, such as tides, wave surge, wind speed, and direction, all of which increase the temporal and spatial variances of beach surveys, making change (e.g. due to mitigating actions) harder to detect (Ryan et al. 2009, Kataoka et al. 2013). Though not commonly done on a daily basis, collection of debris each day can provide improved variance estimates (Eriksson et al. 2013, Smith and Markic 2013). Despite being challenging, shoreline cleanups can be used to increase social awareness of the issue, identify particular plastic items to target mitigation efforts (e.g. uncut strapping bands, six-pack beverage rings, plastic pellets and weather balloons) and if done systematically, provide a comparative baseline on distribution, abundance and accumulation of plastic debris (Edyvane et al. 2004, Ribic et al. 2010, 2011, 2012a, Wilcox et al. 2013, Rosevelt et al. 2013, Thiel et al. 2013, Eriksson et al. 2013). Improving data collection from beach surveys and ensuring that data collection is useful for managers will require an improved understand how local circulation and weather patterns (e.g. tide cycle, wind strength and direction, and storms) affect the number and type of plastic marine debris items that wash ashore and are washed back into the water (i.e. can be bounced along a coastline).

While debris loads on shore can reflect debris loads in coastal waters (Thiel et al. 2013), understanding debris loads in the open ocean is challenging due to economics (e.g. ship costs for dedicated surveys) and the spatial area for surveying (Morishige et al. 2007). However, these issues could be at least partially overcome by implementation of techniques that use ships of opportunity (Ryan 2013, Reisser et al. 2013), which have been used successfully for continuous at-sea monitoring of parameters such as chlorophyll, salinity, and even zooplankton. Regular data flows from instruments deployed on commercial vessels that agree to participate could be used to monitor plastic pollution loads. Additionally, it is possible that relatively "low-tech" sampling can be developed to access materials filtered from seawater intakes for engine cooling water used by shipping, ballast water sampling protocols that have been developed may be a reasonable starting point for this. Also, field techniques currently used for biological oceanographic studies could be refined or developed to quantify debris loads, particularly microplastics, e.g. plastic debris can be quantified in known volumes of sea water sieved by neuston net, plankton net or even by known surface areas and depths sampled by other means such as by pump (e.g. Hidalgo-Ruz et al. 2012, Howell et al. 2012, Eriksen et al. 2013). Larger macroplastic items (too large to be sampled by nets) can be surveyed with ship-based or aerial surveys (e.g. Lecke-Mitchell & Mullin 1997), though understanding the many biases associated with these types of surveys for plastic marine debris needs development (Ryan 2013). There may be future possibilities in using satellite imagery of the sea surface to estimate the abundance of debris and also to characterize the wavelength reflectance of plastics to distinguish them from foam and organic materials.

Irrespective of the habitat being sampled the greatest limitation to the quantification of marine plastic debris loadings remains its general dependence on the human eye. While many other disciplines overcome similar challenges to provide quantitative measures, avenues for future research would be to improve the way data on plastic pollution is collected by visual cues, refinement of sampling techniques for fragmented plastic pollution and development of a quantitative "characteristic chemical signature" analysis systems for plastic polymers. These would expand our understanding of the ubiquity of plastic items and their potential impact on marine wildlife.

12. What are the barriers to, and opportunities for delivering effective education and awareness strategies regarding plastic pollution?

Public concern over marine debris received a tremendous boost after the 1999 discovery of a region in the North Pacific in which plastic litter was accumulating, later termed the "Great Pacific Garbage Patch" (e.g. Moore et al. 2001, Moore 2008). By the mid-2000s the sensationalized media portrayal of a mythical floating island of plastic waste created a wave of outrage against the amount of plastic in the ocean. The plastics industry, environmental organizations, legislators wishing to calm constituents, and entrepreneurs of all kinds raced to understand and explain the problem and solutions on their own terms, creating a glut of misinformation about the size, contents, source, and fate of plastic in the ocean. Media strategies have ranged from dozens of short films, to a variety of advertising campaigns aired on television, the web, billboards, and in print. While it is clear that traditional and social media can work in tandem to distribute a story widely, research in the health sector is demonstrating that more emphasis should be placed on the outcome evaluation of communication strategies (Schneider 2006).

Delivery of an education and awareness strategy to minimize current and future impacts of plastic pollution on marine wildlife and their habitats requires developing and distributing messages aimed at altering human behaviors associated with the manufacture, purchase, use, and disposal of plastic products. The message needs to be built on a communication and interpretation science, accurate scientific information and delivered to the public and decision makers through traditional and social media, conferences, popular press, websites, and advertising. However, the provision of information is only part of the solution (Bates 2010, Weiss et al. 2012). A key role for research in developing and communicating education and awareness strategies involves – developing and testing incentives aimed at inducing effective behavior change. There is a substantial body of empirical literature on eliciting behavioral change in the public health and environmental sectors (see review by Darnton 2008). However, few studies relate specifically to minimizing plastic pollution (see Slavin et al. 2012 for a focus on marine debris, including plastics). As a starting point, there is a need for researchers to test the models used in environmental psychology (e.g. theory of planned behavior, Ajzen, 1991), environmental economics (see Butler et al. 2013), persuasive communication (see Ham et al, 2008) and social marketing (e.g. Peattie & Peattie 2009) to understand factors that will influence changes to behavior and how to test the effectiveness of marine debris campaigns. It is important to involve these disciplines because they directly inform a greater understanding of the barriers and opportunities that drive human behavior and governance, as well as determining the costs versus benefits of these changes.

13. What are the economic and social effects of plastic pollution in marine and coastal habitats?

One of the more obvious knowledge gaps for plastic pollution mitigation relates to social and economic aspects. Indeed, less than 5% of the relevant literature (i.e. in Fig 1) comprises social or economic studies (but see Nash 1992, McIlgorm et al. 2011). Changes to the condition of natural assets due to plastic pollution can influence social and economic systems by altering environmental quality for future generations (e.g. beach litter, Balance et al. 2000), decreasing the value of ecosystem services, and potentially causing negative health implications (Talsness et al. 2009). The cleanup of existing debris, which can be very costly, often falls on local authorities and environmental organizations, and often relies heavily on volunteer workforce. For example the cost of debris-related damage to marine industries in the Asia-Pacific rim and in Sweden were recently estimated at US$1.26 billion and US$3.7 million per annum, respectively (Hall 2000, McIlgorm et al. 2011). Power companies in Europe report spending more than US$75,000 each year to keep their water intake screens clear of debris. However it is not clear how many intakes are screened (Hall 2000).

Research is needed to examine the direct and indirect costs and benefits of plastic manufacture, use and disposal, and relative comparisons between the use of plastic and alternative materials. Useful starting points for this research could include surveys of people regarding the use and disposal of plastic products and the collection of empirical information on the cost of disposal and recycling gathered from waste management companies There is a clear need for future research to include collaboration with economists, neuroscientists and psychologists to quantify the cognitive and economic benefits provided by healthy, unpolluted waterways. These benefits likely include relaxation, insight, self-reflection, a sense of well-being, and creativity (White et al. 2010). Fouled environments may add to emotional stress and diminish social well-being.

14. What are the costs and benefits of mitigating plastic pollution, and how do we determine viable mitigation options?

There are a range of tools available to manage environmental issues such as plastic pollution, including government regulation, market instruments (e.g. incentives), and technical and operational procedures (Kolstad 1986). The costs and benefits of these management options vary according to a number of factors, which for marine pollution, typically include distance to point source, population size, and wealth (poverty) of coastal populations. Preventative technical measures, such as debris-retention booms that intercept plastic debris prior to dilution at sea, can significantly reduce damage to wildlife and economic costs to industry (Durrum 1997, Carson et al. 2013). Regulatory approaches to environmental management are commonly used, as they typically have low transaction costs due to operator compliance (McIlgorm et al. 2008). Unfortunately, legislation specifically designed to address the marine pollution issue (e.g. MARPOL Annex V) has not reduced the amount of debris entering the sea or the impact of debris on marine wildlife (Arnould & Croxall 1995, Henderson 2001).

Economic incentives e.g. container deposit recycling schemes; Bor et al. (2004) and programs that explicitly pass costs for packaging such as shopping bags (e.g. Ryan et al. 1996, Convery et al. 2007, Ayalon et al. 2009) or packaging (e.g. Barlow & Morgan 2013) onto the consumer are increasingly used in environmental management (Ferrara & Missios 2005), but their success is rarely evaluated. Operational programs such as beach cleanups can require substantial financial and social input to build and maintain networks, with benefits either limited to a small area, or not observed at all (e.g. no direct benefit for wildlife reported; McIlgorm et al. 2008, Page et al. 2004). A key research question is – do the cost-benefit ratios differ between measures aimed at preventing plastic pollution entering the marine system, rather than reactive measures (e.g. beach clean ups McIlgorm et al. 2008 or derelict fishing gear recovery Gilardi et al. 2010). Furthermore, clean up events are likely to have social benefits and these can be difficult to quantify and may be underestimated (Storrier & McGlashan 2006, Topping 2000). A useful starting point for research could be to quantify the costs and benefits of removing marine debris and how/if cleanup events can be organized to achieve higher ecological, social and economic value (see Q10).

The complexity and increasing scale of the marine plastic pollution issue is too large for any single agency or country to resolve (Donohue 2003), hence the need for empirical data at scales related to management and the development of cost effective regulatory tools to reduce and prevent debris at its source. Key priorities for research include developing and testing economic and social mechanisms that can be used to compare the relative costs and benefits of different mitigation techniques and research to develop and test new products and technologies that may prevent the release of debris into our waterways (see Q17). An aspect of this could include research that improves our knowledge of alternatives to plastic use in high-risk applications (e.g. single-use plastics), the promotion of recycle-friendly packaging that does not generate litter-prone items, and development of more efficient waste disposal systems.

15. How can we improve data integration to evaluate and refine management of plastic pollution?

One problem with combatting the global issue of plastic pollution through local or regional initiatives is that it requires coordination and management across a number of different fronts. This requires the development of aligned sampling and collection initiatives coupled with intent to share data (e.g. Carr et al. 2011, Duffy et al. 2013, Meiner 2013, Yang et al. 2013). For example, at a regional scale, the United Nations Environment Program (UNEP) is using its Regional Seas Programme (RSP) to develop response activities to the marine debris issue (UNEP 2009) and to collect and disseminate information. However, while 18 regional seas are recognized within the RSP, only 12 are participating in UNEP-assisted marine litter activities. Most of these regions have limited data on the magnitude of the problem, have no standardized reporting or archiving of data, and few recognize marine debris as an emerging issue. This lack of information needs to be addressed in order to have a scientifically based global understanding of the plastic pollution issue.

First steps towards addressing this issue should include the promulgation of standard approaches and methods for collecting (Q10), archiving, and reporting data, in addition to efforts to reduce barriers concerned with educating people and raising awareness (Q11). Another priority for national and regional mitigation of plastic pollution is the development of databases that store standard information that can then be shared via the internet(e.g. Simpson 2004, Simpson et al 2006, Carr et al. 2011, Costello et al 2013). By providing a standardized suite of database fields, or creating open commons data sharing, information can be made available for national or global assessments (Simpson et al. 2006), with appropriate strategies being developed to help refine management of plastic pollution. For example, in the US, the West Coast Governor's Agreement Marine Debris Action Coordination Team has recently established an online database to collate standardized marine debris data available for the entire US West Coast http://debris-db.westcoastoceans.org and in Australia, a non-profit organization, Tangoroa Blue has created a similar online database for storing beach clean up data http://www.tangaroablue.org/database.html. These are relatively recent and spatially limited initiatives however continued research, monitoring and use of these databases and development of similar databases in additional regions will enable identification of strengths, weaknesses and where possible improvements and coordination. This will be especially true if these and similar databases are able to record baseline marine wildlife impacts and thus enable identification of future changes to impact rates of occurrence.

16. What are the alternatives to plastic?

The plastics industry is one of the largest and fastest growing manufacturing industries worldwide, driven to a large extent by increased global consumerism and social pressure to favour convenient, single-use products. However, although plastic products offer short term benefits, the longer term, or whole of life, costs are rarely calculated (Rochman et al. 2013b). An important area for future work will be in the development of indicators and techniques to assess the benefits of a product relative to the costs of its lifetime environmental, carbon and toxic footprints. Single-use plastic products (e.g. packaging, straws, disposable cutlery, cups, food trays, and bags) may be suitable products for such risk assessment.

Very few empirical data exist on the carbon and toxin footprint of single-use plastics (Yates & Barlow 2013, Hendrickson et al. 2006), but work on alternatives to plastic has focused on this group of products. Included in the growing list of alternate materials are biodegradable materials such as those made with prodegradant concentrates (PDCs), additives known as TDPA (Totally Degradable Plastic Additives) or MasterBatch Pellets (MBP). However, the environmental cost of biodegradable alternatives is rarely assessed and warrants further research attention. As an example, plastics made from polylactic acid (PLA), a polymer-derived plant sugar, require a specific controlled environment in order to degrade: temperatures must be very high and oxygen absent for bacteria to break down PLA plastics. The majority of landfills and at-home composting systems cannot provide these conditions, resulting in degradation times for PLA products similar to those of traditional plastic items (ref?). Other emerging problems with "biodegradable plastics" are that they often cannot be bundled with traditional plastic items for recycling, and are often considered contaminants in recycling centers. Furthermore, biodegradable plastics may fragment at a great rate, resulting in an increase in the environmental burden of microplastics, and packaging labeled as biodegradable may lead to increased littering. Hence there is a clear need for further research to develop and test approaches for comparing the relative life cycle cost and benefits of alternate materials when compared to the plastic products they replace.

One method of reducing plastic is to use products made from a wide range of alternative materials such as cotton/hemp (e.g. shopping bags), stainless steel (e.g. lunch boxes or drink containers), or glass (e.g. straws). Yet, rarely have the efficiency and effectiveness of these changes been assessed(Barlow & Morgan 2013). Moreover, while it is clear that engineering and product design efforts are ongoing, and the development of alternative products or materials to reduce plastic footprints is gaining momentum, there is a clear need for research on economic and social drivers to ensure uptake of alternatives. Explicit costing of the cradle-to-grave cost of 'free' plastic packaging is an effective way to change consumer behavior (Ryan et al. 1996), but there is substantial scope for further economic and social based research in this field.

Overall, the key challenge is to understand the relative economic, environmental and social costs and benefits of products, and new alternative materials. Collectively these data are essential to allow effective evaluation of product changes in order to ensure a net long-term environmental benefit.

Discussion

Harnessing the knowledge and ideas of multiple experts on a single topic is powerful because it highlights important research questions or topics to help focus attention on areas considered to be issues of immediate importance for the conservation of affected wildlife and habitats (Hamann et al. 2010, Sutherland et al. 2010, Laurance et al. 2011, Lewison et al. 2012). Herein, we identified as critical the improvement in our understanding of the magnitude of the plastic pollution issue, the threats of plastic pollution to marine wildlife and their habitats, how these threats are currently managed, how mitigating actions are currently implemented and evaluated, and how mitigation measures can be improved in the future. Collectively, the questions generated in our study demonstrate that understanding and mitigating the impacts of plastic pollution on marine wildlife will require a multi-disciplinary approach delivered across various spatial and temporal scales.

- While it is clear that plastic pollution impacts a large number of marine wildlife species, our study reveals an obvious need to (1) understand vulnerability at the level of species or other management units (e.g. genetic stocks, Dethmers et al. (2006) or regional management units (Wallace et al. 2010) and (2) improve knowledge of species, populations or habitats at scales relative to management. Ultimately, understanding vulnerability to plastic pollution at a mix of ecologically and management relevant scales (species or geographic) can assist with both local and regional priority setting and mitigation across a range of pressures.

We have provided a context for the key research questions to guide management of plastic pollution impacts to marine wildlife. We identify a strong need to involve disciplines related to understanding economic and social barriers and opportunities to change behavior (individual and governance), market for change (Stern 2000, Brulle 2010, Ham 2013) and evaluate the benefits. Understanding human behavior has traditionally been the purview of psychology and there is substantial scope to test and apply behavior change models such as the Theory of Planned Behavior (see Darnton 2008 for a review) or Prospect Theory (see Kahneman & Tversky 1979, Wakker 2010) to adjust social attitudes towards managing plastic pollution (e.g. Tonglet et al. 2004) and changing littering behaviors (see Cialdini 2003). Similarly, there is scope to include business themes such as social marketing (see Peattie & Peattie 2009), viral marketing (see Leskovec et al. 2007), social network analysis (see Scott 1988, Weiss et al. 2012) and cost-benefit analysis to support alterations in consumption, use, disposal and recycling to achieve the best outcomes (e.g. Butler et al. 2013). Research in these social domains should increase knowledge and allow targeted dissemination of information, improve attitudes towards plastic pollution impacts and its mitigation, improve aspirations toward enabling changes (e.g. Ham 2013), and enable evaluation of management instruments and strategies (e.g. plastic bag use, Luis & Spinola 2010, Dikgang et al. 2012) to quantify benefit.

This paper reflects the ideas from an expert group of researchers with a broad range of backgrounds. It is the most current attempt to assemble the opinions of experts in the field of plastic pollution and its impact on marine wildlife and their habitats. By focusing effort and expertise on what are collectively agreed on as priority research questions for the mitigation of plastic pollution impacts on marine species around the globe, we aim to move research and management forward. Although there are still many questions surrounding the issue, the numerous negative impacts of plastic pollution make it clear that we must strive to reduce the amount of plastics reaching our oceans. Given that methods for doing so are attainable (i.e. reducing plastic use, improvements in waste management, better access to recycling) and the costs are non prohibitive we should act now to deal with what is ultimately an entirely avoidable problem.

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References

Ajzen I (1991) The theory of planned behavior. Organizational Behavior and Human Decision Processes 50 (2):179-211

Allen R, Jarvis D, Sayer S, Mills C (2012) Entanglement of grey seals *Halichoerus grypus* at a haul out site in Cornwall, UK. Marine Pollution Bulletin 64: 2815-2819

Aloy AB, Vallejo BM, Juinio-Meñez MA (2011) Increased plastic litter cover affects the foraging activity of the sandy intertidal gastropod *Nassarius pullus*. Marine Pollution Bulletin 62: 1772-1779

Andrady AL, Hamid SH, Hu X, Torikai A (1998) Effects of increased solar ultraviolet radiation on materials. Journal of Photochemistry and Photobiology B: Biology 46: 96-103

Anon (1955) Observations on diving of the Australian Gannet (*Sula bassana serrator* Gray). Notornis 6:72-76

Arnould JPY, Croxall JP (1995) Trends in entanglement of antarctic fur seals (*Arctocephalus-gazella*) in man-made debris at South Georgia. Marine Pollution Bulletin 30: 707-712

Artham T, Sudhakar M, Venkatesan R, Madhavan Nair C, Murty KVGK, Doble M (2009) Biofouling and stability of synthetic polymers in sea water. International Biodeterioration and Biodegradation 63: 884-890

Ashton K, Holmes L, Turner A (2010) Association of metals with plastic production pellets in the marine environment. Marine Pollution Bulletin 60: 2050-2055

Asoh K, Yoshikawa T, Kosaki R, Marschall EA (2004) Damage to cauliflower coral by monofilament fishing lines in Hawaii. Conservation Biology 18: 1645-1650

Auman HJ, Woehler EJ, Riddle MJ, Burton H (2004) First evidence of ingestion of plastic debris by seabirds at sub-Antarctic Heard Island. Marine Ornithology 32: 105-106

Ayalon O, Goldrath T, Rosenthal G, Grossman M (2009) Reduction of plastic carrier bag use: An analysis of alternatives in Israel. Waste Management 29: 2025-2032

Azzarello MY, VanVleet ES (1987) Marine birds and marine pollution. Marine Ecology Progress Series 37: 295-303

Balance A, Ryan PG, Turpie JK (2000) How much is a clean beach worth? The impact of litter on beach users in the Cape Peninsula, South Africa. South African Journal of Science 96: 210-213

Balazs G (1985) Impact of ocean debris on marine turtles: entanglement and ingestion. Proceedings of the Workshop on the Fate and Impact of Marine Debris, US NOAA Technical Memorandum MNFS SWFC-54: 387-429

Barlow CY, Morgan DC (2013) Polymer film packaging for food: an environmental assessment. Resources, Conservation and Recycling 78: 74-80

Barnes DKA, Milner P (2005) Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. Marine Biology 146: 815-825

Barnes DKA, Galgani F, Thompson RC, Barlaz M (2009) Accumulation and fragmentation of plastic debris in global environments. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 1985-1998

Bates, C. H. (2010) Use of social marketing concepts to evaluate ocean sustainability campaigns. Social Marketing Quarterly, 16: 71-96

Baulch S, Perry C (2012) A sea of plastic: Evaluating the impacts of marine debris on cetaceans. Paper SC/64/E10, 64th meeting of the International Whaling Commission Science Committee, Panama

Beall G (2009) By Design: World War II, Plastics, and NPE. http://www.plasticstoday.com/imm/articles/design-world-war-ii-plastics-and-npe Retrieved June, 2013

Beck CA, Barros NB (1991) The impact of debris on the Florida manatee. Marine Pollution Bulletin 22: 508-510

Bern L (1990) Size-related discrimination of nutritive and inert particles by freshwater zooplankton. Journal of Plankton Research 12, 1059-1067

Besseling E, Wegner A, Foekema EM, Van Den Heuvel-Greve MJ, Koelmans AA (2013) Effects of Microplastic on Fitness and PCB Bioaccumulation by the lugworm *Arenicola marina* (L.). Environmental Science & Technology 47: 593-600

Bjorndal KA, Bolten AB, Lagueux CJ (1994) Ingestion of marine debris by juvenile sea turtles in coastal Florida habitats. Marine Pollution Bulletin 28: 154-158

Boerger CM, Lattin GL, Moore SL, Moore CJ (2010) Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Marine Pollution Bulletin 60: 2275-2278

Boland RC, Donohue MJ (2003) Marine debris accumulation in the nearshore marine habitat of the endangered Hawaiian monk seal, *Monachus schauinslandi* 1999-2001. Marine Pollution Bulletin 46: 1385-1394

Bond AL, Lavers JL (2013) Effectiveness of emetics to study plastic ingestion by Leach's Storm-petrels (*Oceanodroma leucorhoa*). Marine Pollution Bulletin 70: 171-175

Bor YJ, Chien YL, Hsu E (2004) The market-incentive recycling system for waste packaging containers in Taiwan. Environmental Science and Policy 7: 509-523

Bouland AJ, White AE, Lonabaugh KP, Varian-Ramos CW, Cristol DA (2012) Female-biased offspring sex ratios in birds at a mercury-contaminated river. Journal of Avian Biology 43: 244-251

Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, Thompson R (2011) Accumulation of microplastic on shorelines woldwide: Sources and sinks. Environmental Science & Technology 45: 9175-9179

Brulle RJ (2010) From environmental campaigns to advancing the public dialog: Environmental communication for civic engagement. Environmental Communication 4: 82-98

Bugoni L, Krause L, Petry MV (2001) Marine debris and human impacts on sea turtles in southern Brazil. Marine Pollution Bulletin 42: 1330-1334

Butler JRA, Gunn R, Berry HL, Wagey GA, Hardesty BD, Wilcox C (2013) A value chain analysis of ghost nets in the Arafura Sea: Identifying trans-boundary stakeholders, intervention points and livelihood trade-offs. Journal of environmental management 123: 14-25

Cadee GC (2002) Seabirds and floating plastic debris. Marine Pollution Bulletin 44: 1294-1295

Campbell M (2012) Flood debris in central Queensland: The social implications of the flood debris from January 2011 Queensland floods. CQ University Technical Report. Gladstone: 78

Carpenter EJ, Smith KL Jr (1972) Plastic on the Sargasso Sea surface. Science 175: 1240-1241

Carpenter EJ, Anderson SJ, Harvey GR, Miklas HP, Peck BB (1972) Polystyrene spherules in coastal waters. Science 178: 749-750

Carr A (1986) Rips, FADS, and little loggerheads. Bioscience 36: 92-100

Carr A (1987) Impact of nondegradable marine debris on the ecology and survival outlook of sea turtles. Marine Pollution Bulletin 18: 352-356

Carr MH, Woodson CB, Cheriton OM, Malone D, McManus MA, Raimondi PT (2011) Knowledge through partnerships: Integrating marine protected area monitoring and ocean observing systems. Frontiers in Ecology and the Environment 9: 342-350

Carson HS, Colbert SL, Kaylor MJ, Mcdermid KJ (2011) Small plastic debris changes water movement and heat transfer through beach sediments. Marine Pollution Bulletin 62: 1708-1713

Carson HS, Lamson MR, Nakashima D, Toloumu D, Hafner J, Maximenko N, Mcdermid KJ (2013) Tracking the sources and sinks of local marine debris in Hawai'i. Marine Environmental Research 84: 76-83

Ceccarelli D (2009) Impacts of plastic debris on Australian marine wildlife. Canberra, Report by C&R Consulting to the Australian Government Department of the Environment, Water, Heritage and the Arts. Canberra: 1-77

Cheshire A, Adler E, Barbière J, Cohen Y, Evans S, Jarayabhand S, Jeftic L, Jung R, Kinsey S, Kusui E, Lavine I, Manyara P, Oosterbaan L, Pereira M, Sheavly S, Tkalin A, Varadarajan S, Wenneker B, Westphalen G (2009) UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter, UNEP Regional Seas Reports and Studies, No 186, IOC Technical Series No 83

Chiappone M, Dienes H, Swanson DW, Miller SL (2005) Impacts of lost fishing gear on coral reef sessile invertebrates in the Florida Keys National Marine Sanctuary. Biological Conservation 121: 221-230

Choy CA, Drazen JC (2013) Plastic for dinner? observations of frequent debris ingestion by pelagic predatory fishes from the central North Pacific. Marine Ecology Progress Series. 485: 155-163

Cialdini R (2003) Crafting normative messages to protected the environment. Current Directions in Psychological Science 12: 105-109

Cliff G, Dudley SFJ, Ryan PEG, Singleton N (2002) Large sharks and plastic debris in KwaZulu-Natal, South Africa. Marine and Freshwater Research 53: 575-581

Colabuono FI, Barquete V, Domingues BS, Montone RC (2009) Plastic ingestion by Procellariiformes in Southern Brazil. Marine Pollution Bulletin 58: 93-96

Cole M, Lindeque P, Fileman E, Halsband C, Goodhead R, Moger J, Galloway TS (2013) Microplastic ingestion by zooplankton. Environmental Science and Technology 47: 6646-6655

Cole M, Lindeque P, Halsband C, Galloway TS (2011) Microplastics as contaminants in the marine environment: A review. Marine Pollution Bulletin 62: 2588-2597

Convention on Biological Diversity (2012) Impacts of marine debris on biodiversity: Current status and potential solutions. Montreal. Technical Series No. 67

Convery F, Mcdonnell S, Ferreira S (2007) The most popular tax in Europe? Lessons from the Irish plastic bags levy. Environmental & Resource Economics 38: 1-11

Convey P, Barnes DKA, Morton A (2002) Debris accumulation on oceanic island shores of the Scotia Arc, Antarctica. Polar Biology 25: 612-617

Cooper DA, Corcoran PL (2010) Effects of mechanical and chemical processes on the degradation of plastic beach debris on the island of Kauai, Hawaii. Marine Pollution Bulletin 60: 650-654

Corcoran PL, Biesinger MC, Grifi M (2009) Plastics and beaches: A degrading relationship. Marine Pollution Bulletin 58: 80-84

Costello MJ, Bouchet P, Boxshall G, Fauchald K, Gordon D, Hoeksema BW, Poore GCB, can Soerst RWM, Stohr S, Walter TC, Vanhoorne B, Decock W, Appeltans W. (2013) Global coordination and standardisation in marine biodiversity through World Register of Marine Species (WoRMS) and related databases. PLoS ONE 8: e51629

Cottingham D (1988) Federal programs and plastics in the oceans. Oceans' 88: a partnership of marine interests, Baltimore, Maryland

Cunningham DJ, Wilson SP (2003) Marine debris on beaches of the Greater Sydney Region. Journal of Coastal Research 19: 421-430

Dantas D, Barletta M, Ramos J, Lima A, Costa M (2013) Seasonal diet shifts and overlap between two sympatric catfishes in an estuarine nursery. Estuaries and coasts 36: 237-256

Darnton A (2008) Reference report: An overview of behaviour change models and their uses. Centre for Sustainable Development, University of Westminster, Westminster. 1-83

Day RH, Wehle DHS & Coleman FC (1985) Ingestion of plastic pollutants by marine birds. Proceedings of the Workshop on the Fate and Impact of Marine Debris, NOAA Technical Memorandum, NMFS, SWFC 54, 344-386

De Mott W (1988) Discrimination between algae and artificial particles by freshwater and marine copepods. Limnological Oceanography, 33:397-408

Denuncio P, Bastida R, Dassis M, Giardino G, Gerpe M, Rodríguez D (2011) Plastic ingestion in franciscana dolphins, *Pontoporia blainvillei* (Gervais and d'Orbigny, 1844), from Argentina. Marine Pollution Bulletin 62: 1836-1841

Derraik JGB (2002) The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 44: 842-852

Dethmers KEM, Broderick D, Moritz C, Fitzsimmons NN, Limpus CJ, Lavery S, Whiting S, Guinea M, Prince RIT, Kennett R (2006) The genetic structure of Australasian green turtles (*Chelonia mydas*): Exploring the geographical scale of genetic exchange. Molecular Ecology 15: 3931-3946

Dikgang J, Leiman A, Visser M (2012) Analysis of the plastic bag levy in South Africa. Res Cons Recycling 66: 59-65

Donlan CJ, Wingfield DK, Crowder LB, Wilcox C (2010) Using expert opinion surveys to rank threats to endangered species: A case study with sea turtles. Conservation Biology 24: 1586-1595

Donohue MJ (2003) How multiagency partnerships can successfully address large-scale pollution problems: a Hawaii case study. Marine Pollution Bulletin 46: 700-702

Duffy JE, Amaral-Zettler LA, Fautin DG, Paulay G, Rynearson TA, Sosik HM, Stachowicz JJ (2013) Envisioning and marine biodiversity observation network. BioScience 63: 350-361

Durrum E (1997) The control of floating debris in an urban river. In Marine Debris: Sources, Impacts, and Solutions. Coe J, Rogers D (eds). New York, Springer-Verlag: 351-358

Edyvane KS, Dalgetty A, Hone PW, Higham JS, Wace NM (2004) Long-term marine litter monitoring in the remote great Australian Bight, South Australia. Marine Pollution Bulletin 48: 1060-1075

Eriksen M, Maximenko N, Thiel M, Cummins A, Lattin G, Wilson S, Hafner J, Zellers A, Rifman S (2013) Plastic pollution in the South Pacific subtropical gyre. Marine Pollution Bulletin 68: 71-76

Eriksson C, Burton H (2003) Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. Ambio 32: 380-384

Eriksson C, Burton H, Fitch S, Schulz M, Van Den Hoff J (2013) Daily accumulation rates of marine debris on sub-Antarctic island beaches. Marine Pollution Bulletin 66: 199-208
Faris, J, Hart K (1994) Seas of Debris: A Summary of the Third International Conference on Marine Debris, N.C. Sea Grant College Program and NOAA: 54
Farrell P, Nelson K (2013) Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). Environmental Pollution 177: 1-3
Feldkamp SD (1985) The effects of net entanglement on the drag and power output of a California sea lion, *Zalophus californianus*. Fishery Bulletin 83: 692-694
Feldkamp SD, Costa DP, Dekrey GK (1989) Energetic and behavioral effects of net entanglement on juvenile northern fur seals, *Callorhinus ursinus*. Fishery Bulletin 87: 85-94
Ferrara I, Missios P (2005) Recycling and waste diversion effectiveness: Evidence from Canada. Environmental & Resource Economics 30: 221-238
Fisher HI (1975) Mortality and survival in the Laysan Albatross, *Diomedea immutabilis*. Pacific Science 29: 279–300
Fossi MC, Panti C, Guerranti C, Coppola D, Giannetti M, Marsili L, Minutoli R (2012) Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (*Balaenoptera physalus*). Marine Pollution Bulletin 64: 2374-2379
Fowler CW (1987) Marine debris and northern fur seals: A case study. Marine Pollution Bulletin 18: 326-335
Furness R (1985) Ingestion of plastic particles by seabirds at Gough Island, South Atlantic Ocean. Environmental Pollution Series A, Ecological and Biological 38: 261-272
Gilardi KVK, Carlson-Bremer D, June JA, Antonelis K, Broadhurst G, Cowan T (2010) Marine species mortality in derelict fishing nets in Puget Sound, WA and the cost/benefits of derelict net removal. Marine Pollution Bulletin 60: 376-382.
Gilman E, Brothers N, Mcpherson G, Dalzell P (2006) A review of cetacean interactions with longline gear. Journal of Cetacean Research and Management 8: 215-223
Glasby TM, Connell SD, Holloway MG, Hewitt CL (2007) Nonindigenous biota on artificial structures: Could habitat creation facilitate biological invasions? Marine Biology 151: 887-895
Gochfeld M (1973) Effect of artefact pollution on the viability of seabird colonies on Long Island, New York. Environmental Pollution 4: 1-6
Goldberg ED (1997) Plasticizing the seafloor: An overview. Environmental Technology 18: 195-201
Goldstein MC, Rosenberg M, Cheng L (2012) Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biology Letters 8: 817-820
Gorman M, (1993) Environmental Hazards - Marine Pollution. ABC- CLIO Inc, Santa Barbara
Gray H, Lattin GL, Moore CJ (2012) Incidence, mass and variety of plastics ingested by laysan (*Phoebastria immutabilis*) and black-footed albatrosses (*P. nigripes*) recovered as by-catch in the North Pacific Ocean. Marine Pollution Bulletin 64: 2190-2192
Gregory MR (1991) The hazards of persistent marine pollution - drift plastics and conservation islands. Journal of the Royal Society of New Zealand 21: 83-100
Gregory MR (2009) Environmental implications of plastic debris in marine settings- entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 2013-2025
Gregory MR, Ryan P (1997) Pelagic plastics and other seaborne persistent synthetic debris: a review of Southern Hemisphere perspectives. In Marine Debris: Sources, Impacts, and Solutions. Coe J, Rogers D (eds). New York, Springer-Verlag: 49-66
Guebert-Bartholo FM, Barletta M, Costa MF, Monteiro-Filho ELA (2011) Using gut contents to assess foraging patterns of juvenile green turtles *Chelonia mydas* in the Paranagua Estuary, Brazil. Endangered Species Research 13: 131-143
Gugumus F (1993) Re-evaluation of the stabilization mechanisms of various light stabilizer classes. Polymer Degradation and Stability 39: 117-135
Gunn R, Hardesty BD, Butler J (2010) Tackling 'ghost nets': Local solutions to a global issue in northern Australia. Ecological Management and Restoration 11: 88-98
Hall K (2000) Impacts of marine debris and oil: Economic and social costs to coastal communities KIMO, c/o Shetland Islands Council, Lerwick. 1-104
Ham S (2013) Interpretation, making a difference on purpose. Fulcrum Publishing, Golden Colorado 1-290

Ham SH, Weiler B, Hughes M, Brown T, Curtis J, Poll M (2008) Asking visitors to help: Research to guide strategic communication for protected area management. Sustainable Tourism CRC, Queensland
Hamann M, Godfrey MH, Seminoff JA, Arthur K, Barata PCR, Bjorndal KA, Bolten AB, Broderick AC, Campbell LM, Carreras C, Casale P, Chaloupka M, Chan SKF, Coyne MS, Crowder LB, Diez CE, Dutton PH, Epperly SP, Fitzsimmons NN, Formia A, Girondot M, Hays GC, Cheng IJ, Kaska Y, Lewison R, Mortimer JA, Nichols WJ, Reina RD, Shanker K, Spotila JR, Tomas J, Wallace BP, Work TM, Zbinden J, Godley BJ (2010) Global research priorities for sea turtles: informing management and conservation in the 21st century. Endangered Species Research 11: 245-269
Hamann M, Grech A, Wolanski E, Lambrechts J (2011) Modelling the fate of marine turtle hatchlings. Ecological Modelling 222: 1515-1521
Hanni KD, Pyle P (2000) Entanglement of pinnipeds in synthetic materials at South-east Farallon Island, California, 1976-1998. Marine Pollution Bulletin 40: 1076-1081
Haydar D (2012) What is natural? The scale of cryptogenesis in the North Atlantic Ocean. Diversity and Distributions 18: 101-110
Hays H, Cormons G (1974) Plastic particles found in tern pellets, on coastal beaches and at factory sites. Marine Pollution Bulletin 5: 44-46
Henderson JR (2001) A pre- and post-MARPOL Annex V summary of Hawaiian monk seal entanglements and marine debris accumulation in the northwestern Hawaiian Islands, 1982-1998. Marine Pollution Bulletin 42: 584-589
Hendrickson CT, Lave LB, Matthews HS (2006) Environmental life cycle assessment of goods and services. An input-output approach. RFF Press, Washington DC. 1-261
Hewitt CL, Campbell ML, Thresher RE, Martin RB, Boyd S, Cohen BF, Currie DR, Gomon MF, Keough MJ, Lewis JA, Lockett MM, Mays N, Mcarthur MA, O'Hara TD, Poore GCB, Ross DJ, Storey MJ, Watson JE, Wilson RS (2004a) Introduced and cryptogenic species in Port Phillip Bay, Victoria, Australia. Marine Biology 144: 183-202
Hewitt CL, Willing J, Bauckham A, Cassidy AM, Cox CMS, Jones L, Wotton DM (2004b) New Zealand marine biosecurity: Delivering outcomes in a fluid environment. New Zealand Journal of Marine and Freshwater Research 38: 429-438
Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: A review of the methods used for identification and quantification. Environmental Science and Technology 46: 3060-3075
Holmes LA, Turner A, Thompson RC (2012) Adsorption of trace metals to plastic resin pellets in the marine environment. Environmental Pollution 160: 42-48
Howell EA, Bograd SJ, Morishige C, Seki MP, Polovina JJ (2012) On North Pacific circulation and associated marine debris concentration. Marine Pollution Bulletin 65: 16-22
Ivar do Sul JA, Barnes DKA, Costa MF, Convey P, Costa ES Campos L (2011) Plastics in the Antarctic environment: are we looking only at the tip of the iceberg? Oecologia Australis 15: 150-170
Ivar do Sul JA, Costa MF (2013) The present and future of microplastic pollution in the marine environment. Environmental Pollution, available online 23 November 2013
Jacobsen JK, Massey L, Gulland F (2010) Fatal ingestion of floating net debris by two sperm whales (*Physeter macrocephalus*). Marine Pollution Bulletin 60: 765-767
Jones MM (1995) Fishing debris in the Australian marine environment. Marine Pollution Bulletin 30: 25-33
Jungling G, Wiessner V, Gebhardt C, Zeitler E, Wunsch P (1994) Enterocolic fistula caused by foreign-body perforation. Deutsche Medizinische Wochenschrift 119: 63-66
Kahneman D, Tverskey A (1979) Prospect thoery: An analysis of decision under risk. Econometrica 47: 263-291
Kaplan-Dau, B, Gilardi KVK, Gulland FM, Higgins A, Holcomb JB, St. Leger J, Ziccardi MH (2009) Fishing gear-related injury in California marine wildlife. Journal of Wildlife Diseases 45: 355-362
Karamanlidis AA, Androukaki E, Adamantopoulou S, Chatzispyrou A, Johnson WM, Kotomatas S, Papadopoulos A, Paravas V, Paximadis G, Pires R, Tounta E, Dendrinos P (2008) Assessing accidental entanglement as a threat to the Mediterranean monk seal *Monachus monachus*. Endangered Species Research 5: 205-213

Karapanagioti HK, Endo S, Ogata Y, Takada H (2011) Diffuse pollution by persistent organic pollutants as measured in plastic pellets sampled from various beaches in Greece. Marine Pollution Bulletin 62: 312-317

Karua J (1992) The control of land based sources of marine pollution: Recent international initiatives and prospects Marine Pollution Bulletin 25: 80-81

Kataoka T, Hinata H, Kato S (2013) Analysis of a beach as a time-invariant linear input/output system of marine litter. Marine Pollution Bulletin 77: 266-273

Katsanevakis S, Verriopoulos G, Nicolaidou A, Thessalou-Legaki M (2007) Effect of marine litter on the benthic megafauna of coastal soft bottoms: A manipulative field experiment. Marine Pollution Bulletin 54: 771-778

Kenyon K, Kridler E (1969) Laysan Albatrosses swallow indigestible matter. The Auk 86: 339-343

Kolstad CD (1986) Empirical properties of economic incentives and command-and-control regulations for air-pollution control. Land Economics 62: 250-268

Kühn S, van Franeker JA (2012) Plastic ingestion by the northern fulmar (*Fulmarus glacialis*) in Iceland. Marine Pollution Bulletin 64: 1252-1254

Laist DW (1987) Overview of the biological effects of lost and discarded plastic debris in the marine environment. Marine Pollution Bulletin 18: 319-326

Laist DW (1997) Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In Marine Debris: Sources, Impacts, and Solutions. Coe J, Rogers D (eds). New York, Springer-Verlag: 99-139

Laurance WF, Dell B, Turton SM, Lawes MJ, Hutley LB, McCallum H, Dale P, Bird M, Hardy G, Prodeaux G, Gawne B, McMahon CR, Yu R, Hero J-M, Schwarzkopf L, Krockenberger AK, Douglas M, Silvester E, Mahony M, Vella K, Saikia U, Wahren C-H, Xu Z, Smith B, Cocklin C (2011) The 10 Australian ecosystems most vulnerable to tipping points. Biological Conservation 144: 1472-1480

Lavers JL, Hodgson J, Clarke RH (2013) Prevalence and composition of marine debris in Brown Booby (*Sula leucogaster*) nests on Ashmore Reef. Marine Pollution Bulletin 77: 320-324

Lavers JL, Bond AL, Hutton I (2014) Plastic ingestion by Flesh-footed Shearwaters (*Puffinus carneipes*): implications for chick body condition and the accumulation of plastic-derived chemicals. Environmental Pollution 187: 124-129

Law KL, Maximenko N (2011) Understanding sources, sinks, and transport of marine debris. Eos 92: 235

Law KL, Morét-Ferguson S, Maximenko NA, Proskurowski G, Peacock EE, Hafner J, Reddy CM (2010) Plastic accumulation in the North Atlantic subtropical gyre. Science 329: 1185-1188

Lazar B, Gračan R (2011) Ingestion of marine debris by loggerhead sea turtles, *Caretta caretta*, in the Adriatic Sea. Marine Pollution Bulletin 62: 43-47

Lebreton LCM, Borrero JC (2013) Modeling the transport and accumulation floating debris generated by the 11 March 2011 Tohoku tsunami. Marine Pollution Bulletin 66: 53-58

Lebreton LCM, Greer SD, Borrero JC (2012) Numerical modelling of floating debris in the world's oceans. Marine Pollution Bulletin 64: 653-661

Lecke-Mitchell KM, Mullin K (1997) Floating marine debris in the US Gulf of Mexico. Marine Pollution Bulletin 34: 702-705

Leskovec J, Adamic L, Huberman B (2007) The dynamics of viral marketing. ACM Transactions on the Web 1: 1-39

Lewis PN, Riddle MJ, Smith SDA (2005) Assisted passage or passive drift: a comparison of alternative transport mechanisms for non-indigenous coastal species into the Southern Ocean. Antarctic Science 17: 183-191

Lewison R, Oro D, Godley BJ, Underhill L, Bearhop S, Wilson RP, Ainley D, Arcos JM, Boersma PD, Borboroglu PG, Boulinier T, Frederiksen M, Genovart M, González-Solís J, Green JA, Grémillet D, Hamer KC, Hilton GM, Hyrenbach KD, Martínez-Abraín A, Montevecchi WA, Phillips RA, Ryan PG, Sagar P, Sydeman WJ, Wanless S, Watanuki Y, Weimerskirch H, Yorio P (2012) Research priorities for seabirds: Improving conservation and management in the 21st century. Endangered Species Research 17: 93-121

Lobelle D, Cunliffe M (2011) Early microbial biofilm formation on marine plastic debris. Marine Pollution Bulletin 62: 197-200

Luis IP, Spinola H (2010) The influence of a voluntary fee in the consumption of plastic bags on supermarkets from Madeira Island (Portugal). Journal of Environmental Planning and Management 53: 883-889
Macfadyen G, Huntington T, Cappell R (2009) Abandoned, lost or otherwise discarded fishing gear. Rome, FAO Fisheries and Aquaculture technical Paper 2009 No. 523: 115
Mader D (2006) Reptile medicine and surgery. Elsevier Inc. St Loius: 1-1242
Martinez E, Maamaatuaiahutapu K, Taillandier V (2009) Floating marine debris surface drift: Convergence and accumulation toward the South Pacific subtropical gyre. Marine Pollution Bulletin 58: 1347-1355
Mato Y, Isobe T, Takada H, Kanehiro H, Ohtake C, Kaminuma T (2001) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environmental Science & Technology 35: 318-324
Maximenko N, Hafner J, Niiler P (2012) Pathways of marine debris derived from trajectories of Lagrangian drifters. Marine Pollution Bulletin 65: 51-62
McCauley SJ, Bjorndal KA (1999) Conservation implications of dietary dilution from debris ingestion: Sublethal effects in post-hatchling loggerhead sea turtles. Conservation Biology 13: 925-929
McIlgorm A, Campbell HF, Rule MJ (2008) Understanding the Economic Benefits and Costs of Controlling Marine Debris in the APEC region (MRC 02/2007). A report to the Asia-Pacific Economic Cooperation Marine Resource Conservation Working Group by the National Marine Science Centre (Univ. of New England & Southern Cross Univ), Coffs Harbour, NSW, Australia, Dec 2008
McIlgorm A, Campbell HF, Rule MJ (2011) The economic cost and control of marine debris damage in the Asia-Pacific region. Ocean and Coastal Management 54: 643-651
Meeker JD, Sathyanarayana S, Swan SH (2009) Phthalates and other additives in plastics: human exposure and associated health outcomes. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 2097-2113
Meiner A (2013) Spatial data management priorities for assessment of Europe's coasts and seas. Journal of Coastal Conservation, Planning and Management. DOI 10.1007/s11852-011-0173-0
Moore CJ (2008) Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. Environmental Research 108: 131-139
Moore CJ, Moore SL, Leecaster MK, Weisberg SB (2001) A comparison of plastic and plankton in the North Pacific central gyre. Marine Pollution Bulletin 42: 1297-1300
Morishige C, Donohue MJ, Flint E, Swenson C, Woolaway C (2007) Factors affecting marine debris deposition at French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument, 1990-2006. Marine Pollution Bulletin 54: 1162-1169
Mrosovsky N, Ryan GD, James MC (2009) Leatherback turtles: The menace of plastic. Marine Pollution Bulletin 58: 287-289
Müller C, Townsend K, Matschullat J (2012) Experimental degradation of polymer shopping bags (standard and degradable plastic, and biodegradable) in the gastrointestinal fluids of sea turtles. Science of the Total Environment 416: 464-467
Nash AD (1992) Impacts of marine debris on subsistence fishermen - an exploratory-study. Marine Pollution Bulletin 24: 150-156
Nollkaemper A (1994) Land-based discharges of marine debris: From local to global regulation. Marine Pollution Bulletin 28: 649-652
O'Hara K, Iudicello S, Bierce R (1988) A citizen's guide to plastics in the ocean: More than a litter problem. Center for Marine Conservation, Washington DC (1988)
O'Shea O, Hamann M, Smith W, Taylor H (2014) Predictable pollution: An assessment of weather balloons and associated impacts on the marine environment – An example for the Great Barrier Reef, Australia. Marine Pollution Bulletin 79: 61-68
Orensanz JM, Schwindt E, Pastorino G, Bortolus A, Casas G, Darrigran G, Elías R, López Gappa JJ, Obenat S, Pascual M, Penchaszadeh P, Piriz ML, Scarabino F, Spivak ED, Vallarino EA (2002) No longer the pristine confines of the world ocean: A survey of exotic marine species in the southwestern Atlantic. Biological Invasions 4: 115-143
Page B, Mckenzie J, Mcintosh R, Baylis A, Morrissey A, Calvert N, Haase T, Berris M, Dowie D, Shaughnessy PD, Goldsworthy SD (2004) Entanglement of Australian sea lions and New Zealand fur seals in lost fishing gear and other marine debris before and after Government and industry attempts to reduce the problem. Marine Pollution Bulletin 49: 33-42

Palmisano AC, Pettigrew CA (1992) Biodegradability of plastics. Bioscience 42: 680-685
Passow U, Alldredge AL (1999) Do transparent exopolymer particles (TEP) inhibit grazing by the euphausiid *Euphausia pacifica*? Journal of Plankton Research 21: 2203-2217
Peattie K, Peattie S (2009) Social marketing: A pathway to consumption reduction? Journal of Business Research 62: 260-268
PEMRG (2011) Plastics - the facts 2011: an analysis of European plastics production, demand and recovery for 2010. Plastics Europe, Belgium: 1-32
Pichel WG, Veenstra TS, Churnside JH, Arabini E, Friedman KS, Foley DG, Brainard RE, Kiefer D, Ogle S, Clemente-Colón P, Li X (2012) GhostNet marine debris survey in the Gulf of Alaska - Satellite guidance and aircraft observations. Marine Pollution Bulletin 65: 28-41
Poon A (2005) Haunted waters: an estimate of ghost fishing of crabs and lobsters by traps. Masters thesis. University of British Columbia, Canada
Possatto F, Barletta M, Costa M, Ivar do Sul J, Dantas D (2011) Plastic debris ingestion by marine catfish: an unexpected fisheries impact. Marine Pollution Bulletin 62: 1098-1102
Potemra JT (2012) Numerical modeling with application to tracking marine debris. Marine Pollution Bulletin 65: 42-50
Pruter AT (1987) Sources, quantities and distribution of persistent plastics in the marine environment. Marine Pollution Bulletin 18: 305-310
Ramos J, Barletta M, Costa M (2012) Ingestion of nylon threads by Gerreidae while using a tropical estuary as foraging grounds. Aquatic Biology 17: 29-34
Reisser J, Shaw J, Wilcox C, Hardesty BD, Proietti M, et al (2013) Marine Plastic Pollution in Waters around Australia: Characteristics, Concentrations, and Pathways. PLoS ONE 8(11): e80466. doi:10.1371/journal.pone.0080466
Ribic CA, Ganio LM (1996) Power analysis for beach surveys of marine debris. Marine Pollution Bulletin 32: 554-557
Ribic CA, Sheavly SB, Rugg DJ, Erdmann ES (2010) Trends and drivers of marine debris on the Atlantic coast of the United States 1997-2007. Marine Pollution Bulletin 60: 1231-1242
Ribic CA, Sheavly SB, Rugg DJ (2011) Trends in marine debris in the US Caribbean and the Gulf of Mexico 1996–2003. Journal of Integrated Coastal Zone Management 11: 7-19
Ribic CA, Sheavly SB, Rugg DJ, Erdmann ES (2012a) Trends in marine debris along the U.S. Pacific Coast and Hawai'i 1998-2007. Marine Pollution Bulletin 64: 994-1004
Richards ZT, Beger M (2011) A quantification of the standing stock of macro-debris in Majuro lagoon and its effect on hard coral communities. Marine Pollution Bulletin 62: 1693-1701
Rochman CM, Hoh E, Kurobe T, Teh SJ (2013a) Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Scientific Reports 3: doi:10.1038/srep03263
Rochman CM, Browne MA, Halpern BS, Hentschel BT, Hoh E, Karapanagioti HK, Rios-Mendoza LM, Takada H, Teh S, Thompson RC (2013b) Classify plastic waste as hazardous. Nature 494: 169-171
Rochman CM, Hentschel BT, Teh SJ (2014) Long-term sorption of metals is similar among plastic types: Implications for plastic debris in aquatic environments. Plos One 9: e85433.
Rosevelt C, Los Huertos M, Garza C, Nevins HM (2013) Marine debris in central California: Quantifying type and abundance of beach litter in Monterey Bay, CA. Marine pollution bulletin 71: 299-306
Rothstein S (1973) Particle pollution of the surface of the Atlantic Ocean: evidence from a seabird. The Condor 73: 344-345
Ryan PG (1987) The incidence and characteristics of plastic particles ingested by seabirds. Marine Environmental Research 23: 175-206
Ryan PG (1988a) Effects of ingested plastic on seabird feeding: Evidence from chickens. Marine Pollution Bulletin 19: 125-128
Ryan PG (1988b) Intraspecific variation in plastic ingestion by seabirds and the flux of plastic through seabird populations. Condor 90: 446-452
Ryan PG (2008) Seabirds indicate changes in the composition of plastic litter in the Atlantic and south-western Indian Oceans. Marine Pollution Bulletin 56: 1406-1409
Ryan PG (2013) A simple technique for counting marine debris at sea reveals steep litter gradients between the Straits of Malacca and the Bay of Bengal. Marine Pollution Bulletin 69: 128-136

Ryan PG, Swanepoel D, Rice N, Preston G (1996) The 'free' shopping bag debate: costs and attitudes. South African Journal of Science 92: 163-165
Ryan PG, Moore CJ, van Franeker JA, Moloney CL (2009) Monitoring the abundance of plastic debris in the marine environment. Philosophical Transactions of the Royal Society B-Biological Sciences 364: 1999-2012
Ryan PG, Branch GM (2012) The November 2011 irruption of buoy barnacles *Dosima fascicularis* in the Western Cape, South Africa. African Journal of Marine Science 34: 157-162
Santos IR, Friedrich AC, Barretto FP (2005) Overseas garbage pollution on beaches of northeast Brazil. Marine Pollution Bulletin 50: 783-786
Schlining K, Von Thun S, Kuhnz L, Schlining B, Lundsten L, Jacobsen Stout N, Chaney L, Connor J (2013) Debris in the deep: Using a 22-year video annotation database to survey marine litter in Monterey Canyon, central California, USA. Deep-Sea Research Part I: Oceanographic Research Papers 79: 96-105
Schneider, T. R. (2006) Getting the biggest bang for your health education buck. message framing and reducing health disparities. American Behavioural Scientist, 49: 812 – 822
Schuyler Q, Hardesty BD, Wilcox C, Townsend K (2012) To eat or not to eat? Debris Selectivity by Marine Turtles. PLoS ONE 7(7): e40884
Schuyler Q, Hardesty B, Wilcox C, Townsend K (2013) Global analysis of anthropogenic debris ingestion by sea turtles. Conservation Biology
Scott J (1988) Social network analysis. Sociology 22: 109-127
Setälä O, Fleming-Lehtinen V, Lehtiniemi M (2014) Ingestion and transfer of microplastics in the planktonic food web. Environmental Pollution 185: 77-83
Sheavly SB, Register KM (2007) Marine debris & plastics: Environmental concerns, sources, impacts and solutions. Journal of Polymers and the Environment 15: 301-305
Shomura RS, Yoshida HO, (eds) (1985) Proc. of the Workshop on the Fate and Impact of Marine Debris, 26–29 November 1984, Honolulu, Hawaii, U.S. Dep. Commer. NOAA. Tech. Memo. NOAA-TM-NMFS-SWFC-54
Simpson A (2004) The global invasive species information network: What's in it for you? BioScience 54: 613-614
Simpson A, Sellers E, Grosse A, Xie Y (2006) Essential elements of online information networks on invasive alien species. Biological Invasions 8: 1579-1587
Slavin C, Grage A, Campbell ML (2012) Linking social drivers of marine debris with actual marine debris on beaches. Marine Pollution Bulletin 64: 1580-1588
Smith SDA (2012) Marine debris: A proximate threat to marine sustainability in Bootless Bay, Papua New Guinea. Marine Pollution Bulletin 64: 1880-1883
Smith SDA, Hattori H (2008) Corals versus monofilament: corals fight back in Savusavu Bay, Fiji. Coral Reefs 27: 321-321
Smith SDA, Markic A (2013) Estimates of marine debris accumulation on beaches are strongly affected by the temporal scale of sampling. PLoS ONE 8, e83694.
Stern PC (2000) New environmental theories: toward a coherent theory of environmentally significant behavior. Journal of Social Issues 56: 407-424
Storrier KL, McGlashan DJ (2006) Development and management of a coastal litter campaign: The voluntary coastal partnership approach. Marine Policy 30: 189-196
Sutherland WJ, Clout M, Cote IM, Daszak P, Depledge MH, Fellman L, Fleishman E, Garthwaite R, Gibbons DW, De Lurio J, Impey AJ, Lickorish F, Lindenmayer D, Madgwick J, Margerison C, Maynard T, Peck LS, Pretty J, Prior S, Redford KH, Scharlemann JPW, Spalding M, Watkinson AR (2010) A horizon scan of global conservation issues for 2010. Trends in Ecology & Evolution 25: 1-7
Sutherland WJ, Fleishman E, Mascia MB, Pretty J, Rudd MA (2011) Methods for collaboratively identifying research priorities and emerging issues in science and policy. Methods in Ecology and Evolution 2: 238-247.
Tagatz ME, Plaia GR, Deans CH (1986) Toxicity of dibutyl phthalate-contaminated sediment to laboratory-colonized and field-colonized estuarine benthic communities. Bulletin of Environmental Contamination and Toxicology 37: 141-150

Talsness CE, Andrade AJM, Kuriyama SN, Taylor JA, Saal FSV (2009) Components of plastic: Experimental studies in animals and relevance for human health. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 2079-2096

Tamburri M, Luckenbach M, Breitburg D, Bonniwell S (2008) Settlement of *Crassostrea ariakensis* larvae: effects of substrate, biofilms, sediment and adult chemical cues. Journal of Shellfish Research 27: 601-608

Tanaka K, Takada H, Yamashita R, Mizukawa K, Fukuwaka MA, Watanuki Y (2013) Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. Marine Pollution Bulletin 69: 219-222

Teuten EL, Rowland SJ, Galloway TS, Thompson RC (2007) Potential for plastics to transport hydrophobic contaminants. Environmental Science & Technology 41: 7759-7764

Teuten EL, Saquing JM, Knappe DRU, Barlaz MA, Jonsson S, Bjorn A, Rowland SJ, Thompson RC, Galloway TS, Yamashita R, Ochi D, Watanuki Y, Moore C, Pham Hung V, Tana TS, Prudente M, Boonyatumanond R, Zakaria MP, Akkhavong K, Ogata Y, Hirai H, Iwasa S, Mizukawa K, Hagino Y, Imamura A, Saha M, Takada H (2009) Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society B-Biological Sciences 364: 2027-2045

Thiel M, Haye PA, (2006) The ecology of rafting in the marine environment. III. Biogeographical and evolutionary consequences. Oceanogr. Mar. Biol. Annu. Rev. 44, 323–429

Thiel M, Hinojosa IA, Miranda L, Pantoja JF, Rivadeneira MM, Vasquez N (2013) Anthropogenic marine debris in the coastal environment: A multi-year comparison between coastal waters and local shores. Marine Pollution Bulletin 71: 307-316

Thompson RC, Olson Y, Mitchell RP, Davis A, Rowland SJ, John AWG, Mcgonigle D, Russell AE (2004) Lost at sea: Where Is all the plastic? Science 304: 838

Thompson RC, Moore CJ, Vom Saal FS, Swan SH (2009) Plastics, the environment and human health: current consensus and future trends. Philosophical Transactions of the Royal Society B-Biological Sciences 364: 2153-2166

Titmus AJ, Hyrenbach KD (2011). Habitat associations of floating debris and marine birds in the North East Pacific Ocean at coarse and meso spatial scales. Marine Pollution Bulletin 62 (11): 2496-2506.

Tomas J, Guitart R, Mateo R, Raga JA (2002) Marine debris ingestion in loggerhead sea turtles, *Caretta caretta* from the Western Mediterranean. Marine Pollution Bulletin 44: 211-216

Tonglet M, Phillips PS, Bates MP (2004) Determining the drivers for householder pro- environmental behaviour: waste minimisation compared to recycling. Resource Conservation and Recycling 42: 27-48.

Topping P (2000) Marine debris: a focus for community engagement. Coastal Zone Canada Conference, Saint John, New Brunswick

Udyawer V, Read MA, Hamann M, Simpfendorfer CA, Heupel MR (2013) First record of sea snake *(Hydrophis elegans*, Hydrophiinae) entrapped in marine debris. Marine Pollution Bulletin

UNEP (2009) Marine Litter: A Global Challenge. Nairobi, United Nations Environment Programme: 232

Uneputty PA, Evans SM (1997) Accumulation of beach litter on islands of the Pulau Seribu Archipelago, Indonesia. Marine Pollution Bulletin 34: 652-655

UNESCO (1994) Marine Debris: Solid Waste Management Action Plan for the Wider Caribbean IOC Technical Series 41: 20

van der Werf EA, Young LC (2011) Estimating survival and life-stage transitions in the Laysan albatross (*Phoebastria Immutabilis*) using multistate mark-recapture models. Auk 128: 726-736

van Franeker JA, Blaize C, Danielsen J, Fairclough K, Gollan J, Guse N, Hansen PL, Heubeck M, Jensen JK, Le Guillou G, Olsen B, Olsen KO, Pedersen J, Stienen EWM, Turner DM (2011) Monitoring plastic ingestion by the northern fulmar *Fulmarus glacialis* in the North Sea. Environmental Pollution 159: 2609-2615

Van Sebille E, England MH, Froyland G (2012) Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environmental Research Letters 7: 044040

Velander K, Mocogni M (1999) Beach litter sampling strategies: is there a 'best' method? Marine Pollution Bulletin 38: 1134-1140

Verlis KM, Campbell ML, Wilson SP (2013) Ingestion of marine debris plastic by the wedge-tailed shearwater *Ardenna pacifica* in the Great Barrier Reef, Australia. Marine Pollution Bulletin

Votier SC, Archibald K, Morgan G, Morgan L (2011) The use of plastic debris as nesting material by a colonial seabird and associated entanglement mortality. Marine Pollution Bulletin 62:168-172
Wabnitz CCC, Nichols WJ (2010) Plastic pollution: an ocean emergency. Marine Turtle Newsletter 129: 1-4
Wakker PP (2010) Prospect theory: for risk and ambiguity. Cambridge University Press, Cambridge UK, 1-500
Waldichuk M (1978) Plastics and seals. Marine Pollution Bulletin 9: 197
Wallace BP, Dimatteo AD, Hurley BJ, Finkbeiner EM, Bolten AB, Chaloupka MY, Hutchinson BJ, Abreu-Grobois FA, Amorocho D, Bjorndal KA, Bourjea J, Bowen BW, Dueñas RB, Casale P, Choudhury BC, Costa A, Dutton PH, Fallabrino A, Girard A, Girondot M, Godfrey MH, Hamann M, López-Mendilaharsu M, Marcovaldi MA, Mortimer JA, Musick JA, Nel R, Pilcher NJ, Seminoff JA, Troëng S, Witherington B, Mast RB (2010) Regional management units for marine turtles: a novel framework for prioritizing conservation and research across multiple scales. PloS ONE 5
Watters DL, Yoklavich MM, Love MS, Schroeder DM (2010) Assessing marine debris in deep seafloor habitats off California. Marine Pollution Bulletin 60: 131-138
Wegner A, Besseling E, Foekema E, Kamermans P, Koelmans A (2012) Effects of nanopolystyrene on the feeding behavior of the blue mussel (*Mytilus edulis* L) Aquatic Ecology 31: 2490-2497
Wegner NC, Cartamil DP (2012) Effects of prolonged entanglement in discarded fishing gear with substantive biofouling on the health and behavior of an adult shortfin mako shark, *Isurus oxyrinchus*. Marine Pollution Bulletin 64: 391-394
Weiss K, Hamann M, Kinney M, Marsh H (2012) Knowledge exchange and policy influence in a marine resource governance network. Global Environmental Change 22: 178-188
White M, Smith A, Humphryes K, Pahl S, Snelling D, Depledge M (2010) Blue space: The importance of water for preference, affect, and restorativeness ratings of natural and built scenes. Journal of Environmental Psychology 30: 482-493
Whitehead TO, Biccard A, Griffiths CL (2011) South African pelagic goose barnacles (*Cirripedia thoracica*): substratum preferences and influence of plastic debris on abundance and distribution. Crustaceana 84: 635-649
Widmer WM, Hennemann MC (2010) Marine debris in the Island of Santa Catarina, South Brazil: Spatial patterns, composition, and biological aspects. Journal of Coastal Research 26: 993-1000
Wilber RJ (1987) Plastic in the North-Atlantic. Oceanus 30: 61
Wilcox C, Hardesty B, Sharples R, Griffin D, Lawson T, Gunn R (2013) Ghost net impacts on globally threatened turtles, a spatial risk analysis for northern Australia. Conservation Letters
Williams AT, Simmons SL (1997) Estuarine litter at the river/beach interface in the Bristol Channel, United Kingdom. Journal of Coastal Research 13: 1159-1165
Willoughby N, Sangkoyo H, Lakaseru B (1997) Beach litter: an increasing and changing problem for Indonesia. Marine Pollution Bulletin 34: 468-478
Winston J, Gregory M, Stevans L (1997) Encrusters, epibionts, and other biota associated with pelagic plastics: a review of biogeographical, environmental, and conservation issues. In Marine Debris: Sources, Impacts, and Solutions. Coe J, Rogers D (eds). New York, Springer-Verlag: 81-97
Wright SL, Thompson RC, Galloway TS (2013) The physical impacts of microplastics on marine organisms: A review. Environmental pollution 178: 483-492
Wyatt ASJ, Hewitt CL, Walker DI, Ward TJ (2005) Marine introductions in the Shark Bay World Heritage Property, Western Australia: A preliminary assessment. Diversity and Distributions 11: 33-44
Wyneken J (2001) The Anatomy of Sea Turtles. U.S. Department of Commerce NOAA Technical Memorandum NMFS SEFSC-470, Washington DC: 1-102
Yang C, Xu Y, Nebert D (2013) Redefining the possibility of digital Earth and geosciences with spatial cloud computing. International Journal of Digital Earth 6: 297-312
Yates MR Barlow CY (2013) Life cycle assessments of biodegradable, commercial biopolymers - a critical review. Resources, Conservation and Recycling 78: 54-66
Ye S, Andrady AL (1991) Fouling of floating plastic debris under Biscayne Bay exposure conditions. Marine Pollution Bulletin 22: 608-613
Yoshikawa T, Asoh K (2004) Entanglement of monofilament fishing lines and coral death. Biological Conservation 117: 557-560

Figure headings

Figure 1. Trends in the number of publications on 'MARINE + PLASTIC POLLUTION' or 'MARINE DEBRIS' or 'MARINE + LITTER' using a Web of Science search from 1972 to 2013. The publication spikes in 1985 and 1987 relate to the proceedings of the first International Marine Debris Conference and a special edition of Marine Pollution Bulletin covering the theme of plastics at sea from the 1986 International Ocean Dispersal Symposium respectively.

Figure 2. Clockwise from top left – Beach debris from a remote beach in Catholic Island, Grenadines (courtesy Jennifer Lavers), debris accumulation on an urban beach (Stradbroke Island, Australia) (courtesy Kathy Townsend), entanglement and damage to soft coral by fishing line (courtesy Stephen Smith), and fishing line entanglement of a pier with algae and sponges growing on it (courtesy Kathy Townsend).

Figure 3. Clockwise from top left – Magnificent frigatebird (*Fregata magnificens)* carcass from Battowia Island, Grenadines, with orange foam contained within stomach (courtesy Jennifer Lavers), Antarctic fur seal (*Arctocephalus gazella)* with plastic ring entanglement in King George Island, Antarctica (courtesy Juliana Ivar do Sul), juvenile green turtle (*Chelonia mydas*) trapped in discarded crab trap and plastic fragments recovered from the gut of a juvenile green turtle (courtesy Kathy Townsend).

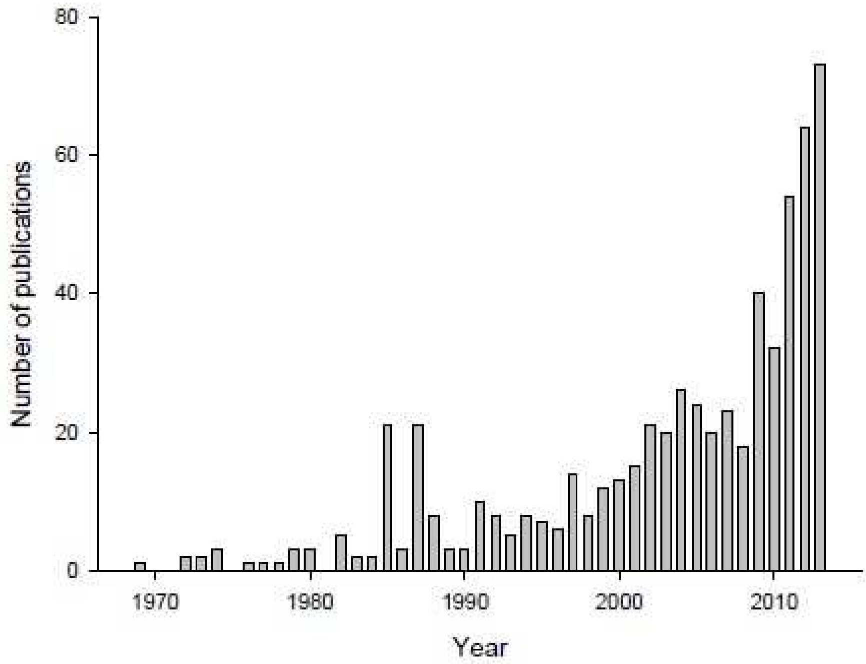
80
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Fig. 2 Clockwise from top left – Beach debris from a remote beach in Catholic Island, Grenadines (courtesy Jennifer Lavers), debris accumulation on an urban beach (Stradbroke Island, Australia) (courtesy Kathy Townsend), entanglement and damage to soft coral by fishing line (courtesy Stephen Smith), and fishing line entanglement of a pier with algae and sponges growing on it (courtesy Kathy Townsend).

Fig. 3 Clockwise from top left – Magnificent frigatebird (*Fregata magnificens)* carcass from Battowia Island, Grenadines, with orange foam contained within stomach (courtesy Jennifer Lavers), Antarctic fur seal (*Arctocephalus gazella)* with plastic ring entanglement in King George Island, Antarctica (courtesy Juliana Ivar do Sul), juvenile green turtle (*Chelonia mydas*) trapped in discarded crab trap and plastic fragments recovered from the gut of a juvenile green turtle (courtesy Kathy Townsend).

Appendix J. To Eat or not to Eat? Debris Selectivity by Marine Turtles, PLOS One 2012

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To Eat or Not to Eat? Debris Selectivity by Marine Turtles

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Abstract

Marine debris is a growing problem for wildlife, and has been documented to affect more than 267 species worldwide. We investigated the prevalence of marine debris ingestion in 115 sea turtles stranded in Queensland between 2006–2011, and assessed how the ingestion rates differ between species (*Eretmochelys imbricata* vs. *Chelonia mydas*) and by turtle size class (smaller oceanic feeders vs. larger benthic feeders). Concurrently, we conducted 25 beach surveys to estimate the composition of the debris present in the marine environment. Based on this proxy measurement of debris availability, we modeled turtles' debris preferences (color and type) using a resource selection function, a method traditionally used for habitat and food selection. We found no significant difference in the overall probability of ingesting debris between the two species studied, both of which have similar life histories. Curved carapace length, however, was inversely correlated with the probability of ingesting debris; 54.5% of pelagic sized turtles had ingested debris, whereas only 25% of benthic feeding turtles were found with debris in their gastrointestinal system. Benthic and pelagic sized turtles also exhibited different selectivity ratios for debris ingestion. Benthic phase turtles had a strong selectivity for soft, clear plastic, lending support to the hypothesis that sea turtles ingest debris because it resembles natural prey items such as jellyfish. Pelagic turtles were much less selective in their feeding, though they showed a trend towards selectivity for rubber items such as balloons. Most ingested items were plastic and were positively buoyant. This study highlights the need to address increasing amounts of plastic in the marine environment, and provides evidence for the disproportionate ingestion of balloons by marine turtles.

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Introduction

Marine Debris and Sea Turtles

Marine debris has become a significant global issue in recent years. Over the past five decades, global plastic production has increased exponentially [1]. Concurrently, plastic has rapidly become the dominant component of marine debris, representing as much as 80% in areas [2,3]. Despite increasing awareness of the prevalence of plastic debris, there is little data on the total amount of debris in the marine environment, or how that quantity may have changed through time [4,5]. The impacts of this debris, however, have been widely documented, with at least 267 marine species known to be affected by anthropogenic debris [6]. Debris can cause a number of different problems for wildlife, but all fall under two main categories: impacts from entanglement and from ingestion. Entanglement can kill wildlife by drowning or inhibiting the ability to escape predation or feed normally, while the implications of debris ingestion include death through perforation or impaction of the digestive system [7]. Additional sublethal impacts include dietary dilution [8] and exposure to chemicals leaching from plastic [9]. All six species of sea turtle listed on the IUCN Red list [10] have been documented to ingest debris [6].

Globally, estimates of debris ingestion rates in turtles vary dramatically with geographical region, species, and year. Recent work from South American populations of marine turtles found that up to 100% of stranded turtles contained marine debris in their gastrointestinal systems [11]. The problem affects turtles of all life stages, from post-hatchlings through adults [12–14]. It is unknown why sea turtles ingest plastic: one hypothesis is that plastic bags resemble a typical prey item, jellyfish [15]. Although this may be the case for turtles that ingest plastic bags, it does not explain the ingestion of other forms of plastic, Styrofoam, rubber, ropes, and the myriad of other items that have been found in turtles [16–21]. Although sea turtles can and do utilize olfaction to orient to prey, they are primarily visual feeders [22]. The presence of at least three different cone photopigments in sea turtle retinas, as well as electrophysiological measurements and behavioral studies, indicate their ability to discriminate color [23–25]. This color vision may play a role in feeding choices, as has been demonstrated in laboratory trials [25–28]. If this is the case, monitoring the color of debris ingested by turtles may offer insights to the reasons why turtles eat debris, and may also lead to conservation and management recommendations. Color preference (or avoidance) has already been investigated as a possible method for decreasing sea turtles' interactions with the bait used in longline fisheries. Unfortunately, although turtles exhibit a preference for natural bait over blue dyed bait in a laboratory situation, dyed bait does not appear to reduce long line interactions in field trials [28].

Hawksbill Turtle and Green Turtle Life History

Both *Chelonia mydas* (green turtles) and *Eretmochelys imbricata* (hawksbill turtles) begin their developmental phase in the open ocean before recruiting back as latter stage juveniles to the coastal environment, where they spend the rest of their lives [29]. Before recruitment, the post-hatchling turtles and early stage juveniles live and feed primarily at the ocean's surface, occasionally diving to shallow depths [30]. They are thought to drift with the currents, aggregating in downwelling lines along with other floating biological material and debris [12]. During this phase they feed on plankton, comprising primarily molluscs, crustaceans, and gelatinous organisms [20]. Living in downwelling zones may provide the young turtles with increased shelter and food opportunities, but also exposes them to concentrated areas of floating debris.

The turtles' feeding behavior changes dramatically once they recruit to the nearshore environment. The size of first recruitment varies between species and geographic region, but on the east coast of Australia, green turtles recruit at approximately 40 cm curved carapace length (CCL) [31], and hawksbill turtles at >35 cm CCL [32]. These coastal turtles feed primarily on benthic resources such as seagrass, crustaceans, sponges, and algae, although even primarily herbivorous green turtles will opportunistically feed on jellyfish when available [33,34]. Green turtles are known to be selective in their feeding, choosing particular species of seagrass over others, and even tending "grazing plots" to gather new shoots that are easier to digest and have higher nutritional value [35]. Hawksbill turtles also feed selectively, preferentially ingesting certain items even when they are less readily available in the environment [36].

With this diversity in feeding habitat and style between pelagic and benthic stage turtles, we predict that exposure to marine debris would differ between the two groups. These differences could be exacerbated by the variability in types, colors, and quantities of debris present in benthic and oceanic environments [1]. It is likely that pelagic stage turtles, which drift in current lines along with other floating debris, would be at greater risk of marine debris ingestion than the larger benthic animals [12,33]. Because of their different diets and feeding styles, pelagic and benthic turtles may vary not only in the amounts of debris they ingest, but also in the type. Analyzing the type and color of debris gives us metrics to compare the variability in debris selection between turtles at different life stages.

Our aims were to 1) investigate whether the incidence of debris ingestion varies between turtle species and between life history stages, 2) determine whether turtles preferentially ingest particular types and colors of debris by comparing the ingested debris to what is available in the environment, and 3) analyze whether selectivity varies between life history stages and between species.

Materials and Methods

This research was reviewed and approved by the University of Queensland Native/Exotic Wildlife and Marine Animals (NEWMA) Animal Ethics Committee. The ethics approval number is ANRFA/MBRS/182/11. Animals involved in the study were already deceased, so no steps were taken to ameliorate suffering.

From 2005–2011, 115 turtles were obtained in southeast Queensland from two sources: dead stranded sea turtles from North Stradbroke Island (n = 64), and sea turtles that did not survive treatment at the marine wildlife rehabilitation facility at Underwater World, in Mooloolaba (n = 51). Eighty-eight were green sea turtles (*C. mydas*), 24 were hawksbill turtles (*E. imbricata*), 2 were loggerhead turtles (*C. caretta*) and one was a flatback turtle (*N. depressus*). The turtles ranged from 5.4–105.8 cm CCL, with a median size of 43.4 cm. Because of the small sample size of loggerhead and flatback turtles, all investigations of inter-species differences were restricted to green and hawksbill turtles.

Necropsies were performed on all animals using standard techniques [37]. Contents of the gastrointestinal system were sieved to retrieve any foreign matter. Debris found in the turtles was washed and stored for analysis. Each piece of debris was weighed (to within 0.01 g) and categorized into one of six main categories and additional subcategories, based on a classification system combining both composition and morphology. The categories were: hard plastic, soft plastic, foam, rope/string, rubber, and miscellaneous (includes glass, metal, paper, cloth). Hard and soft plastic objects were further categorized by color. Positive or negative buoyancy was also measured for each item. For six of the turtles, debris samples were not retained; so detailed categorical information is not available. The majority of rope and string items (>85%) were composed of plastic material, but were categorized separately due to their morphology.

We calculated the frequency of ingestion of each category of debris using the following equation:

$$F = (N_i / N) * 100$$

where N_i is the number of turtles having ingested a particular type of debris, i, and N is the total number of turtles for which detailed debris information is available [38]. We also determined the relative percent abundance of debris types ingested by each turtle by calculating the percentage

$$\%A = Nd / Nt * 100$$

where Nd is the number of items of each type of debris, and Nt is the total number of items of debris found in the turtle. Turtles were divided into two groups; pelagic sized feeders and benthic sized animals. We categorized pelagic feeders as those animals smaller than 35.0 cm, and benthic feeders as those >35 cm CCL.

To estimate availability of anthropogenic debris, we conducted beach surveys between 2009–2011 on four beaches on N. Stradbroke Island and four beaches on the Sunshine coast, in the region where the Underwater World turtles stranded. We collected all pieces of debris over 5 mm found in a 100 m long strip transect running parallel to the water line on each beach. The strip transect width varied depending on tide and the beach in question, but encompassed the distance from the waterline to the dominant landward vegetation line. Beach debris was assigned to the same categories as debris found in turtles. We calculated the relative abundance of each type and color of plastic debris found in the environment using equations parallel to those above. For simplicity of analysis, and because no individual color represented more than 10% of the sample, we combined our color and debris types to create 10 categories in order to measure selectivity indices for the turtles. These types were: hard white plastic, hard colored plastic, hard clear plastic, soft white plastic, soft colored plastic, soft clear plastic, rope/string, rubber, foam, and miscellaneous.

Table 1. Debris ingestion probability for pelagic and benthic stage turtles, and characteristics of these turtles.

	Total number of turtles	Number of turtles having ingested debris (% of total)	Range of CCL (cm)	Mean CCL (+/− s.e.)
All turtles	115	39 (33.9%)	5.4–105.8	39.08±19.35
Pelagic	22	12 (54.5%)	5.4–34.9	20.44±11.61
Benthic	93	27 (29.0%)	35.31–44.7	47.37±16.08

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We used a binomial regression to predict the probability of ingestion based on the descriptive variables CCL and species (*C. mydas* and *E. imbricata*), and a chi square analysis to determine differences between ingestion probabilities for life history stages. For the turtles that had ingested debris, we tested the relationship between CCL and debris load (both total weight and also number of pieces of debris ingested) using a generalized linear model (GLM, Gaussian model). Finally, we calculated Manly's selectivity ratio for each debris category ingested for both life history stages. This technique has been widely used to estimate resource selection functions for habitat or diet [39]. The index takes into account the availability of each type of resource in the environment. A value greater than 1 indicates a positive selectivity for that category, while a value less than one suggests that turtles avoid ingesting that type of debris compared to what is available in the environment. All analyses were performed using R version 2.14, package nnet and adehabitat [40–42].

Results

Debris Ingestion

Of the 115 necropsied animals, 22 were oceanic-size turtles, and 93 were from benthic habitats (Table 1). A total of 33.9% (N = 39) of the turtles were found to have ingested debris. Ingestion frequencies differed significantly between oceanic (n = 12, 54.5%) and benthic-sized turtles (n = 27, 29.0%), despite our uneven sample sizes (chi-square 4.09, df = 1, p = 0.043). There was a significant negative correlation between CCL and probability of debris ingestion (p = 0.0338), but no correlation with the weight of debris ingested (p = 0.942), or total number of pieces of debris ingested (p = 0.215). Nor was there a significant effect of species on the probability of ingesting debris (p = 0.445), or a species by size interaction (p = 0.430). Because we do not have detailed debris information for six of the turtles, calculations on the weight and total number of debris items were carried out only on n = 33 turtles.

A total of 1057 pieces of debris were ingested by 33 turtles. The number of pieces ingested by each individual turtle ranged from 1–329 with an average of 31.7±10.18 (s.e.) pieces per turtle. The total weight of all items found within each turtle ranged from non-detectable (<0.01 g) to 10.41 g. The average proportion of positively buoyant items ingested by the turtles was approximately 80% and did not vary significantly between the two life stages (Table 2). Hard plastic comprised 33.11% of the total number of debris items ingested, 34.25% was soft plastic, and plastic rope followed at 13.06% (Table 3). Including fishing line and packing straps, the total amount of plastic debris ingested by turtles made up nearly 90% of all debris items. When data were analyzed by life history stages, oceanic sized turtles ingested significantly more hard plastic and rubber than benthic turtles, while benthic turtles ingested more foam and rope than pelagic turtles (Fig. 1). Colors varied between the two classes, but not significantly. The color of plastic debris found in both pelagic and benthic turtles was primarily clear or translucent, followed by white (Fig. 2). Black debris comprised mainly black plastic bags, while green and blue were mostly plastic rope and string. Other colors (red, orange, yellow, and brown) were found in very small quantities.

Environment and Selectivity

The majority of the debris found during all beach surveys was hard plastic, with only one other category (miscellaneous) at over 15% (Fig. 1). White debris made up over 30% of collected items, followed by blue and clear/translucent (Fig. 2). Using beach debris as a measure of environmental availability, Manly's selectivity ratio highlighted the selectivity differences between turtles from different life stages. Benthic sized turtles showed strong selectivity for soft plastics in general, particularly for clear soft plastics, and for rope. They appeared to avoid hard white and colored debris (Fig. 3). Pelagic turtles had the highest selection ratios for rubber, rope, and hard plastic, but these did not differ significantly from the environment (Fig. 4).

Discussion

Marine debris or more specifically, plastic ingestion by sea turtles is a global phenomenon, affecting populations worldwide. The vast majority (nearly 90%) of all ingested items in this study were plastic in origin, a finding common to most other studies reporting debris ingestion in turtles [16,43–45]. This reflects the

Table 2. Characteristics of debris items found within turtles that had ingested debris, for which detailed debris information is available (n = 33).

	Number of items ingested per turtle (avg ± s.e.)	Weight of items ingested (avg ± s.e.)	% of positively buoyant items ingested (avg ± s.e.)
Turtles (n = 33)	1–329 (31.7±10.18)	n.d.–10.41 g (1.58±0.50)	81.59±7.09
Pelagic (n = 11)	1–69 (22.5±6.78)	0.03–2.16 g (0.86±0.33)	80.51±13.91
Benthic (n = 22)	1–329 (38.8±15.01)	n.d.–10.41 g (1.89±0.70)	81.99±8.47

doi:10.1371/journal.pone.0040884.t002

Table 3. Number of turtles ingesting each type of debris, and proportions of total for different debris categories (out of n = 33 turtles for which detailed debris categories are available).

Type of debris	Number of turtles (and % of total) with ingested debris	Percentage of total amount of debris ingested by all turtles (n = 1057)
Hard plastic	19 (57.6%)	33.11
Soft plastic	24 (72.7%)	34.25
Plastic rope/string/twine	14 (42.4%)	13.06
Non plastic rope	1 (3.0%)	1.80
Packing straps	1 (3.0%)	3.12
Fishing items	15 (45.5%)	4.73
Balloons	10 (30.3%)	3.20
Other rubber	5 (15.2%)	0.9
Foam	4 (12.1%)	3.50
Other	10 (30.3%)	2.33

doi:10.1371/journal.pone.0040884.t003

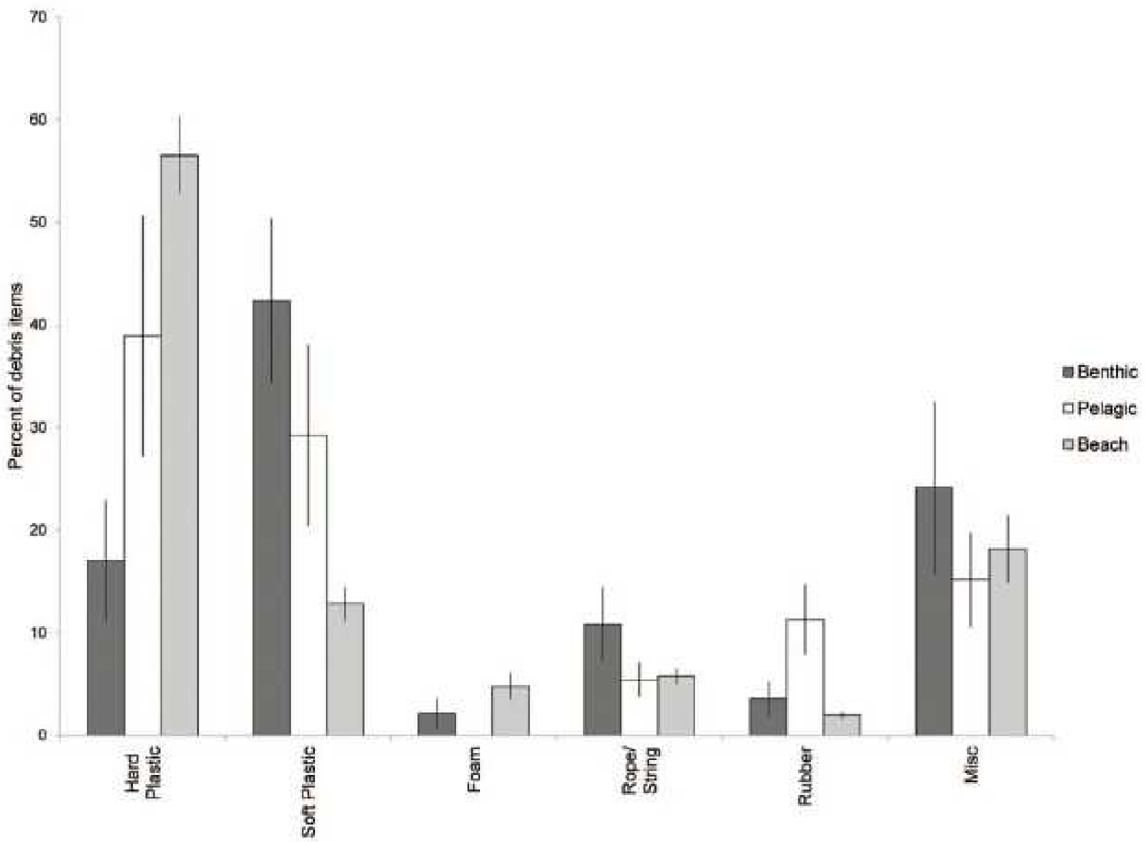

Figure 1. Debris types found in turtles and on beaches. Types of debris found during beach surveys, and in the gastrointestinal system of stranded sea turtles. Reported as an average of the percentage of each category found within each animal (benthic n = 22, pelagic n = 11), and during each beach survey (n = 25). Error bars indicate standard error.
doi:10.1371/journal.pone.0040884.g001

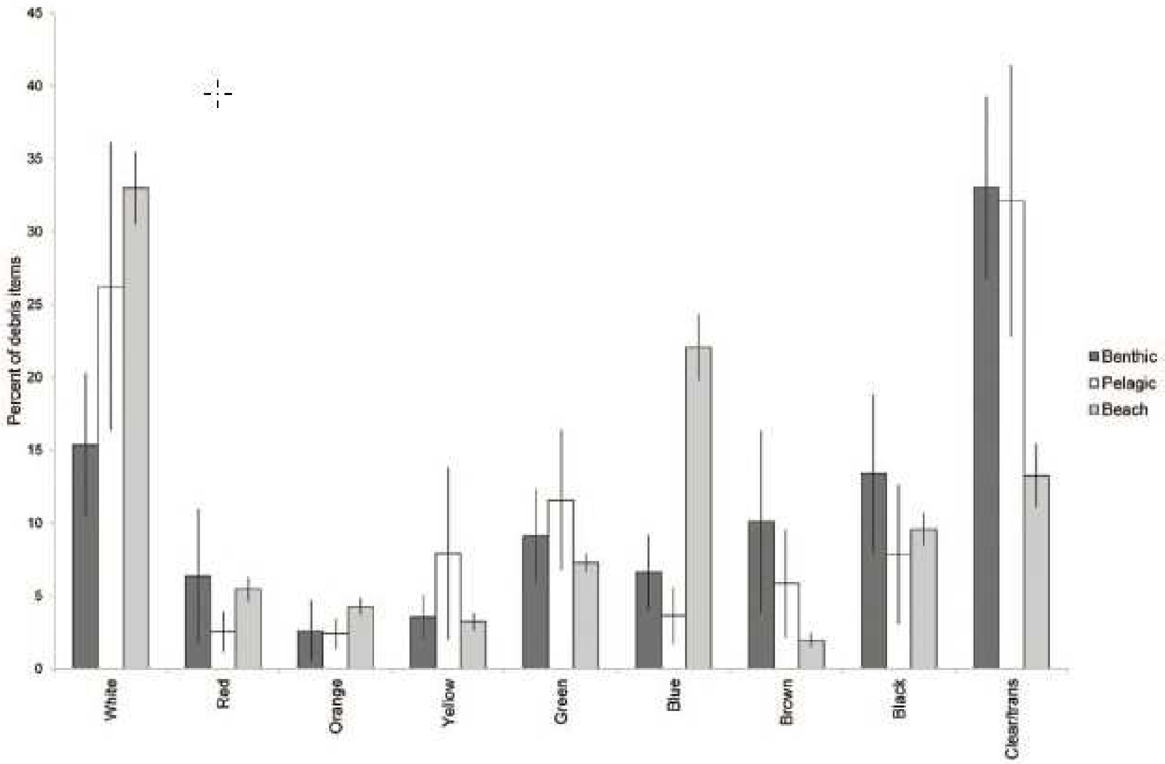

Figure 2. Debris colors found in turtles and on beaches. Colors of debris found during beach surveys, and in the gastrointestinal system of stranded sea turtles. Reported as an average of the percentage of each category found within each animal (benthic n = 22, pelagic n = 11), and during each beach survey (n = 25). Error bars indicate standard error.
doi:10.1371/journal.pone.0040884.g002

significant contribution of plastic to the global marine debris problem [5].

This study discovered no significant differences in debris ingestion between the species investigated; *C. mydas* and *E. imbricata*. This is perhaps due to the fact that the two species exhibit similar feeding behavior, with smaller turtles feeding pelagically, and larger turtles shifting to benthic feeding [46]. Although species had little effect on debris ingestion rates, size did. The probability of debris ingestion was inversely correlated with size (CCL), and when broken down into size classes, smaller pelagic turtles were significantly more likely to ingest debris than larger benthic feeding turtles. These results are in line with research conducted by Balazs [47] and Plotkin and Amos [17], though other studies found no significant relationship between size or life history stage and debris ingestion. Most of these studies investigated the relationship between turtle size (CCL) and weight, number, or size of the pieces of debris ingested, but did not analyze the probability of debris ingestion [16,44,45], nor did they investigate differences between life history stages [16,45]. Bjorndal's [13] analysis of ingestion probability and size class of green turtles suggested that a higher percentage of turtles <30 cm had ingested debris in comparison to their larger counterparts, however this difference was not significant. Size class or life history stage appears to be an important factor in determining the probability of debris ingestion, but the number of pieces, total weight, or volume of ingested debris rarely correlates with size class or life history stage, as highlighted by this and other studies.

Turtles in this study from different life history stages varied not only in their likelihood of ingesting debris, but also in the types of debris ingested. Pelagic turtles ingested significantly more rubber and hard plastic than did benthic feeding turtles, who primarily ingested soft plastic (Fig. 1). While there was not a significant difference in the colors ingested between the two groups, they did differ from what was available in the environment, ingesting clear debris in greater proportions, and blue at lower proportions (Fig. 2). Manly's selectivity ratio, and its significance level, also varied with life history stage. Neritic turtles actively selected white and clear soft plastics, while avoiding hard white and colored plastics (Fig. 1). They also showed selectivity for rope and string, but this could be an artifact of the way the samples were tallied. Counts of the total number of items were used to quantify the amount of debris in each category. Multi-stranded rope and string may more readily unravel into smaller (and therefore, more numerous) pieces within the gastrointestinal system than other types of debris, which could be reflected in our results.

Pelagic turtles were much less selective than their neritic counterparts, with most of their selectivity indices not found to be significantly different to environmental levels. Only foam (with zero pieces ingested) and hard colored debris fell significantly below 1, indicating avoidance of these categories. Interestingly, the single highest preference in the pelagic turtles was for rubber. Although the preference was not statistically significant, this may be due in part to the smaller sample size of the pelagic turtles. Of the 41 pieces of rubber found inside all turtles, 32 pieces (78%)

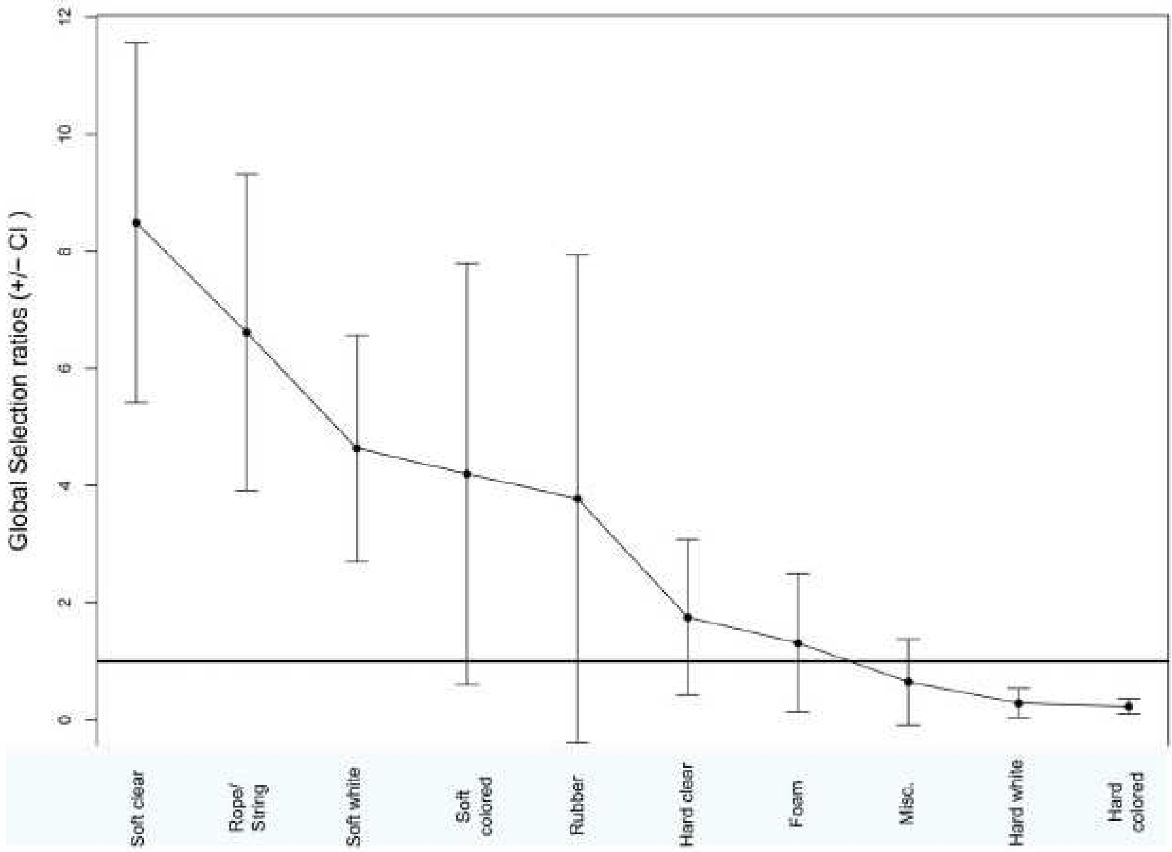

Figure 3. "Jellyfish" balloon. Beach-washed balloon found after brittle fracture. Note the resemblance to jellyfish, common prey items for turtles.
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were fragments of balloons. When helium balloons are released into the environment, they rise to a height of approximately 8 kilometers before undergoing a process known as "brittle fracture", where the balloon fragments into long strands [48]. The resulting debris bears a strong resemblance to jellyfish or squid (Fig. 5). Indeed, the brittle fracturing of balloons creates tentacle-like structures typical of *Scyphomedusae* which all species of sea turtles have been documented to eat [46,49–51]. This may be the cause for the high ingestion selectivity seen in both pelagic and neritic turtles. Several studies have reported ingestion of balloons by sea turtles [11,17,52,53], and anecdotal evidence exists for ingestion of balloons by whales and dolphins [54]. Worldwide cleanups sponsored by the Ocean Conservancy over the past 25 years have found over 1.2 million balloons, or about 0.7% of all debris items collected [55]. This is in line with our study, which found a total of 0.9% of rubber items on the beach. Although balloons and other rubber items make up only a small fraction of the total amount of debris collected, the current data indicating that turtles may selectively ingest balloons and other rubber could provide guidance for policy makers addressing mass balloon releases.

The differences in debris preference and selectivity may be a result of feeding styles; young pelagic turtles live an epipelagic lifestyle, floating at the surface and feeding within the top five meters [30]. As they drift with the currents, encountering pelagic gyres and downwelling zones where debris accumulates, they may be susceptible to accidental or purposeful ingestion of debris along with their natural food sources. The presence of encrusting organisms further blurs the line between food and debris. Post hatchlings are thought to be relatively non-selective feeders [56], a finding supported by this research. Conversely, benthic-feeding green turtles and hawksbill turtles are thought to be more selective about their diet [35,36]. They also may be less likely to come into contact with plastic marine debris, much of which is positively buoyant [57,58]. However, they also eat gelatinous organisms, which are usually soft and transparent, much like the debris that they most commonly ingest. Our findings lend further support to the hypothesis that turtles mistakenly eat plastic because of its similarity to jellyfish [15]. Other factors may also contribute to the differences in ingestion rates; for example as turtles grow, the internal diameter of their digestive tract becomes larger, making it easier for plastics to pass through, and not accumulate. Pelagic turtles, therefore, may experience a higher risk of mortality from debris ingestion, not only because they are more likely to ingest debris, but also because they are smaller in this life history stage than they are in the benthic stage and their digestive tract is correspondingly smaller. Hence, this may result in an increased possibility of impaction or perforation of the gastrointestinal tract.

There are limitations to using beach surveys as a proxy for the debris that sea turtles encounter. Differences in buoyancy, degradability, and other characteristics may result in certain types of marine debris more frequently stranding on or being retained

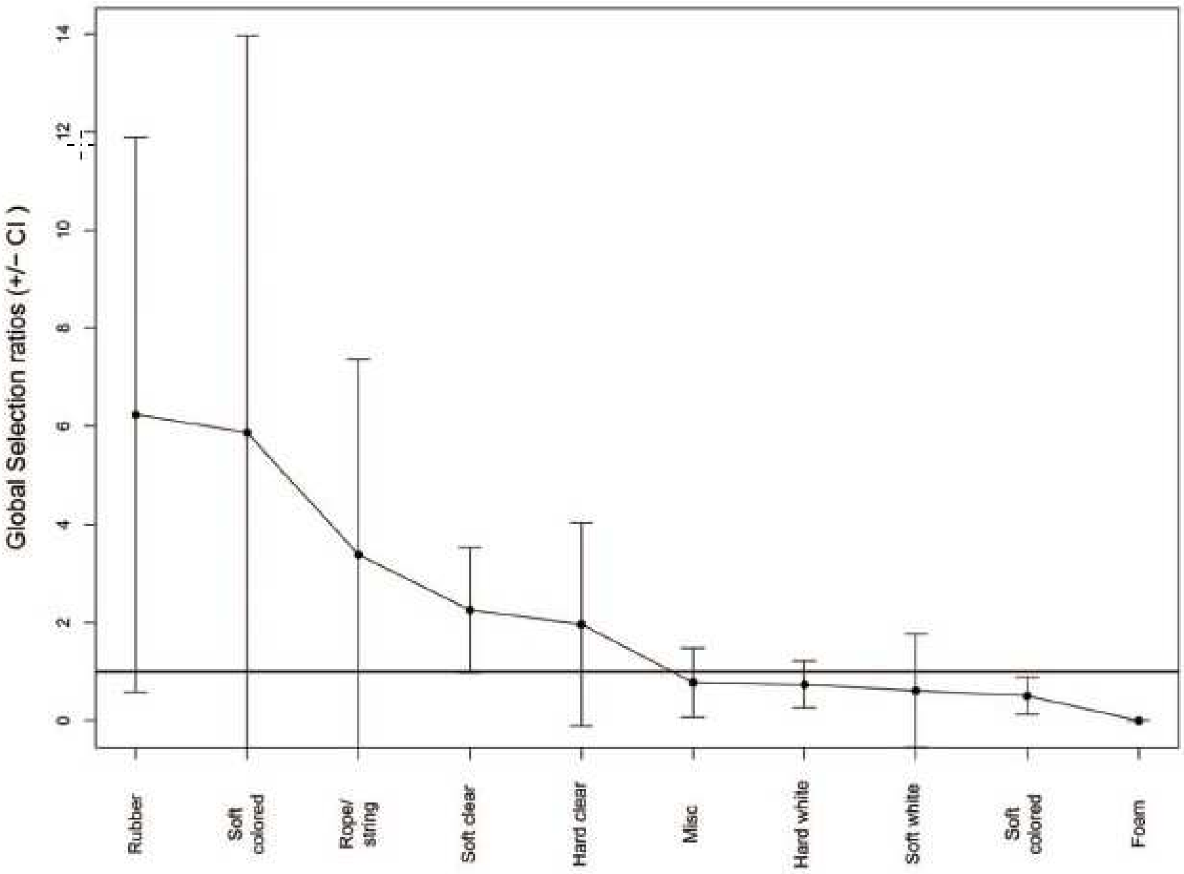

Figure 4. Manly selectivity measure for benthic turtles. Selectivity index for various types of debris ingested by benthic-feeding turtles. Where index is larger than one, selectivity for that item is greater than its availability in the environment. Error bars indicate 95% confidence interval.
doi:10.1371/journal.pone.0040884.g004

on beaches. Conversely, some land-based materials disposed on beaches may not ultimately end up in the marine environment, and thus available to turtles. However, despite these constraints, beach debris has widely been used as an indicator of marine debris, for several key reasons [59,60]. First, it is much less resource intensive to monitor beach debris, and collected debris can be characterized comprehensively, unlike with visual at-sea sampling. Second, because debris accumulates on beaches, statistically robust sample sizes can be gathered, while in-water sampling can lead to a paucity of data and the need to extrapolate from small sample sizes [60]. Finally, items on the beach are in dynamic flux with the nearshore marine environment, and can easily become resuspended [61], so while not ideal, beach debris measurements provide a reasonable proxy for environmental availability. However, it is recommended that more in-water sampling of marine debris be carried out to provide quantitative estimates of marine debris and types of marine debris, especially in areas where turtles are likely to occur.

Research in Australia and elsewhere has shown an inverse correlation between the amount of beach debris and the distance from major population centers [3,62], suggesting that neritic turtles in SE Queensland, near Australia's 3rd largest city, Brisbane (population >2 million), might come into contact with different amounts of debris than would open ocean turtles. Despite this, pelagic turtles in this study are more likely to ingest debris than are the benthic turtles. This leads us to speculate as to whether pelagic turtles encounter increased amounts of debris in oceanic gyres and in wind rows [63], whether they are less selective due to the decreased food availability in the open ocean, or whether their feeding ecology simply places them at higher risk for debris ingestion.

Conclusions

This study found that pelagic and neritic turtles exhibit significant differences in their likelihood of ingesting debris, as well as in their selectivity of debris types. These differences are likely related to their life style and feeding habits, but may also be linked to differing debris availability in the habitats that they frequent. In order to assess population scale impacts from debris ingestion, a greater understanding of the distribution of debris, as well as the long and short-term impacts of ingested debris is required. Further research and modeling of debris in both the nearshore and oceanic environment, in addition to research on the lethal and sublethal impacts of various types of debris loading will provide more accurate and precise estimates of what is available to marine wildlife, the likelihood of encounter rate, and ultimately the risks associated with anthropogenic marine debris ingestion.

Figure 5. Manly selectivity measure for pelagic turtles. Selectivity index for various types of debris ingested by pelagic-feeding turtles. Where index is larger than one, selectivity for that item is greater than its availability in the environment. Error bars indicate 95% confidence interval.
doi:10.1371/journal.pone.0040884.g005

It is also important to continue conducting necropsies and to create standardized reporting mechanisms, as the percent and types of debris ingested may be used as an indicator of the impacts of marine debris to wildlife, and only with long-term consistent data collection and recording can we begin to understand how this may change through time.

Close to ninety percent of the debris ingested by turtles in this study was plastic in origin. Observationally it would appear over half of the animals had a non-trivial debris load. As the global production and use of plastics continues to rise, it is likely that impacts to turtles will not abate. Additionally, the observed trend towards selectivity for rubber items, particularly balloons, highlights the need for targeted pollution prevention plans. Appropriate waste disposal measures to reduce debris through local measures would help to decrease the amount of anthropogenic debris entering the ocean; an important first step in reducing encounter rates and impacts to marine wildlife from ingestion or entanglement.

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Author Contributions

Conceived and designed the experiments: QS KT. Performed the experiments: QS KT. Analyzed the data: QS CW. Contributed reagents/materials/analysis tools: KT. Wrote the paper: QS. Major reviews and revisions of article: BDH KT.

References

1. Kershaw P, Katsuhiko S, Lee S, Samseth J, Woodring D, et al. (2011) Plastic debris in the ocean.
2. Derraik J (2002) The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 44: 842–852.
3. Barnes DKA, Galgani F, Thompson RC, Barlaz M (2009) Accumulation and fragmentation of plastic debris in global environments. Philosophical Transactions of the Royal Society B: Biological Sciences 364: 1985–1998.
4. Ryan PG, Moloney CL (1993) Marine litter keeps increasing. Nature 361: 23.

5. Barnes D, Milner P (2005) Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. Marine Biology 146: 815–825.
6. Laist D (1997) Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. Springer Series on Environmental Management.
7. Wallace N (1985) Debris entanglement in the marine environment: a review. In: Shomura RS, Yoshido HO, editors. Proceedings of the Workshop on the Fate and Impact of Marine Debris. Honolulu, Hawaii: US Department of Commerce, NOAA Technical Memo. NMFS, NOAA-TM-MMFS-SWFC-54. 259–277.
8. McCauley SJ, Bjorndal KA (1999) Conservation implications of dietary dilution from debris ingestion: Sublethal effects in post-hatchling loggerhead sea turtles. Conservation Biology 13: 925–929.
9. Meeker JD, Sathyanarayana S, Swan SH (2009) Phthalates and other additives in plastics: human exposure and associated health outcomes. Philosophical Transactions of the Royal Society B-Biological Sciences 364: 2097–2113.
10. IUCN (2010) IUCN Red List of threatened species. Version 2010.3.
11. Tourinho PS, do Sul JAI, Fillmann G (2010) Is marine debris ingestion still a problem for the coastal marine biota of southern Brazil? Marine Pollution Bulletin 60: 396–401.
12. Witherington BE (2002) Ecology of neonate loggerhead turtles inhabiting lines of downwelling near a Gulf Stream front. Marine Biology 140: 843–853.
13. Bjorndal KA, Bolten AB, Lagueux CJ (1994) Ingestion of marine debris by juvenile sea turtles in coastal Florida habitats. Marine Pollution Bulletin 28: 154–158.
14. Duguy R (1997) Marine turtles of the Gulf of Gascony. Annales de la Societe des Sciences Naturelles de la Charente-Maritime 8: 633–645.
15. Mrosovsky N (1981) Plastic jellyfish. Marine Turtle Newsletter 17.
16. Tomas J, Guitart R, Mateo R, Raga JA (2002) Marine debris ingestion in loggerhead sea turtles, *Caretta caretta* from the Western Mediterranean. Marine Pollution Bulletin 44: 211–216.
17. Plotkin P, Amos A (1990) Effects of anthropogenic debris on sea turtles in the northwestern Gulf of Mexico. In: Shomura R, Yoshida H, editors. Proceedings of the 2nd International Conference on Marine Debris. Honolulu, HI: NOAA. 736–743.
18. Plotkin P, Wicksten M, Amos A (1993) Feeding ecology of the loggerhead sea turtle *Caretta caretta* in the Northwestern Gulf of Mexico. Marine Biology 115: 1–5.
19. Shaver DJ (1991) Feeding Ecology of Wild and Head-Started Kemp's Ridley Sea Turtles in South Texas Waters. Journal of Herpetology 25: 327–334.
20. Boyle MC, Limpus CJ (2008) The stomach contents of post-hatchling green and loggerhead sea turtles in the southwest Pacific: an insight into habitat association. Marine Biology 155: 233–241.
21. Parker DM, Cooke WJ, Balazs GH (2005) Diet of oceanic loggerhead sea turtles (*Caretta caretta*) in the central North Pacific. Fishery Bulletin 103: 142–152.
22. Constantino MA, Salmon M (2003) Role of chemical and visual cues in food recognition by leatherback posthatchlings (*Dermochelys coriacea L*). Zoology 106: 173–181.
23. Granda A (1979) Eyes and their sensitivity to light of differing wavelengths. In: Warless M, Morlock H, editors. Turtles: Perspectives and Research. New York: John Wiley and Sons. 247–266.
24. Bartol S, Musick J (2003) Sensory Biology of Sea Turtles. In: Lutz P, Musick JA, Wyneken J, editors. The biology of sea turtles: CRC. 79–102.
25. Fehring WK (1972) Hue discrimination in hatchling loggerhead turtles (*Caretta caretta caretta*). Animal Behaviour 20: 632–636.
26. Swimmer Y, Brill RW (2006) Sea turtle and pelagic fish sensory biology: developing techniques to reduce sea turtle bycatch in longline fisheries: US Dept. of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Pacific Islands Fisheries Science Center.
27. Vorobyev M, Marshall J, Osorio D, de Ibarra NH, Menzel R (2001) Colourful objects through animal eyes. Color Research and Application 26: S214–S217.
28. Swimmer Y, Arauz R, Higgins B, McNaughton L, McCracken M, et al. (2005) Food color and marine turtle feeding behavior: Can blue bait reduce turtle bycatch in commercial fisheries? Marine Ecology-Progress Series 295: 273–278.
29. Bolten AB (2003) Variation in sea turtle life history patterns: neritic vs. oceanic developmental stages. The biology of sea turtles 2: 243–257.
30. Frick MG, Williams KL, Bolten AB, Bjorndal KA, Martins HR (2010) Foraging ecology of oceanic-stage loggerhead turtles *Caretta caretta*. Endangered Species Research 9: 91–97.
31. Limpus C (2009) A biological review of Australian marine turtles: Queensland Environmental Protection Agency.
32. Limpus C (1992) The hawksbill turtle, *Eretmochelys imbricata*, in Queensland: population structure within a southern Great Barrier Reef feeding ground. Wildlife Research 19: 489–505.
33. Carr A (1987) Impact of nondegradable marine debris on the ecology and survival outlook of sea turtles. Marine Pollution Bulletin 18: 352–356.
34. Arthur KE, O'Neil JM, Limpus CJ, Abernathy K, Marshall G (2007) Using animal-borne imaging to assess green turtle (Chelonia mydas) foraging ecology in Moreton Bay, Australia. Marine Technology Society Journal 41: 9–13.
35. Bjorndal K (1980) Nutrition and grazing behavior of the green turtle *Chelonia mydas*. Marine Biology 56: 147–154.
36. Leon YM, Bjorndal KA (2002) Selective feeding in the hawksbill turtle, an important predator in coral reef ecosystems. Marine Ecology Progress Series 245.
37. Wyneken J (2001) The Anatomy of Sea Turtles. 1–172 p.
38. Windell J, Bowen S (1978) Methods for study of fish diets based on analysis of stomach contents. Methods for assessment of fish production in fresh waters: 219–226.
39. Heisey DM (1985) Analyzing selection experiments with log-linear models. Ecology: 1744–1748.
40. R Development Core Team (2011) R: A language and environment for statistical computing. Vienna, Austria: R foundation for statistical computing.
41. Venables WN, Ripley BD (2002) Modern Applied Statistics with S. New York: Springer.
42. Calenge C (2006) The package adehabitat for the R software: a tool for the analysis of space and habitat use by animals. Ecological Modelling 197: 1516–1519.
43. Duguy R, Moriniere P, Meunier A (2000) The ingestion of floating debris by Luth's turtle Dermochelys coriacea (Vandelli, 1761) in the Gulf of Gascony. Annales de la Societe des Sciences Naturelles de la Charente-Maritime 8: 1035–1038.
44. Lazar B, Gracan R (2011) Ingestion of marine debris by loggerhead sea turtles, *Caretta caretta*, in the Adriatic Sea. Marine Pollution Bulletin 62: 43–47.
45. Bugoni L, Krause L, Petry MV (2001) Marine debris and human impacts on sea turtles in southern Brazil. Marine Pollution Bulletin 42: 1330–1334.
46. Bjorndal K (1997) Foraging Ecology and Nutrition of Sea Turtles. In: Lutz PL, Musick JA, editors. The biology of sea turtles: CRC Press. 199–232.
47. Balazs G (1985) Impact of ocean debris on marine turtles: entanglement and ingestion. In: Shomura RS, Yoshido HO, editors. Proceedings of the Workshop on the Fate and Impact of Marine Debris. Honolulu, Hawaii: US Department of Commerce, NOAA Technical Memo. NMFS, NOAA-TM-MMFS-SWFC-54. 387–429.
48. Burchette D (1989) A study of the effect of balloon releases on the environment. National Association of Balloon Artists.
49. Prichard PCH, Márquez R (1973) Kemp's ridley turtle or Atlantic ridley. IUCN Monograph.
50. Mrosovsky N, Ryan G, James M (2009) Leatherback turtles: The menace of plastic. Marine Pollution Bulletin 58: 287–289.
51. Houghton JDR, Doyle TK, Wilson MW, Davenport J, Hays GC (2006) Jellyfish aggregations and leatherback turtle foraging patterns in a temperate coastal environment. Ecology 87: 1967–1972.
52. Cannon AC (1998) Gross Necropsy Results of Sea Turtles Stranded on the Upper Texas and Western Louisiana Coasts, 1January-31 December 1994. Characteristics and Causes of Texas Marine Strandings US Dep Commerce, NOAA Tech Rep NMFS 143: 81.
53. Stamper MA, Spicer CW, Neiffer DL, Mathews KS, Fleming GJ (2009) Morbidity in a juvenile green sea turtle (*Chelonia mydas*) due to ocean-borne plastic. Journal of Zoo and Wildlife Medicine 40: 196–198.
54. Keep Wales Tidy Policy paper on balloon litter.
55. Fox C (2011) Tracking trash, 25 years of action for the ocean. Ocean Conservancy.
56. Boyle MC (2006) Post-hatchling sea turtle biology. Ph.D. Thesis. Townsville: James Cook University.
57. Lobelle D, Cunliffe M (2010) Early microbial biofilm formation on marine plastic debris. Marine Pollution Bulletin 62: 197–200.
58. Ryan PG, Moore CJ, van Franeker JA, Moloney CL (2009) Monitoring the abundance of plastic debris in the marine environment. Philosophical Transactions of the Royal Society B-Biological Sciences 364: 1999–2012.
59. Sheavly S (2007) National Marine Debris Monitoring Program: final program report, data analysis and summary. Washington, DC, USA: Ocean Conservancy.
60. Dixon TR, Dixon TJ (1981) Marine litter surveillance. Marine Pollution Bulletin 12: 289–295.
61. Cheshire A, Adler E, Barbière J, Cohen Y, Evans S, et al. (2009) UNEP/IOC Guidelines on survey and monitoring of marine litter. UNEP Regional Seas Reports and Studies 186.
62. Hardesty BD, Wilcox C (2011) Understanding the types, sources and at-sea distribution of marine debris in Australian waters. CSIRO. 33 p.
63. Law KL, Moret-Ferguson S, Maximenko NA, Proskurowski G, Peacock EE, et al. (2010) Plastic accumulation in the North Atlantic subtropical gyre. Science 329: 1185.

Conservation Biology

Contributed Paper

Global Analysis of Anthropogenic Debris Ingestion by Sea Turtles

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Abstract: *Ingestion of marine debris can have lethal and sublethal effects on sea turtles and other wildlife. Although researchers have reported on ingestion of anthropogenic debris by marine turtles and implied incidences of debris ingestion have increased over time, there has not been a global synthesis of the phenomenon since 1985. Thus, we analyzed 37 studies published from 1985 to 2012 that report on data collected from before 1900 through 2011. Specifically, we investigated whether ingestion prevalence has changed over time, what types of debris are most commonly ingested, the geographic distribution of debris ingestion by marine turtles relative to global debris distribution, and which species and life-history stages are most likely to ingest debris. The probability of green (*Chelonia mydas*) and leatherback turtles (*Dermochelys coriacea*) ingesting debris increased significantly over time, and plastic was the most commonly ingested debris. Turtles in nearly all regions studied ingest debris, but the probability of ingestion was not related to modeled debris densities. Furthermore, smaller, oceanic-stage turtles were more likely to ingest debris than coastal foragers, whereas carnivorous species were less likely to ingest debris than herbivores or gelatinovores. Our results indicate oceanic leatherback turtles and green turtles are at the greatest risk of both lethal and sublethal effects from ingested marine debris. To reduce this risk, anthropogenic debris must be managed at a global level.*

Keywords: Caretta caretta, *Dermochelys coriacea*, Eretmochelys imbricata, garbage, Lepidochelys kempii, litter, rubbish, trash

Análisis Global de la Ingesta de Residuos Antropogénicos por Tortugas Marinas

Resumen: *La ingesta de residuos marinos puede tener efectos letales y subletales sobre las tortugas marinas y otros animales. Aunque hay investigadores que han reportado la ingesta de residuos antropogénicos por tortugas marinas y la incidencia de la ingesta de residuos ha incrementado con el tiempo, no ha habido una síntesis global del fenómeno desde 1985. Por esto analizamos 37 estudios publicados, desde 1985 hasta 2012, que reportan datos colectados desde antes de 1900 y a lo largo del 2011. Investigamos específicamente si el predominio de la ingesta ha cambiado con el tiempo, qué tipos de residuos se ingieren comúnmente, la distribución geográfica de la ingesta de residuos por tortugas marinas en relación a la distribución global de residuos y cuáles especies y etapas de vida tienen más probabilidad de ingerir residuos. La probabilidad de que las tortugas verdes (*Chelonia mydas*) y laúd (*Dermochelys coriacea*) ingieran escombros incrementa significativamente con el tiempo; plástico fue el residuo que más se ingirió. Las tortugas en casi todas las regiones estudiadas ingieren residuos, pero la probabilidad de ingesta no estuvo relacionada con las densidades modeladas de residuos. Además de esto, tortugas más pequeñas, en etapa oceánica de vida, tuvieron una mayor probabilidad de ingerir residuos que las tortugas forrajeras terrestres, mientras que las especies carnívoras tuvieron menos probabilidad de ingerir residuos que las herbívoras o las gelatinívoras. Nuestros resultados indican que las tortugas verdes y laúd tienen el mayor riesgo de efectos letales y subletales*

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de la ingesta de residuos marinos. Para reducir el riesgo, los residuos antropogénicos deben manejarse en un nivel global.

Palabras Clave: basura, Caretta caretta, Dermochelys coriacea, escombros, Eretmochelys imbricata, Lepidochelys kempii, residuos

Introduction

Plastics in the Environment

Although there are little to no empirical data on the quantity of anthropogenic debris (hereafter debris) entering the marine environment, estimates place it at approximately 6.4 million tons annually (UNEP 2005), about 80% of which is thought to originate from land-based sources (Faris & Hart 1994). However, these estimates do not take into account aperiodic events that can cause dramatic point-source increases, such as the 2011 Japanese tsunami which created an estimated 1.5 million tons of floating debris (NOAA 2012). Because there is presently no way to map the movement of debris in real time, best estimates of where debris accumulates come from oceanographic models. Recent work by Lebreton et al. (2012) predicts that floating debris accumulates in 5 main oceanic gyres and occurs predominantly in subtropical regions. Debris gathers in drift lines and convergence zones, which are also important feeding areas for many oceanic species, including sea birds, pelagic fish, and sea turtles (Ashmole & Ashmole 1967; Carr 1986).

Plastic is the primary type of debris found in marine and coastal environments (Derraik 2002), and plastics are the most common form of debris ingested by wildlife (Mrosovsky et al. 2009; van Franeker et al. 2011; Schuyler et al. 2012). With the exponential increase in global plastic production over the past 60 years (PlasticsEurope 2009), it is likely that effects on marine wildlife from ingestion of plastic have also increased. Ingestion of marine debris affects over 170 species (Laist 1997). Debris ingestion can result in death by perforation or impaction of the gastrointestinal system and toxic compounds in plastics may have sublethal effects on development and population dynamics (Oehlmann et al. 2009).

Six of the world's 7 species of sea turtles have been found to ingest debris, with the exception of the flatback sea turtle (*Natator depressus*) (Balazs 1985; Ceccarelli 2009). All 6 are listed as globally vulnerable or endangered (IUCN 2012). In 1985, Balazs summarized all known cases of sea turtle interactions with marine debris. Since then, researchers from around the world have investigated debris ingestion by turtles on local or regional scales (e.g., Tomas et al. 2002; Lazar & Gracan 2011; Schuyler et al. 2012). Results of a historical analysis of debris ingestion by leatherback turtles showed a long-term increase in ingestion frequency (Mrosovsky et al. 2009), but there has been no global review of debris ingestion for all turtle species since 1985. Understanding the factors that affect debris ingestion by turtles, including types of debris ingested, global distribution of debris, and life history and feeding ecology, may help focus management priorities on reducing plastics in the marine environment and decreasing the potential for debris ingestion.

Turtle Life History and Feeding Ecology

Sea turtle species have different lifestyles. At various stages of their lives, they may live and feed primarily in open ocean, predominantly in neritic areas, or they may switch back and forth. (Walker & Parmenter 1990; Bolten 2003; Godley et al. 2008; Rees et al. 2012). Turtles living in oceanic or coastal environments and feeding pelagically or benthically may encounter very different densities and types of marine debris and may therefore have different probabilities of debris ingestion.

Feeding preference may also affect the probability of debris ingestion by turtles. Most neonate turtles have generalist diets that become more specialized as they recruit to the coastal environment (Plotkin et al. 1993; Boyle & Limpus 2008). Adult green turtles are primarily herbivorous (Bjorndal 1997), whereas loggerhead (*Caretta caretta*) and Kemp's ridley (*Lepidochelys kempii*) turtles are primarily carnivorous and eat crustaceans, molluscs, and other hard-bodied organisms (Bjorndal 1997). Although flatback turtles are also carnivorous, they eat primarily soft-bodied invertebrates (Sperling et al. 2007). Olive ridley (*Lepidochelys olivacea*) and hawksbill turtles (*Eretmochelys imbricata*) are omnivorous, although hawksbills feed mostly on sponges and algae (Bell 2012). Leatherback turtles feed exclusively on jellyfish and other gelatinous organisms (Shaver 1991; Bjorndal 1997). These different feeding preferences may affect the types and amount of debris turtles encounter and are likely to ingest.

Estimating Frequency of Plastic Ingestion

There is currently no reliable method for assessing plastic ingestion in live turtle populations. Results of some dietary studies in which lavage (Seminoff et al. 2002; Witherington 2002) or fecal analyses were used showed turtles ingested plastics (e.g., Seminoff et al. 2002; Casale et al. 2008), but these techniques almost certainly underestimate debris ingestion because only a small subset of the gastrointestinal tract is sampled. Seminoff et al. (2002) found 1.9% of 101 lavaged turtles had ingested debris: 41 of these turtles were kept in a tank and their feces collected. Of these, 19% excreted debris, 10 times the amount found through lavage. Seven turtles from the same population died and their stomach contents were

Table 1. Articles published since 1985 that report on studies in which a systematic survey of turtles ($n \geq 7$ animals) was conducted and necropsies were performed to determine contents of the gastrointestinal system.

Reference	*Study dates*	*Country or region*	*Number of turtles in study*	*Species*	*Turtles with ingested debris (%)*
Bjorndal et al. (1994	1988–1993	USA	51	multiple	49
Boyle and Limpus (2008)	2002–2006	Australia	54	green, loggerhead	65
Bugoni et al. (2001)	1997–1998	Brazil	50	multiple	50
Burke et al. (1994)	1985–1989	USA	18	Kemp's ridley	0
Cannon (1998)	1994	USA	158	multiple	11
Casale et al. (2008)	2001–2005	central Mediterranean	33	loggerhead	52
Duguy (1997)	1978–1995	France	141	multiple	17
Duguy et al. (2000)	1979–1999	France	87	leatherback	55
Duronslet et al. (1991)	1987–1989	USA	32	multiple	59
Foley et al. (2007)	2000–2001	USA	44	green	2
Frick et al. (2009)	1986–2001	Azores	12	loggerhead	25
Garnett et al. (1985)	1979	Australia	44	green	0
Guebert-Bartholo et al. (2011)	2004–2007	Brazil	76	green	70
Hasbun et al. (2000)	1997	UAE	13	green	0
Kaska et al. (2004)	2001	Turkey	65	loggerhead	5
Lazar and Gracan (2011)	2001–2004	Eastern Adriatic	54	loggerhead	35
Limpus et al. (2001)	1989–1998	Australia	47	loggerhead	0
Lopez-Mendilaharsu (2005)	2000–2002	USA	24	green	0
Mrosovsky et al. (2009)	1885–2007	Global	408	leatherback	34
Parker et al. (2005)	1990–1992	northern Pacific	52	loggerhead	35
Parker et al. (2011)	1990–2004	USA	10	green	70
Peckham et al. (2011)	2003–2007	USA	82	loggerhead	0
Plotkin & Amos (1990)	1986–1988	Texas	23	green, hawksbill	61
Plotkin et al. (1993)	1986–1988	Texas	82	loggerhead	51
Quinones et al. (2010)	1987	Peru	192	green	42
Revelles et al. (2007)	2002–2004	Mediterranean	19	loggerhead	37
Ross (1985)	1977–1979	Oman	9	green	0
Russo et al. (2003)	1994–1998	Mediterranean	45	green, loggerhead	18
Sadove and Morreale (1989)	1979–1988	USA	116	multiple	12
Santos et al. (2011)	2007–2008	Brazil	15	green	20
Schuyler et al. (2012)	2006–2011	Australia	115	multiple	33
Seminoff et al. (2002)	1995–1999	Mexico	7	green	29
Seney and Musick (2007)	1983–2002	USA	166	loggerhead	0
Shaver (1991)	1983–1989	USA	101	Kemp's ridley	29
Shaver (1998)	1984	USA	37	Kemp's ridley	19
Tomas et al. (2002)	N/A	Spain	54	loggerhead	80
Tourinho et al. (2010)	2006–2007	Brazil	34	green	100

analyzed; 2 had ingested debris. Necropsy, therefore, is the most effective method of identifying debris ingestion by turtles; however, necropsy limits the study population to deceased animals.

We analyzed literature published since 1985 to compile a global assessment of the prevalence of marine debris ingestion by sea turtles. We focused on factors that might be useful in prioritizing management actions by investigating whether ingestion prevalence changed over time, the types of debris most commonly ingested, the geographic distribution of debris ingestion by marine turtles relative to global debris distribution, and the species of turtle and life-history stages at which turtles are most likely to ingest debris.

Methods

We reviewed the literature on the gastrointestinal contents of sea turtles published after Balazs' (1985) review. We searched ISI Web of Knowledge and the Aquatic Sciences and Fisheries Abstracts for the terms *feeding ecology*, *foraging ecology*, or *diet* and *plastic*, *debris*, *marine debris*, *litter*, *flotsam*, *detritus*, or *tar balls*. In each string of terms we included *sea turtle* plus the genus and species names of all 7 species of sea turtles. Because analysis of gastrointestinal contents is the most accurate way to determine the presence or absence of marine debris, we used only studies in which a systematic necropsy of at least 7 individuals was conducted. Most of the articles we included in our study were peer-reviewed publications, but we also included 3 conference proceedings (Sadove & Morreale 1989; Plotkin & Amos 1990; Duguy et al. 2000) and 3 government reports (Duronslet et al. 1991; Cannon 1998; Shaver 1998). For papers that did not explicitly report debris ingestion, we asked authors whether debris had not been found or whether it was not reported. When we were unable to contact an author, we assumed debris was not found.

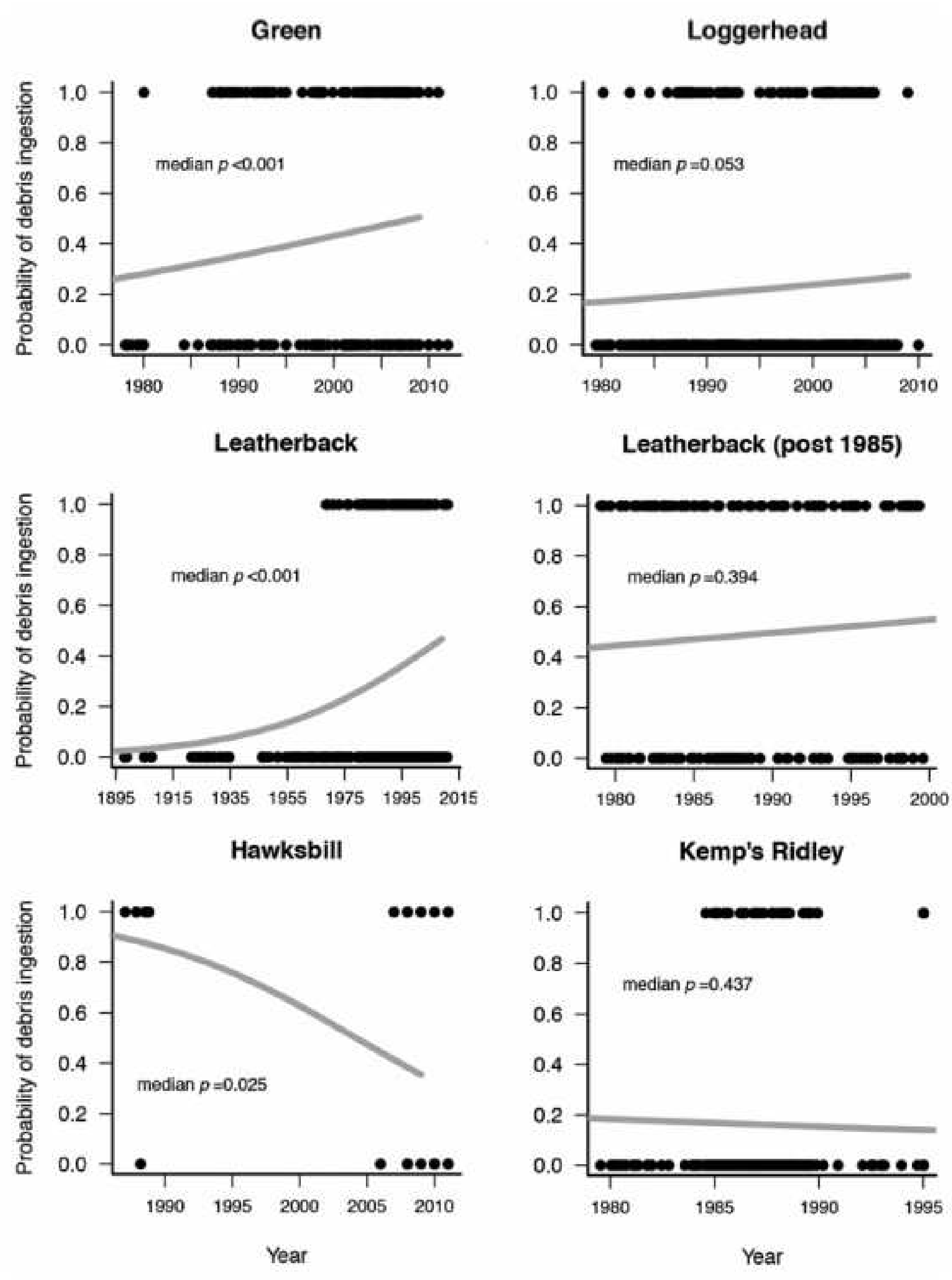

Figure 1. Change in probability of ingestion of debris over time for different species of sea turtles (black dots, presence [1.0] or absence [0.0] of debris in turtles from one iteration of a Monte Carlo function; gray lines, inverse logit calculation of the probability of a turtle ingesting debris on the basis of the median slope and intercept for 100 iterations of the Monte Carlo function; p values, median values for 100 iterations of the Monte Carlo function). For the leatherback turtle graph, data are for all leatherback turtles, and for the leatherback post 1985 graph, data from Mrosovsky et al. (2009) are excluded.

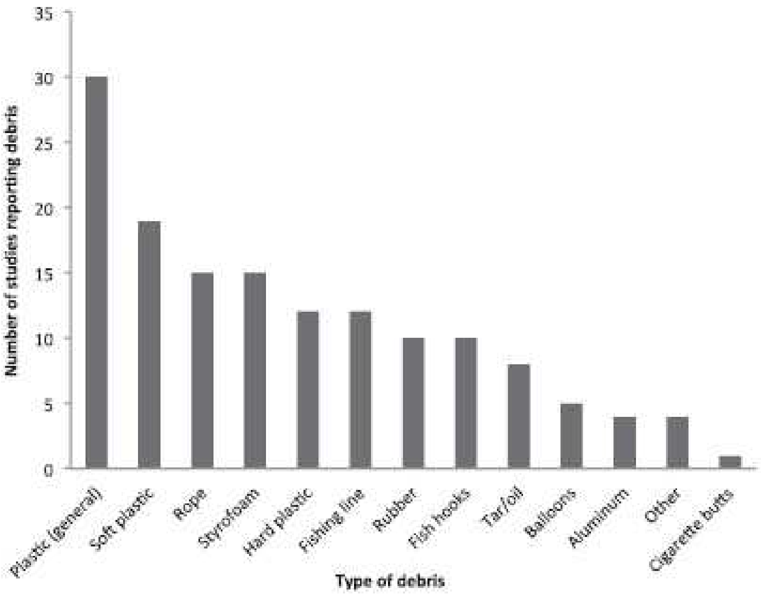

Figure 2. Total number of studies reporting on ingestion of particular types of marine debris by sea turtles. In many cases, multiple types of debris were found, so a study could be counted in more than one category.

When studies reported on the same set of turtles (Plotkin & Amos 1990; Plotkin et al. 1993; Duguy 1997; Duguy et al. 2000; Mrosovsky et al. 2009), we counted each turtle only once in our analyses.

Because each study varied in length and no study specified how many turtles were analyzed each year or the proportion that ingested plastic in each year, we used a Monte Carlo simulation to determine whether the likelihood of marine debris ingestion by turtles changed over time (sensu Efron & Tibshirani 1994). We randomly assigned turtles with and without debris from each study to years, drawn with replacement, for the duration of each study. We then fit a logistic regression to the full simulated data set across all studies. We repeated this process to generate 100 logistic regressions fit to independently simulated data and calculated the median slope, intercept, and p value from all regressions. To determine whether there were differences among species, we ran the same analyses individually for each species. Although we analyzed only papers published after Balazs' 1985 review, one paper reported on a compilation of studies of leatherback turtles since 1895 (Mrosovsky et al. 2009). Because we did not conduct an exhaustive literature search for other studies in this time frame, we conducted a second analysis for leatherbacks excluding the Mrosovsky data.

We calculated the total number of studies reporting ingestion of multiple types of debris. We mapped the percentage of turtles found to have ingested debris at each study site overlaid on a global map of marine debris accumulation, as modeled by Lebreton et al. (2012). Due to a lack of standardized reporting in studies, we were unable to investigate quantitatively the effects of debris ingestion on different life-history stages; however, we considered these effects in qualitative terms. To determine which species were most likely to ingest debris, we aggregated reports from all studies for each species and used logistic regression to determine the species' effect on the probability of ingesting debris.

Results

Thirty-seven studies met our criteria (Table 1). Over 116 years (1895–2012), the probability of debris ingestion increased significantly for green and leatherback turtles (median $p < 0.001$) and increased nonsignficantly for loggerhead turtles (median $p = 0.053$) (Fig. 1). The probability of leatherback turtles ingesting debris did not change significantly from 1985 to 2012. The probability of Kemp's ridley turtles ingesting debris also did not change over time. The probability of debris ingestion for hawksbill turtles decreased from 1985 to 2012.

Of 31 studies providing details of ingested debris, 96.8% ($n = 30$), reported that sea turtles ingested some form of plastic. Some studies differentiated between soft ($n = 19$) and hard plastic ($n = 12$). Rope, fishing line, Styrofoam, tar, and fishhooks were other commonly ingested items (Fig. 2). About half the studies that reported debris ingestion ($n = 16$) did not report whether ingestion was the primary cause of death. In 15 studies, researchers determined whether debris ingestion resulted in mortality. Of these studies, 11 reported debris was responsible for 2–17% of total turtle mortality; 5–35% of the turtles that ingested plastic were reported as being

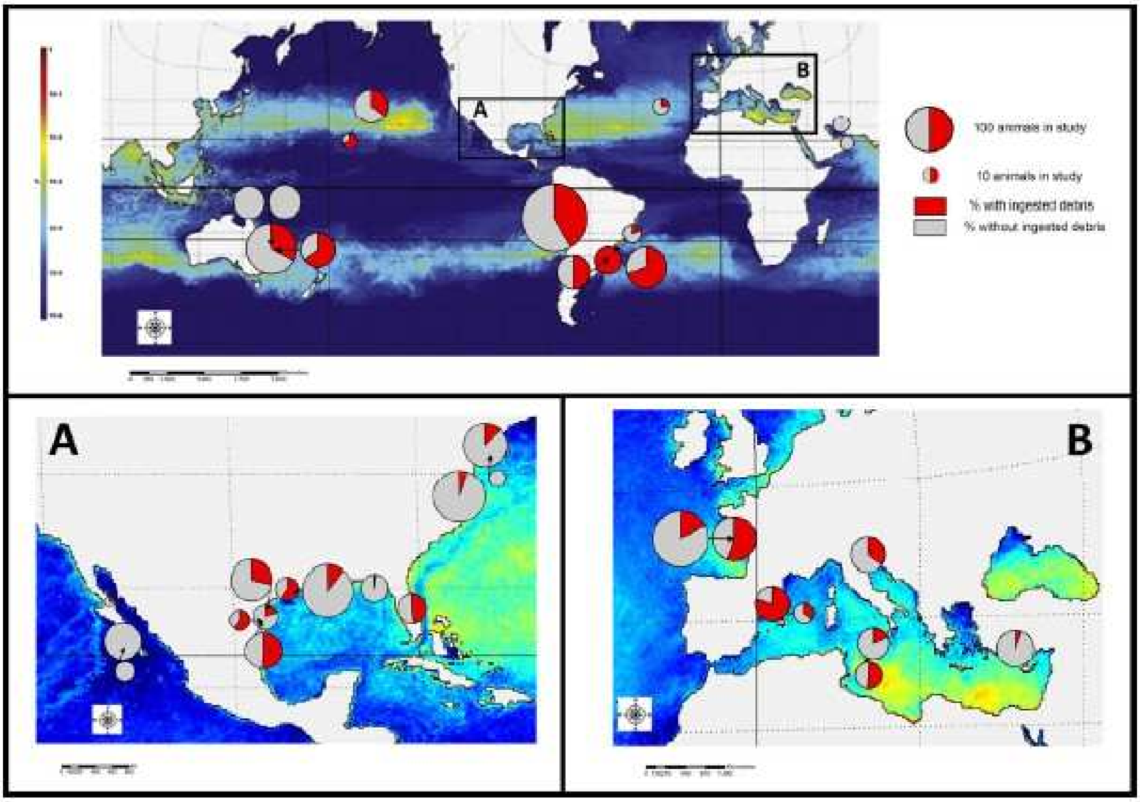

Figure 3. Locations of studies of ingested debris by sea turtles worldwide (enlargements: [a] the Gulf of Mexico and [b] the Mediterranean) overlaid on a 30-year model of global debris distribution (red and yellow areas on maps, high debris concentration) (Lebreton et al. 2012). Circles are sized relative to the total number of turtles necropsied (large, 100 turtles; small, 10 turtles). Red areas in circles indicate the percentage of turtles in each study found with ingested debris. All species have been amalgamated. (Background map reprinted from Marine Pollution Bulletin [Vol. 64], L. C.-M. Lebreton, S. D. Greer, and J. C. Borrero. Numerical Modelling of Floating Debris in the World's Oceans. Pages 653–661. Copyright 2012, with permission from Elsevier.)

killed by it. Four studies, of 12–37 animals each, reported that debris ingestion killed no turtles.

There was no discernible geographic pattern of debris ingestion relative to global models of debris distribution (Fig. 3). In all regions studied, aside from the Persian Gulf, turtles ingested debris.

Hawksbill turtles were most likely to ingest debris, followed by green and leatherback turtles (Fig. 4). The carnivorous species (loggerhead and Kemp's ridley) were least likely to ingest debris. Aside from the hawksbill, which did not differ significantly from either green or loggerhead turtles, all species differed significantly from one another in probability of ingesting debris (logistic regression, $p < 0.0148$ for all factor levels). Ingestion of debris by a flatback turtle was reported only once, so we excluded it from our analyses.

Discussion

Debris Ingestion over Time and Debris Types

The majority of debris consumed by all turtles was composed of plastic (Fig. 2). Even in 1985, when plastic production levels were still relatively low, plastic was the most widely reported debris item ingested (Balazs 1985).

The likelihood of a green turtle ingesting debris nearly doubled from an approximate 30% likelihood in 1985 to nearly 50% in 2012 (Fig. 1). Leatherbacks showed a significant increase in debris ingestion when historical data were included in the analyses, but the increase leveled off after 1985. Data from 1985 to 2012 did not show a significant increase in the probability of debris ingestion. This result is consistent with that of Mrosovsky et al. (2009), who also found that debris ingestion by leatherback

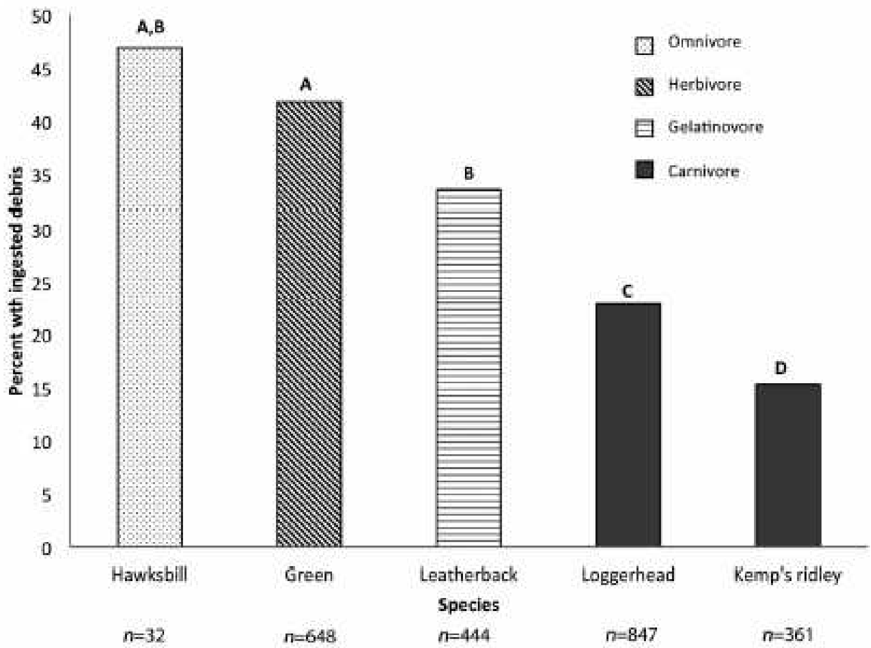

Figure 4. Percentage of the total number of each species of turtle across all studies that were reported to have ingested debris. Different letters above bars indicate significant differences between species ($p < 0.05$) (n, total number of turtles necropsied for each species).

turtles leveled off in the 1980s. The results with leatherback turtles suggest the environment has reached a saturation point, at least with respect to debris distribution. When running oceanic debris models similar to C. W. Lebreton's (unpublished data) noted that after releasing hypothetical debris particles for about 10 years, debris distribution stabilized (i.e., debris continued to enter the system, but it ended up in the same areas). This possible saturation might also explain our results with Kemps' ridley turtles.

The decrease in hawksbill turtle ingestion of debris we found may be due to small sample size. Only 2 studies reported on hawksbill gut contents, and these studies were conducted at the very beginning and very end of the literature-review period (Plotkin & Amos 1990; Schuyler et al. 2012).

It is possible that increasing awareness of debris ingestion may have affected necropsy methods. As more studies were published on debris ingestion, researchers may have become more meticulous in their necropsy techniques. However, because our analyses included feeding studies, in which gut contents are investigated carefully, and studies reporting null ingestion, it is reasonable to expect that observed increases were not due to differences in necropsy methods among studies. Additionally, our finding of increasing plastic ingestion is consistent with findings of other researchers for both turtles and seabirds (e.g., Mrosovsky et al. 2009; van Franeker et al. 2011).

Many of the turtles examined in the studies we reviewed did not ingest large quantities of debris. However, even small amounts of ingested debris can result in gut obstruction and mortality (Bjorndal et al. 1994). Although many studies did not report mortality of turtles, for those that did, about 4% of the total number of turtles necropsied ($n = 1106$) were reportedly killed by plastic ingestion. Of those turtles that ingested debris ($n = 454$) 42 (9%) were killed by it (range 0–35%). Although this number is relatively small, mortality is not the only risk associated with debris ingestion. Plasticizers, such as bisphenol-A (BPA) and phthalates, incorporated into plastics at production can leach into the environment or into tissue (Oehlmann et al. 2009). One group of researchers hypothesizes that plasticizers function as endocrine disruptors (Krishnan et al. 1993) and thus may have population-level effects on seabirds (van Franeker & SNS Fulmar Study Group 2011). Floating plastics also readily absorb heavy metals and other toxins from the ocean and can release these into the tissues of animals upon ingestion (Teuten et al. 2009), although little is known about the effects of metal or toxin release on marine species.

Location of Turtles and Debris

Debris ingestion by sea turtles occurs worldwide. Although not every study reported turtles with ingested debris, in every region of the world where gastrointestinal contents were examined, debris was detected. Similarly, Balasz (1985) reported debris ingestion by turtles at 19 locations worldwide, including all continents except Antarctica, where turtles do not occur.

No relation was observed between high proportions of debris ingestion at locations where stranded turtles were found and areas of high debris concentrations as determined from ocean-current modeling. We considered analyzing the correlation between coastal human population density and debris ingestion by turtles at study sites, but decided this analysis would have little relevance due to the large-scale migratory paths and motility of turtles and the wide distribution of marine debris from its source. For instance, results of a study conducted in the New York Bight, adjacent to the New York City metropolitan area (1990 population 16.4 million inhabitants) (Bureau of the Census 1990), showed only 12% of turtles ingested debris (Sadove & Morreale 1989). The results of a second study 5 years later in the same region showed no evidence of debris ingestion (Burke et al. 1994). Conversely, Tourinho et al. (2010) studied turtles in a "relatively undeveloped" area of southern Brazil. Here, over 200 km from Porto Alegre (2010 metropolitan area population 4.4 million) (IBGE 2010), 100% of turtles surveyed had ingested debris. Because most turtles migrate long distances during their posthatchling pelagic phase and during breeding migrations (Musick & Limpus 1997; Luschi et al. 2003), they are highly likely to encounter ocean-borne debris at some life stage, particularly when they passively drift in oceanic gyres, where debris accumulates. Because debris does not decompose as rapidly as food items and given that the physiology of turtles does not permit regurgitation or expulsion (Sheavly & Register 2007), turtles may encounter and ingest the debris far from where they strand.

Life-History Stage of Turtles

Anthropogenic debris accumulates in oceanic gyres far from shore (sensu Lebreton et al. 2012) (Fig. 3). Accordingly, one might expect oceanic-phase turtles to be more likely to ingest debris than coastal foragers. The 4 studies that reported on turtles sampled from oceanic waters found an average of 49.2% of turtles ($n = 128$) ingested debris (Parker et al. 2005; Boyle & Limpus 2008; Frick et al. 2010; Parker et al. 2011). Casale et al. (2008) investigated loggerhead turtles accidentally caught in oceanic waters on longlines and those accidentally caught in nearby benthic waters by trawl fishers. Of the oceanic turtles ($n = 13$), 64% had ingested debris, whereas 22% ($n = 9$) of benthic turtles had ingested debris. Similarly, results of a comparison of 2 populations of similarly sized juvenile loggerhead turtles with different foraging strategies showed that 35% of animals that foraged in the open ocean had ingested debris (Parker et al. 2005), whereas none of the coastal benthic-feeding turtles ingested debris (Peckham et al. 2011). Other studies in which stranded turtles were analyzed report that smaller oceanic turtles are more likely to ingest debris than larger turtles (Plotkin & Amos 1990; Schuyler et al. 2012). Balazs (1985) presented similar results: 69% of immature turtles ingested debris, whereas 31% of adult turtles ingested debris. This means young oceanic turtles may be more at risk from debris ingestion than older benthic-feeding turtles. Not only are they more likely to ingest debris, but their relatively small, thinner digestive systems will be more vulnerable to impaction by and perforation from the debris (Schuyler et al. 2012).

Species

All species studied ingested debris, but green and leatherback turtles were significantly more likely to ingest debris than were Kemp's ridley or loggerhead turtles. Hawksbills were the most likely to ingest debris, but the sample size was small ($n = 32$) and came from only 2 studies, so other factors such as geography or life stage may have skewed results (Plotkin & Amos 1990; Schuyler et al. 2012). Our results differ from Balazs' (1985), who reported that green turtles were most likely to ingest debris (32%), followed by loggerhead (26%), leatherback (24%), and hawksbill (19%) turtles. However, his data were reported only as the total number of cases for each species, not on the basis of the percentage of the total number of animals of that species that had ingested debris, given all animals sampled.

Carnivorous species (e.g., loggerhead and Kemp's ridley turtles) appear less susceptible to debris ingestion than herbivores (green), gelatinovores (leatherback), and omnivores (hawksbill), or perhaps they are less likely to retain the ingested debris. One possible explanation of the lower incidence of debris ingestion in carnivorous species is that noncarnivores may be more likely to ingest debris or be more likely to die from ingestion of debris than carnivorous turtles. This could be because they have a greater affinity for gelatinous organisms and eat soft plastic because of its similarity to their prey, because they are less selective and feed on a variety of items including plastics, or because they feed in areas that accumulate debris.

The differences in debris ingestion by species may also be attributed to differences in the biology of the animals and how their digestive systems cope with debris once ingested. Adult and subadult loggerhead sea turtles have a larger-diameter digestive tract than green turtles of a similar age class; thus, they may more readily pass ingested materials (Bugoni et al. 2001) or perhaps they have different enzymes or microflora that act differently on ingested debris (Bjorndal 1997).

Debris Management

The differences in how debris ingestion is investigated and reported make it challenging to develop relevant global analyses on which to base management recommendations. Standardized reporting methods on debris effects on wildlife, including debris type and size, species, and life-history stage of animals affected, would go a long way toward creating a globally consistent and comparable data set. Furthermore, increased efforts to understand debris effects in underresearched areas where turtles occur in great numbers (especially Southeast Asia, western and northern Australia, South America, and Africa), and in mid-ocean pelagic turtles would be beneficial.

Our results show clearly that debris ingestion by sea turtles is a global phenomenon of increasing magnitude. Our finding that oceanic-stage green and leatherback turtles are at higher risk than benthic-feeding carnivorous turtles means management actions to target these species and life stages should be considered. This is particularly important for leatherback turtles that spend the bulk of their lives in oceanic waters, and are listed as critically endangered (IUCN 2012).

Ingestion prevalence at stranding locations was not related to predicted debris density, likely due to the long migrations of turtles. Thus, conducting coastal cleanups will not solve the problem of debris accumulation in the pelagic environment, where animals are most commonly affected, although it is an important step in preventing marine debris input into the ocean. Anthropogenic debris is not only a problem for endangered turtles and other marine wildlife, but also affects human health and safety (e.g., discarded sharps and medical waste and ship encounters with large items). Debris also has aesthetic and economic consequences and may result in decreased tourism (Ballance et al. 2000), reduced economic benefits from fisheries (Havens et al. 2008), and damage to vessels (Jones 1995). Furthermore, debris destroys habitats and aids in the transport of invasive species (Sheavly & Register 2007). It is therefore a high priority to address this global problem. An estimated 80% of debris comes from land-based sources; hence, it is critical to implement effective waste management strategies and to create and maintain a global survey and comprehensive database of marine debris ingestion and entanglement. Additionally, it is worth engaging with industry to create and implement appropriate innovations and controls to assist in decreasing marine debris.

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Literature Cited

Ashmole, N. P., and M. J. Ashmole 1967. Comparative feeding ecology of sea birds of a tropical oceanic island. Peabody Museum of Natural History, Yale University, New Haven, Connecticut.

Balazs, G. 1985. Impact of ocean debris on marine turtles: entanglement and ingestion. Pages 387–429 in R. S. Shomura and H. O. Yoshido, editors. Proceedings of the workshop on the fate and impact of marine debris. U.S. National Oceanic and Atmospheric Administration (NOAA) Technical memorandum 54. National Marine Fisheries Service, Honolulu.

Ballance, A., P. G. Ryan, and J. K. Turpie. 2000. How much is a clean beach worth? The impact of litter on beach users in the Cape Peninsula, South Africa. South African Journal of Science **96**:210–213.

Bell, I. 2012. Algivory in hawksbill turtles: *Eretmochelys imbricata* food selection within a foraging area on the Northern Great Barrier Reef. Marine Ecology **34**:43–55.

Bjorndal, K. 1997. Foraging ecology and nutrition of sea turtles. Pages 199–232 in P. L. Lutz and J. A. Musick, editors. The biology of sea turtles. CRC Press, Boca Raton, Florida.

Bjorndal, K. A., A. B. Bolten, and C. J. Lagueux. 1994. Ingestion of marine debris by juvenile sea turtles in coastal Florida habitats. Marine Pollution Bulletin **28**:154–158.

Bolten, A. B. 2003. Variation in sea turtle life history patterns: neritic vs. oceanic developmental stages. The Biology of Sea Turtles **2**:243–257.

Boyle, M. C., and C. J. Limpus. 2008. The stomach contents of post-hatchling green and loggerhead sea turtles in the southwest Pacific: an insight into habitat association. Marine Biology **155**:233–241.

Bugoni, L., L. Krause, and M. V. Petry. 2001. Marine debris and human impacts on sea turtles in southern Brazil. Marine Pollution Bulletin **42**:1330–1334.

Bureau of the Census. 1990. 1990 Census of population general population characteristics: New York. U.S. Department of Commerce, Washington, D.C.

Burke, V. J., S. J. Morreale, and E. A. Standora. 1994. Diet of the Kemp's ridley sea turtle, *Lepidochelys kempii*, in New York waters. U.S. National Marine Fisheries Service Fishery Bulletin **92**:26–32.

Cannon, A. C. 1998. Gross necropsy results of sea turtles stranded on the upper Texas and western Louisiana coasts, 1 January–31 December 1994. Pages 81–85 in Characteristics and causes of Texas marine strandings. U.S. National Oceanic and Atmospheric Administration (NOAA) technical report 143. National Marine Fisheries Service, Seattle.

Carr, A. 1986. Rips, FADS, and little loggerheads. BioScience **36**:92–100.

Casale, P., G. Abbate, D. Freggi, N. Conte, M. Oliverio, and R. Argano. 2008. Foraging ecology of loggerhead sea turtles *Caretta caretta* in the central Mediterranean Sea: evidence for a relaxed life history model. Marine Ecology-Progress Series **372**:265–276.

Ceccarelli, D. M. 2009. Impacts of plastic debris on Australian marine wildlife. Report. Department of the Environment, Water, Heritage and the Arts, Canberra, Australia.

Derraik, J. 2002. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin **44**:842–852.

Duguy, R. 1997. Marine turtles of the Gulf of Gascony. Annales de la Societe des Sciences Naturelles de la Charente-Maritime **8**:633–645.

Duguy, R., P. Moriniere, and A. Meunier. 2000. The ingestion of floating debris by Luth's turtle *Dermochelys coriacea* (Vandelli, 1761) in the Gulf of Gascony. Annales de la Societe des Sciences Naturelles de la Charente-Maritime **8**:1035–1038.

Duronslet, M. J., D. B. Revera, and K. M. Stanley. 1991. Man-made marine debris and sea turtle strandings on beaches of the upper Texas and southwestern Louisiana coasts, June 1987 through September 1989. National Oceanic and Atmospheric Administration (NOAA) technical memorandum 279. National Marine Fisheries Service Galveston, Texas.

Efron, B., and R. Tibshirani. 1994. An introduction to the bootstrap. Chapman & Hall/CRC, New York.

Faris, J., and K. M. Hart. 1994. Seas of debris: a summary of the Third international conference on marine debris. North Carolina Sea Grant College Program, Raleigh, North Carolina.

Foley, A. M., K. E. Singel, P. H. Dutton, T. M. Summers, A. E. Redlow, and J. Lessman. 2007. Characteristics of a green turtle (*Chelonia mydas*) assemblage in northwestern Florida determined during a hypothermic stunning event. Gulf of Mexico Science **25**:131–143.

Frick, M. G., K. L. Williams, A. B. Bolten, K. A. Bjorndal, and H. R. Martins. 2010. Foraging ecology of oceanic-stage loggerhead turtles *Caretta caretta*. Endangered Species Research **9**:91–97.

Garnett, S. T., I. R. Price, and F. J. Scott. 1985. The diet of the green turtle, *Chelonia mydas* (L), in Torres Strait. Australian Wildlife Research **12**:103–112.

Godley, B., J. Blumenthal, A. Broderick, M. Coyne, M. Godfrey, L. Hawkes, and M. Witt. 2008. Satellite tracking of sea turtles: Where have we been and where do we go next? Endangered Species Research **4**:3–22.

Guebert-Bartholo, F. M., M. Barletta, M. F. Costa, and E. L. A. Monteiro-Filho. 2011. Using gut contents to assess foraging patterns of juvenile green turtles *Chelonia mydas* in the Paranagua Estuary, Brazil. Endangered Species Research **13**:131–143.

Hasbun, C. R., A. J. Lawrence, J. H. Samour, and S. M. Al-Ghais. 2000. Preliminary observations on the biology of green turtles, *Chelonia mydas*, from the United Arab Emirates. Aquatic Conservation-Marine and Freshwater Ecosystems **10**:311–322.

Havens, K. J., D. M. Bilkovic, D. Stanhope, K. Angstadt, and C. Hershner. 2008. The effects of derelict blue crab traps on marine organisms in the lower York River, Virginia. North American Journal of Fisheries Management **28**:1194–1200.

IBGE (Brazilian Institute of Geography and Statistics). 2010. Censo 2010. IBGE, location. Available from http://censo2010.ibge.gov.br/en/sobre-censo (accessed April 2013).

IUCN (International Union for Conservation of Nature). 2012. IUCN red list of threatened species. Version 2012.2. IUCN, Gland, Switzerland. Available from http://www.iucnredlist.org (accessed December 2012).

Jones, M. M. 1995. Fishing debris in the Australian marine environment. Marine Pollution Bulletin **30**:25–33.

Kaska, Y., A. Celik, H. Bag, M. Aureggi, K. Ozel, A. Elci, A. Kaska, and L. Elca. 2004. Heavy metal monitoring in stranded sea turtles along the Mediterranean coast of Turkey. Fresenius Environmental Bulletin **13**:769–776.

Krishnan, A. V., P. Stathis, S. F. Permuth, L. Tokes, and D. Feldman. 1993. Bisphenol-A: an estrogenic substance is released from polycarbonate flasks during autoclaving. Endocrinology **132**:2279–2279.

Laist, D. 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. Pages 99–139 in J. M. Coe and D. B. Rogers, editors. Marine debris: sources, impacts, and solutions. Springer, New York.

Lazar, B., and R. Gracan. 2011. Ingestion of marine debris by loggerhead sea turtles, *Caretta caretta*, in the Adriatic Sea. Marine Pollution Bulletin **62**:43–47.

Lebreton, L. C. M., S. Greer, and J. Borrero. 2012. Numerical modelling of floating debris in the world's oceans. Marine Pollution Bulletin **64**:653–661.

Limpus, C. J., D. L. de Villiers, M. A. de Villiers, D. J. Limpus, and M. A. Read. 2001. The loggerhead turtle, *Caretta caretta* in Queensland: feeding ecology in warm temperate waters. Memoirs of the Queensland Museum **46**:631–645.

Lopez-Mendilaharsu, M., S. C. Gardner, J. A. Seminoff, and R. Riosmena-Rodriguez. 2005. Identifying critical foraging habitats of the green turtle (*Chelonia mydas*) along the Pacific coast of the Baja California peninsula, Mexico. Aquatic Conservation-Marine and Freshwater Ecosystems **15**:259–269.

Luschi, P., G. C. Hays, and F. Papi. 2003. A review of long-distance movements by marine turtles, and the possible role of ocean currents. Oikos **103**:293–302.

Mrosovsky, N., G. Ryan, and M. James. 2009. Leatherback turtles: the menace of plastic. Marine Pollution Bulletin **58**:287–289.

Musick, J. A., and C. J. Limpus. 1997. Habitat utilization and migration in juvenile sea turtles. The Biology of Sea Turtles **1**:137–163.

NOAA (National Oceanic and Atmospheric Organization). 2012. Japan Tsunami debris: information and FAQs. NOAA, Silver Spring, Maryland. Available from http://marinedebris.noaa.gov/info/japanfaqs.html (accessed June 2012).

Oehlmann, J., et al. 2009. A critical analysis of the biological impacts of plasticizers on wildlife. Philosophical Transactions of the Royal Society B: Biological Sciences **364**:2047–2062.

Parker, D. M., W. J. Cooke, and G. H. Balazs. 2005. Diet of oceanic loggerhead sea turtles (Caretta caretta) in the central North Pacific. Fishery Bulletin **103**:142–152.

Parker, D. M., P. H. Dutton, and G. H. Balazs. 2011. Oceanic diet and distribution of haplotypes for the green turtle, *Chelonia mydas*, in the Central North Pacific. Pacific Science **65**:419–431.

Peckham, S. H., D. Maldonado-Diaz, Y. Tremblay, R. Ochoa, J. Polovina, G. Balazs, P. H. Dutton, and W. J. Nichols. 2011. Demographic implications of alternative foraging strategies in juvenile loggerhead turtles *Caretta caretta* of the North Pacific Ocean. Marine Ecology Progress Series **425**:269–280.

PlasticsEurope. 2009. The compelling facts about plastics 2009: an analysis of European plastics production, demand and recovery for 2008. PlasticsEurope, Brussels.

Plotkin, P. and A. Amos. 1990. Effects of anthropogenic debris on sea turtles in the northwestern Gulf of Mexico. Pages 736–743 in R. Shomura, and H. Yoshida, editors. Proceedings of the 2nd international conference on marine debris. National Oceanic and Atmospheric Administration, Honolulu.

Plotkin, P., M. Wicksten, and A. Amos. 1993. Feeding ecology of the loggerhead sea turtle *Caretta caretta* in the Northwestern Gulf of Mexico. Marine Biology **115**:1–5.

Quinones, J., V. Gonzalez Carman, J. Zeballos, S. Purca, and H. Mianzan. 2010. Effects of El Nino-driven environmental variability on black turtle migration to Peruvian foraging grounds. Hydrobiologia **645**:69–79.

Rees, A., A. Al-Kiyumi, A. Broderick, N. Papathanasopoulou, and B. Godley. 2012. Conservation related insights into the behaviour of the olive ridley sea turtle *Lepidochelys olivacea* nesting in Oman. Marine Ecology Progress Series **450**:195–205.

Revelles, M., L. Cardona, A. Aguilar, and G. Fernandez. 2007. The diet of pelagic loggerhead sea turtles (*Caretta caretta*) off the Balearic archipelago (western Mediterranean): relevance of long-line baits. Journal of the Marine Biological Association of the United Kingdom **87**:805–813.

Ross, J. P. 1985. Biology of the green turtle, *Chelonia mydas*, on an Arabian feeding ground. Journal of Herpetology **19**:459–468.

Russo, G., C. Di Bella, G. R. Loria, G. Insacco, P. Palazzo, C. Violani, and B. Zava. 2003. Notes on the influence of human activities on sea chelonians in Sicilian waters. Ibex Journal of Mountain Studies 7:37–41.

Sadove, S., and S. Morreale. 1989. Marine mammal and sea turtle encounters with marine debris in the New York Bight and the northeast Atlantic. Pages 2–7 in R. Shomura, editor. Proceedings of the 2nd international conference on marine debris. National Oceanic and Atmospheric Administration, Honolulu.

Santos, R. G., et al. 2011. Coastal habitat degradation and green sea turtle diets in Southeastern Brazil. Marine Pollution Bulletin **62**:1297–1302.

Schuyler, Q., B. D. Hardesty, C. Wilcox, and K. Townsend. 2012. To eat or not to eat? Debris selectivity by marine turtles. PLoS ONE 7. DOI: 10.1371/journal.pone.0040884.

Seney, E. E., and J. A. Musick. 2007. Historical diet analysis of loggerhead sea turtles (*Caretta caretta*) in Virginia. Copeia **2007**: 478–489.

Seminoff, J. A., A. Resendiz, and W. J. Nichols. 2002. Diet of east Pacific green turtles (*Chelonia mydas*) in the central Gulf of California, Mexico. Journal of Herpetology **36**:447–453.

Shaver, D. J. 1991. Feeding ecology of wild and head-started Kemp's Ridley sea turtles in South Texas waters. Journal of Herpetology **25**:327–334.

Shaver, D. J. 1998. Sea turtle strandings along the Texas coast, 1980–94. Pages 57–72 in Characteristics and causes of Texas marine strandings. U.S. National Oceanic and Atmospheric Administration (NOAA) technical report 143. National Marine Fisheries Service, Seattle.

Sheavly, S., and K. Register. 2007. Marine debris & plastics: environmental concerns, sources, impacts and solutions. Journal of Polymers and the Environment **15**:301–305.

Sperling, J. B., G. C. Grigg, L. A. Beard, and C. J. Limpus. 2007. Respiratory properties of blood in flatback turtles (*Natator depressus*). Journal of Comparative Physiology B: Biochemical, Systemic, and Environmental Physiology **177**:779–786.

Teuten, E. L., et al. 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society B: Biological Sciences **364**:2027–2045.

Tomas, J., R. Guitart, R. Mateo, and J. A. Raga. 2002. Marine debris ingestion in loggerhead sea turtles, *Caretta caretta* from the Western Mediterranean. Marine Pollution Bulletin **44**:211–216.

Tourinho, P. S., J. A. I. do Sul, and G. Fillmann. 2010. Is marine debris ingestion still a problem for the coastal marine biota of southern Brazil? Marine Pollution Bulletin **60**:396–401.

UNEP (United Nations Environment Programme). 2005. Marine litter, an analytical overview. UNEP, Nairobi.

van Franeker, J. A., et al. 2011. Monitoring plastic ingestion by the northern fulmar *Fulmarus glacialis* in the North Sea. Environmental Pollution **159**:2609–2615.

van Franeker, J. A., and SNS Fulmar Study Group. 2011. Chemicals in marine plastics and potential risks for a seabird like the Northern Fulmar (*Fulmarus glacialis*). Pages 415–418 in B. Carswell, K. McElwee, and S. Morison, editors. Fifth international marine debris conference. National Oceanic and Atmospheric Adminstration, Honolulu.

Walker, T., and C. Parmenter. 1990. Absence of a pelagic phase in the life cycle of the flatback turtle, *Natator depressa* (Garman). Journal of Biogeography **17**:275–278.

Witherington, B. E. 2002. Ecology of neonate loggerhead turtles inhabiting lines of downwelling near a Gulf Stream front. Marine Biology **140**:843–853.

Appendix L. Mistaken identity? Visual similarities of marine debris to natural prey items of sea turtles BMC Ecology 2014.

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RESEARCH ARTICLE Open Access

Mistaken identity? Visual similarities of marine debris to natural prey items of sea turtles

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Abstract

Background: There are two predominant hypotheses as to why animals ingest plastic: 1) they are opportunistic feeders, eating plastic when they encounter it, and 2) they eat plastic because it resembles prey items. To assess which hypothesis is most likely, we created a model sea turtle visual system and used it to analyse debris samples from beach surveys and from necropsied turtles. We investigated colour, contrast, and luminance of the debris items as they would appear to the turtle. We also incorporated measures of texture and translucency to determine which of the two hypotheses is more plausible as a driver of selectivity in green sea turtles.

Results: Turtles preferred more flexible and translucent items to what was available in the environment, lending support to the hypothesis that they prefer debris that resembles prey, particularly jellyfish. They also ate fewer blue items, suggesting that such items may be less conspicuous against the background of open water where they forage.

Conclusions: Using visual modelling we determined the characteristics that drive ingestion of marine debris by sea turtles, from the point of view of the turtles themselves. This technique can be utilized to determine debris preferences of other visual predators, and help to more effectively focus management or remediation actions.

Keywords: *Chelonia mydas*, Chromatic space, *Eretmochelys imbricata*, Marine debris, Vorobyev-Osorio model

Background

Sea turtles, like many other marine taxa, are increasingly prone to marine debris ingestion and associated problems [1]. Despite many studies recording instances of debris ingestion e.g. [2,3], little is known about the cues that attract turtles to eat plastic debris. The predominant hypotheses are that 1) turtles, as opportunistic feeders, simply consume items in proportion to what they encounter in the environment, including plastics; and 2) that turtles feed on plastic because of its similarity to prey, particularly jellyfish [4,5]. Though the proportion of gelatinous prey in a turtle's diet varies depending on the life stage and the species of the turtle, all species do target these prey at some stage of their lives [6,7].

Turtles are primarily visual predators. Research indicates that loggerhead turtles have limited ability to find food based on chemical stimuli alone [8], which may explain why they are primarily caught during the day on longline fishing lines, and rarely at night [9]. Similarly, when presented with both chemical and visual cues, leatherback turtles responded exclusively to visual cues [10]. Therefore, the visual similarity between plastic bags and jellyfish can cause confusion even in the absence of chemical stimuli associated with food sources. Loggerhead sea turtles have been shown to approach plastic bags in a similar manner to gelatinous prey, indicating that they use visual characteristics to select their food [11].

The spectral sensitivity of an animal depends not only on its photopigments, but also on the transmissivity of the ocular media and, in the case of turtles, of the oil droplets associated with the cones. Turtles have a well-developed visual system with at least three different photopigments, indicating the ability to see colour [12]. The visual system of sea turtles is similar to that of fresh water turtles; however, the sea turtles' visual pigments are slightly shifted towards the shorter wavelengths, due to the differences in spectral characteristics of the waters in which the different animals live [13]. Sea turtles generally inhabit clearer, oceanic waters, whereas fresh water contains many dissolved organics and sediments, shifting the maximum light transmission to longer wavelengths [13-15]. The bulk of sea turtle vision studies to date have been conducted on green (*Chelonia mydas*) and

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loggerhead (*Caretta caretta*) sea turtles e.g. [16,17]. Liebman and Granda found 3 photopigments in the green turtle retina absorbing maximally at 440 nm (SWS), 502 nm (MWS), and 562 nm (LWS) [18]. Recent evidence indicates that green turtles are also likely to have a fourth, ultraviolet sensitive (UVS) photo-pigment, like their fresh-water relatives [17]. Turtles possess at least four different types of oil droplets, again indicating they have four spectral sensitivities, like birds [17]. Each type of oil droplet may be associated with a specific photopigment, or may combine with different photopigments to produce multiple cone receptor types [14,19].

Turtles, like many other vertebrates, also possess double cones, a specialized structure consisting of two cones joined together [20]. The function of the double cone is still unknown; however it has been hypothesized in both birds and reptiles to play a role in discriminating between levels of luminosity or brightness [20-23]. Although the exact composition of the double cone structure is unknown, in fresh water turtles both of the members that make up the double cone have LWS photoreceptors [19].

We created a chromatic space model of the green turtle visual system (sensu [24]) to investigate the following questions: Are green, hawksbill, and flatback turtles selectively ingesting particular types of debris over others, and if so, what characteristics of that debris (colour, texture, translucency, luminance, or background contrast) are most relevant to turtles' foraging choices?

Results

Our visual model resulted in peak sensitivities of 365, 440, 515, and 560–565 (Figure 1). The mixed effects modelling results indicate that sea turtles select the debris they ingest based on a variety of physical properties. In fact, debris ingested by turtles was significantly different from beach debris for all environmental variables investigated with the exception of background contrast and the contribution of the UV cone (Table 1). Turtles differentiated items most strongly based on their luminance ($p < 0.001$, selectivity ratio = 0.640), flexibility ($p < 0.001$, selectivity ratio = 0.437), and translucency ($p = 0.001$, selectivity ratio = 0.290). Items ingested by turtles tend to be less bright (i.e. lower luminance value), more flexible, and more translucent than items found in the environment. With respect to wavelengths, items ingested by turtles had significantly lower short wavelength spectrum values ($p < 0.001$, selectivity ratio = 0.215).

A simple inspection of the turtle visual space models (Figure 2) shows the difference in the wavelengths of ingested debris and beach debris. The average value of debris ingested by turtles is lower in the short wavelength spectrum than that of beach debris, indicating that the items turtles eat are less blue than what is available to them in the environment.

There were no significant differences observed between plastics ingested by sea turtles of different life history stages (new recruits and juvenile turtles) with respect to the factors tested (colour, texture, translucency, luminance, and background contrast). However, hawksbill and flatback turtles did exhibit some significant differences compared to green turtles. Because we only had a small sample size for hawksbills ($n = 2$) and flatbacks ($n = 1$), we omitted them from analyses.

Discussion

The spectral sensitivities we calculated (365, 440, 515 and 560–565) are well matched with previously published electroretinography (ERG) data of *C. mydas* spectral

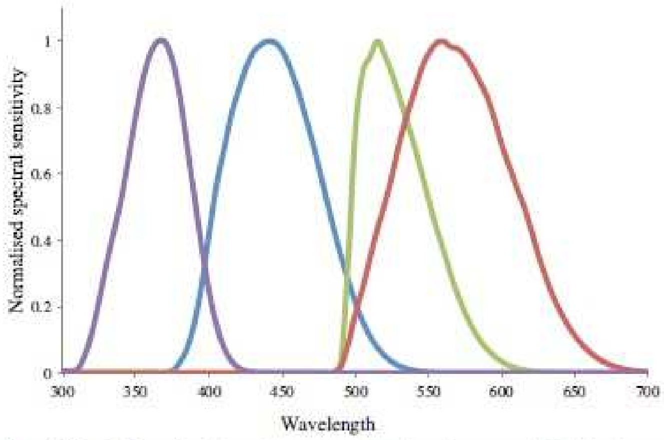

Figure 1 Modelled spectral sensitivity of *C. mydas*. Each peak represents the photopigment multiplied by the transmissivity of its associated oil droplet and by the ocular media.

Table 1 Model coefficients for physical factors influencing the selectivity of debris ingestion by sea turtles

	Intercept	SE of intercept	Turtle effect	SD of turtle effect	p-value	Selectivity ratio[a]
Flexibility	1.755	0.088	0.767	0.133	<0.001*	0.437
Translucency	1.295	0.069	0.375	0.104	0.001*	0.290
SWS	0.268	0.006	−0.058	0.010	<0.001*	0.215
MWS	0.291	0.005	0.028	0.008	0.002*	0.096
LWS	0.311	0.008	0.040	0.012	0.002*	0.127
UVS	0.130	0.007	−0.010	0.010	0.345	0.075
Contrast	25.981	1.551	−1.468	2.356	0.573	0.057
Luminance (sum of cones)	239.27	16.225	−153.144	24.569	<0.001*	0.640
Luminance (double cone)	74.978	4.930	−43.441	7.47	<0.001*	0.579

Note that the selectivity ratio indicates the relative strength of the turtles' selectivity based on each factor. *indicate p values that are significant at the 0.05 level.
[a]Calculated as the absolute value of the ratio of the size of the turtle effect to the size of the intercept.

sensitivities. Levenson and colleagues [25] observed well-defined peaks at 515 and 570, with a relatively constant sensitivity below 500 nm; an earlier study found peaks at 450, 520, and 600 [18]. The technique of high frequency flicker ERG used by Levenson et al. [25] is likely more accurate in the longer wavelengths, as it more successfully isolates the cone response from the rod response. However, the turtles in this study were older than those used by Liebman and Granda and may have experienced a decline in short wavelength vision similar to elderly humans, explaining the lack of a defined short wavelength peak [25]. Our model, therefore, matches observed sensitivities based on ERG.

We assumed that beach debris was a reasonable proxy for ocean-borne debris in the nearshore area inhabited by these turtles, and therefore represents the debris "available" to the turtles. Although there are limitations of using beach debris as a proxy for ocean debris, it has been widely used in previous studies [26]. Thiel et al. [27] conducted a multi-year comparison of anthropogenic marine debris on beaches and in nearshore waters, finding the proportions of different items to be similar. Locally, an analysis of beach debris and nearshore trawl debris for locations around North Stradbroke Island found similar proportions of different colors of debris in both beach and trawl surveys (unpublished observations, Q. Schuyler). We are therefore confident that local beach debris is representative of nearshore ocean debris available to turtles analysed here.

It is clear from the statistical results, as well as from inspection of the turtle visual space data that turtles are selective in what they eat (Table 1, Figure 2). Turtles do not tend to ingest debris that is reflective in the short wavelengths; i.e. blue items. When turtle preferences were analysed based on a human categorical description of colour rather than a turtle visual space model, blue was similarly found to be less prevalent in turtle samples than in beach surveys [28]. Also in support of our findings, a laboratory-based study of loggerhead and Kemp's ridley turtles indicated that both species avoided blue dyed bait [29].

Colour is not the only visual factor employed in food selection. In other animal species, contrast has been found to be as important or even more influential than colour in selecting food sources [30,31]. The fact that turtles are selecting against blue items could indicate that blue plastics are less readily visible against the blue background of the open ocean. We measured this contrast value by calculating the tetrachromatic distance between each debris item and a background measurement of open ocean water, but found that turtles did not selectively ingest items based on contrast. However, this may be partially due to limitations of the model. Similar models calculating colour space distances have reliably predicted honeybee behaviour when visiting orchid mimics. Bees were more likely to visit an orchid mimic when there was a small colour distance between the orchid and its preferred food source than when the colour space distance was large; in other words, when the mimic was a similar colour to their preferred food choice [32]. However, the honeybee model was only successful when incorporating second order visual processing, assuming interactions between photoreceptor types [33]. Our model did not incorporate these interactions, which may explain why turtles did not appear to select for high contrast items.

Turtles selected debris with significantly lower luminance values than those of beach debris, possibly because dark objects stand out better against the bright ocean background [34]. However, we cannot completely exclude the possibility that the prevalence of darker objects in the turtles is partially an artefact of our study design, as the debris in the turtles' gastrointestinal system is exposed to digestive fluids and other waste, which may result in a reduction of luminance. Further work on clarifying the differences in selectivity between contrast and colour would help to elucidate these results.

The visual space model investigates colour and luminance, but other characteristics influence ingestion selectivity in turtles even more than colour. Turtles select plastics most strongly based on their flexibility and

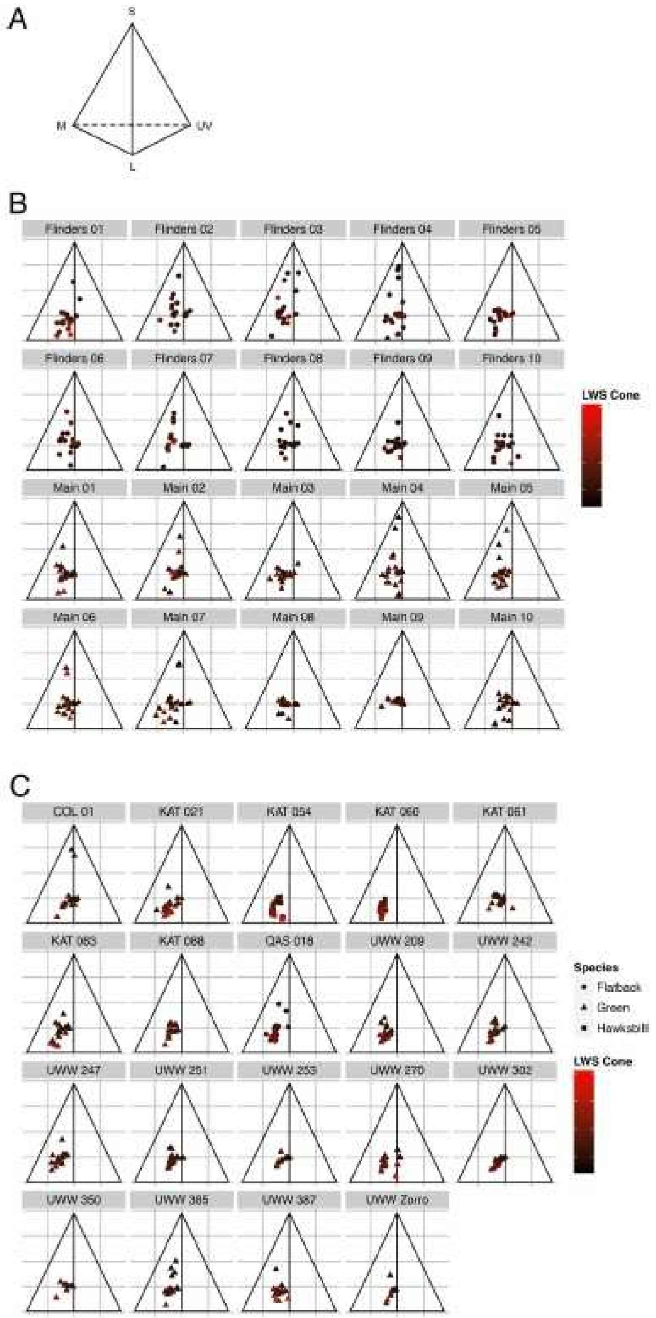

Figure 2 (See legend on next page.)

(See figure on previous page.)
Figure 2 Colour space triangles. The visual space of a tetrachromatic sea turtle can be represented as a tetrahedron (**2A**). Each vertex represents the contribution from a different cone. The lower left corner is the medium wavelength cone, the lower right corner is the UV wavelength cone, and the top vertex is the short wavelength cone. In order to portray a 3 dimensional image in a 2 dimensional space, we use colour to represent the contribution from the fourth vertex, the LWS cone (red is a strong contribution from the long wavelength, black is not). We plot the plastic from each beach sample (**2B**) and turtle sample (**2C**) on a separate triangle. Every dot is a single piece of plastic, and the closer the dot to the vertex, the greater the contribution from that cone. n = 20 for all samples except KAT 88 (n = 13), UWW 242 (n = 19), and UWW 350 (n = 9).

translucency. Our model suggests that turtles prefer highly flexible and translucent objects, both of which are key characteristics of one of their preferred natural prey items: jellyfish. This work demonstrates that turtles are indeed selective, and it also provides support for the widely postulated "jellyfish hypothesis". Proper waste disposal, particularly for common end user items such as plastic bags and other soft, translucent items which are preferentially ingested by marine turtles, may help to reduce the rapidly increasing debris ingestion rates in threatened sea turtles. We hope this research can inform conservation efforts not only for endangered sea turtles, but we also suggest applying similar analyses for other visual predators to investigate the key factors that drive ingestion rates and anthropogenic debris selectivity.

Conclusions

Using models to visualize how turtles "see" the plastic they ingest, we find strong support for the hypothesis that they ingest plastic because of its resemblance to a typical prey item, jellyfish. Our model can be extended to other species to better understand why wildlife consume plastic and to effectively focus conservation and remediation efforts.

Methods

Visual system model

We modelled the spectral sensitivity of the green sea turtle by incorporating measurements of the photopigments, oil droplets, and ocular media. We generated generic spectral photopigment curves [35-37] based on the peak absorbances for the three known green turtle photopigments: 440 nm, 502 nm, and 562 nm [18]. Since measurements of the green turtle UVS pigment have not been conducted, we simulated a UVS curve based on the UVS pigment of the freshwater turtle *Pseudomys scripta*. As freshwater turtles tend to have pigment maxima at longer wavelengths than sea turtles, we shifted the peak absorbance for the *Pseudomys* UVS curve 7 nm shorter to 365 nm [19].

For oil droplet measurements, we assumed that the orange oil droplets were associated only with photoreceptors containing the LWS visual pigments, yellow with the MWS, clear (UV-reflective) with the SWS pigments, and colourless (UV-transmissive) with the UVS photoreceptors. We used published curves for yellow and orange oil droplets from green turtles [18], and clear oil droplets from *Pseudomys* scripta [19]. We shifted the clear oil droplet spectrum shorter by 15 nm, corresponding to the difference in peak wavelength between the SWS pigments of *P. scripta* and of *C. mydas* [19]. We were unable to find published spectra for the UV-transmissive oil droplet in turtles, but as it has no significant absorbance above 325 nm, it would not affect the shape of the UV photopigment curve.

We applied the Hart correction to each oil droplet [38], converted to transmissivity, and multiplied the photopigment curve by the transmissivity of its associated oil droplet. We then multiplied the four resulting curves by the transmissivity of the ocular media [17] and normalized the result for each cone to an absorbance maximum of 1 to create a modelled spectral sensitivity curve for green sea turtles.

Debris collection and measurement

We conducted necropsies on sea turtles stranded in southeast Queensland, Australia, between 2006 and 2013, and collected all pieces of debris that had been ingested by the animals (Table 2). For more details see [28]. Of 115 necropsied animals, nineteen had ingested sufficient quantities of debris for our analysis (16 green turtles, 2 hawksbill turtles, and 1 flatback turtle). To estimate the debris to which animals would have been exposed we conducted ten beach surveys on each of two different ocean-facing beaches on North Stradbroke Island (Flinders Beach and Main Beach) between 2011–2013 (for detailed methodology see [28]). All items of anthropogenic debris over 5 mm in length between the water line and the dominant vegetation line were collected in a 100 m transect. We selected 20 random debris subsamples from

Table 2 Characteristics of necropsied turtles

	All turtles necropsied	Turtles with debris
Species		
Green	88	16
Hawksbill	24	2
Flatback	1	1
Loggerhead	2	0
Size class		
Pelagic (CCL < 35 cm)	22	12
Benthic (CCL > 35)	93	27

each beach and each turtle sample. Three of the turtles had ingested fewer than 20 items of debris, so for these turtles, all pieces were analysed.

We assigned each piece of debris a measurement of flexibility between 1 (impossible to bend without breaking) and 3 (easily malleable). We also assigned a measure of translucency between 1 (completely opaque) and 3 (possible to read text through the item). We chose translucency and flexibility because they are visual characteristics in addition to colour which might be used for prey selection. Using an Ocean Optics JAZ spectrophotometer we measured the reflectance of each item between 300–800 nm wavelength. In 49 of the plastic samples we did not dark-calibrate the spectra, so some of the reflectances were slightly below zero. To each of the measurements for these samples we added a constant value (equal to the largest negative value for the sample) in order to ensure that the minimum value was non-negative. Because the negative values were quite small with respect to the maximum reflectances, and represent only a linear shift, this correction factor did not affect the outcome of our modelling.

We used our calculated green turtle spectral sensitivities to model how each item of debris would appear in the turtles' visual space [39]. Because there are virtually no studies on the visual systems of hawksbill and flatback turtles (but see [40]), we used the green turtle spectral sensitivity curves (as modelled above) for all species. The visual space for a tetrachromatic animal can be represented as a three dimensional tetrahedron with one vertex for each cone. Plotting the relative excitation of each photoreceptor within this space generates a representation of the colour of an object as it would appear to a turtle's visual system.

Using the Vorobyev-Osorio noise-limited chromatic space model [41] we also calculated the three-dimensional distances between each piece of debris and a measurement of background colour that turtles would be likely to encounter; open ocean water. This gives an indication of the contrast of each item to the background colour. This calculation relies on an estimate of the proportions of cones present in the retina. Although these data are not known for sea turtles, the proportions of oil droplets are [17], so we assumed the proportions of cones in the retina to be equal to the proportions of oil droplets associated with them. Finally, we calculated two different measures of luminance. For the first we added the total reflectance values for all four cones. Since the double cone may be responsible for luminance discrimination, we calculated a second measurement using the total reflectance of the LWS cone only [19].

In order to determine whether turtles exhibited a selectivity for debris based on the physical characteristics measured (colour, texture, translucency, luminance, and background contrast), we used linear mixed effects models (R version 3.0.1, package lme4) [42] with the physical factors as response variables, and the location the plastic was found (turtle or beach) as the predictor variable. In order to control for autocorrelation among plastic items within a beach or stomach sample, we incorporated a random effect for each beach or turtle sample. We also investigated the differences between species and life history stages of turtles with respect to each physical characteristic. Because of the complex nature of the data set, we analysed each factor separately. In order to obtain a relative measurement of the strength of each term, we calculated the absolute value of the ratio of the effect size to the intercept term. Note that the larger the ratio, the more highly selective the turtles are for the variable.

Ethical statement

Because this research was carried out on dead stranded sea turtles, no ethical approval was required.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

QS carried out the field and lab work and drafted the manuscript. CW assisted in statistical analysis. KT and JM conceived of the study. BDH contributed substantial editing of the manuscript. JM participated in the design and coordination of the study. All authors read and approved the final manuscript.

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References

1. Schuyler QA, Hardesty BD, Wilcox C, Townsend K: **Global analysis of anthropogenic debris ingestion by sea turtles.** *Conserv Biol* 2014, 28(1):128–139.
2. Tomas J, Guitart R, Mateo R, Raga JA: **Marine debris ingestion in loggerhead sea turtles, Caretta caretta from the Western Mediterranean.** *Mar Pollut Bull* 2002, 44(3):211–216.
3. Tourinho PS, Do Sul JAI, Fillmann G: **Is marine debris ingestion still a problem for the coastal marine biota of southern Brazil?** *Mar Pollut Bull* 2010, 60(3):396–401.
4. Carr A: **Rips, FADS, and little loggerheads.** *BioScience* 1986, 36(2):92–100.
5. Mrosovsky N, Ryan G, James M: **Leatherback turtles: the menace of plastic.** *Mar Pollut Bull* 2009, 58(2):287–289.
6. Shaver DJ: **Feeding ecology of wild and head-started Kemp's Ridley sea turtles in South Texas waters.** *J Herpetol* 1991, 25(3):327–334.

7. Bjorndal K: **Foraging ecology and nutrition of sea turtles.** In *The Biology of Sea Turtles.* Edited by Lutz PL, Musick JA. Boca Raton, Florida: CRC Press; 1997:199–232.
8. Southwood A, Higgins B, Brill R, Swimmer Y: **Chemoreception in loggerhead sea turtles: an assessment of the feasibility of using chemical deterrents to prevent sea turtle interactions with longline fishing gear.** In *US Department of Commerce, NOAA Technical Memo NOAA-TM-NMFS-PIFSC–10.* Honolulu, HI: U. S. Department of Commerce; 2007:1–17.
9. Baez JC, Real R, Caminas JA: **Differential distribution within longline transects of loggerhead turtles and swordfish captured by the Spanish Mediterranean surface longline fishery.** *J Mar Biol Assoc UK* 2007, **87**(3):801–803.
10. Constantino MA, Salmon M: **Role of chemical and visual cues in food recognition by leatherback posthatchlings (Dermochelys coriacea L).** *Zoology* 2003, **106**:173–181.
11. Narazaki T, Sato K, Abernathy KJ, Marshall GJ, Miyazaki N: **Loggerhead turtles (*Caretta caretta*) use vision to forage on gelatinous prey in mid-water.** *PLoS One* 2013, **8**(6).
12. Fritsches KA, Warrant EJ: **Vision.** In *The Biology of Sea Turtles, vol III.* vol. 3rd edition. Edited by Wyneken J, Lohmann KJ, Musick JA. New York: CRC Press; 2013.
13. Lythgoe JN: *The Ecology of Vision.* Oxford: Clarendon Press; 1979.
14. Granda A: **Eyes and their sensitivity to light of differing wavelengths.** In *Turtles: Perspectives and Research.* Edited by Harless M, Morlock H. New York: John Wiley and Sons; 1979:247–266.
15. Jerlov NG: *Marine Optics.* New York: Elsevier; 1976.
16. Bartol SM, Musick JA: **Morphology and topographical organization of the retina of juvenile loggerhead sea turtles (Caretta caretta).** *Copeia* 2001, **3**:718–725.
17. Mathger LM, Litherland L, Fritsches KA: **An anatomical study of the visual capabilities of the green turtle, Chelonia mydas.** *Copeia* 2007, **1**:169–179.
18. Liebman PA, Granda A: **Microspectrophotometric measurements of visual pigments in two species of turtle, Pseudemys scripta and Chelonia mydas.** *Vision Res* 1971, **11**:105–114.
19. Loew ER, Govardovskii VI: **Photoreceptors and visual pigments in the red eared turtle, Trachemys scripta elegans.** *Vis Neurosci* 2001, **18**:753–757.
20. Marchiafava PL: **Cell coupling in double cones of the fish retina.** *Proc R Soc Lond B Biol Sci* 1985, **226**(1243):211–215.
21. Marshall NJ, Jennings K, McFarland WN, Loew ER, Losey GS: **Visual biology of Hawaiian coral reef fishes. III. Environmental light and an integrated approach to the ecology of reef fish vision.** *Copeia* 2003, **3**:467–480.
22. Bowmaker J: **Visual pigments of fishes.** In *The Visual System of Fish.* Edited by Douglas R, Djamgoz M. Netherlands: Springer; 1990:81–107.
23. Loew ER, Lythgoe JN: **The ecology of cone pigments in teleost fishes.** *Vision Res* 1978, **18**(6):715–722.
24. Kelber A, Vorobyev M, Osorio D: **Animal colour vision — behavioural tests and physiological concepts.** *Biol Rev* 2003, **78**(1):81–118.
25. Levenson DH, Eckert SA, Crognale MA, Deegan JF II, Jacobs GH: **Photopic spectral sensitivity of green and loggerhead sea turtles.** *Copeia* 2004, **4**:908–914.
26. Dixon TR, Dixon TJ: **Marine litter surveillance.** *Mar Pollut Bull* 1981, **12**(9):289–295.
27. Thiel M, Hinojosa IA, Miranda L, Pantoja JF, Rivadeneira MM, Vasquez N: **Anthropogenic marine debris in the coastal environment: A multi-year comparison between coastal waters and local shores.** *Mar Pollut Bull* 2013, **71**:307–316.
28. Schuyler Q, Hardesty BD, Wilcox C, Townsend K: **To eat or not to eat? Debris selectivity by marine turtles.** *PLoS One* 2012, **7**(7). doi:10.1371/journal.pone0040884.
29. Swimmer Y, Arauz R, Higgins B, McNaughton L, McCracken M, Ballestero J, Brill R: **Food color and marine turtle feeding behavior: Can blue bait reduce turtle bycatch in commercial fisheries?** *Mar Ecol-Prog Ser* 2005, **295**:273–278.
30. Schmidt V, Martin Schaefer H, Winkler H: **Conspicuousness, not colour as foraging cue in plant–animal signalling.** *Oikos* 2004, **106**(3):551–557.
31. Ginetz R, Larkin P: **Choice of colors of food items by rainbow trout (Salmo gairdneri).** *J Fish Board Canada* 1973, **30**(2):229–234.
32. Gumbert A, Kunze J: **Colour similarity to rewarding model plants affects pollination in a food deceptive orchid, Orchis boryi.** *Biol J Linn Soc* 2001, **72**(3):419–433.
33. Brandt R, Vorobyev M: **Metric analysis of threshold spectral sensitivity in the honeybee.** *Vision Res* 1997, **37**(4):425–439.
34. Lythgoe J: **Light and vision in the aquatic environment.** In *Sensory Biology of Aquatic Animals.* Edited by Atema J, Fay R, Popper A, Tavolga W. New York: Springer; 1988:57–82.
35. Stavenga D, Smits R, Hoenders B: **Simple exponential functions describing the absorbance bands of visual pigment spectra.** *Vision Res* 1993, **33**(8):1011–1017.
36. Hart NS: *Avian Photoreceptors. PhD Thesis.* Bristol, UK: University of Bristol; 1999.
37. Palacios AG, Goldsmith TH, Bernard GD: **Sensitivity of cones from a cyprinid fish (Danio aequipinnatus) to ultraviolet and visible light.** *Vis Neurosci* 1996, **13**(3):411–421.
38. Hart N, Vorobyev M: **Modelling oil droplet absorption spectra and spectral sensitivities of bird cone photoreceptors.** *J Comp Physiol A Neuroethol Sens Neural Behav Physiol* 2005, **191**(4):381–392.
39. Marshall NJ, Cheney K: **Color vision and color communication in reef fish.** In *Encyclopedia of Fish Physiology: From Genome to Environment,* Volume 1. Edited by Farrell AP. San Diego: Academic Press; 2011:150–158.
40. Northmore DPM, Granda AM: **Ocular dimensions and schematic eyes of freshwater and sea turtles.** *Visual Neurosci* 1991, **7**(06):627–635.
41. Vorobyev M, Osorio D: **Receptor noise as a determinant of colour thresholds.** *Proc R Soc Lond B Biol Sci* 1998, **265**(1394):351–358.
42. R Core Team: *R: A Language and Environment for Statistical Computing.* Vienna, Austria: R foundation for statistical computing; 2013.

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Appendix M. Comparing plastic ingestion in juvenile and adult stranded short- tailed Shearwaters (Puffinus tenuirostris) in Eastern Australia, Marine Pollution Bulletin 2014.

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Comparing plastic ingestion in juvenile and adult stranded short-tailed shearwaters (*Puffinus tenuirostris*) in eastern Australia

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A R T I C L E I N F O

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A B S T R A C T

Numerous species of seabirds have been shown to ingest anthropogenic debris, but few studies have compared ingestion rates between adults and juveniles of the same species. We investigated marine debris ingestion by short-tailed shearwaters (*Puffinus tenuirostris*) obtained through two stranding events on North Stradbroke Island, Australia in 2010 ($n = 102$; adult) and 2012 ($n = 27$; juveniles). Necropsies were conducted and solid contents found in guts were categorized into type and color. Over 67% of birds ingested anthropogenic debris; 399 pieces of debris were identified. We found no significant relationship between body condition of birds which had ingested anthropogenic debris and those that had not. Juvenile birds were more likely to ingest debris than were adult birds and juveniles ingested significantly more pieces of debris than did adults. Male and female birds ingested similar amounts and weights of debris. To determine if *P. tenuirostris* actively selects for certain types of debris, we compared ingested debris to samples obtained from boat-based tows. Significant differences were found, suggesting that the birds select for hard plastic, rubber and balloons.

1. Introduction

Marine debris, defined as anthropogenic waste that reaches the ocean, is a global issue. It is composed primarily of plastic polymers (Derraik, 2002), despite the fact that plastics have existed for less than a century (Gorman, 1993). It has been suggested that the deposition rate of plastics has now outgrown production rate (Moore, 2008) and that plastics are overly represented in the environment due to their slow and variable decomposition times (Gregory, 1978). Many plastic polymers are buoyant, allowing them to be entrained in currents and increasing their ability to travel long distances far from their source. This buoyancy means they are available to a wide range of pelagic-feeding marine species (Schuyler et al., 2013).

Worldwide, at least 267 marine species are known to have been affected by plastic debris including numerous pelagic seabirds (Laist, 1987). Many studies have hypothesized why marine animals ingest anthropogenic debris. However, the role of selectivity by seabirds when assessing marine debris as a potential food item is currently not fully understood. Selectivity relies heavily on the foraging strategy of the animals, which will automatically include or exclude certain types of debris due to its specific gravity (does it float, sink or is it neutrally buoyant) and its visual characteristics (does it mimic a prey item in shape or color). Hypotheses as to why wildlife ingest food include misidentification of prey items (Mrosovsky et al., 2009; Schuyler et al., 2012) and debris becoming hidden or masked within natural food sources (Balazs, 1985).

Derraik (2002) suggested that the ingestion of plastic by seabirds is directly connected to diet, foraging strategy and foraging location. For example researchers in Alaska found that plastic fragments in bird stomachs were small and brown, leading to the conclusion that these could have been mistaken as fish eggs or larvae, the natural prey items of the focal species (Day, 1980). Also, birds that forage via "pursuit diving" in open ocean areas tend to have increased plastic ingestion (Day et al., 1985). Procellariiformes such as shearwaters are pursuit divers that take advantage of gyres and upwellings (Hunt et al., 1996), where debris also accumulates (Laist, 1987; Lebreton et al., 2012).

It is important to understand the possible mechanisms that may drive birds to ingest debris. For example, is there selectivity for color or size? Moser and Lee (1992) presented evidence that some seabirds select certain shapes and colors of plastic, possibly mistaking them for prey items. Azzarello and Van Vleet (1987) believed that planktivores are more likely to ingest plastic particles than are piscivores, while starving birds might not be selective at all. Furthermore, in some studies, plastic loads in adults and juveniles have been shown to differ, with juveniles containing

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higher plastic loads than adults of two related shearwater species off the east coast of Australia (Hutton et al., 2008).

Our focal species, the short-tailed Shearwater (*Puffinus tenuirostris*; Temminck 1835) feeds primarily at sea and is known to forage by pursuit diving (plunging from height while searching for surface prey) and hydroplaning (Morgan, 1982; Ogi, 1990). It is likely that while on the wing it is hard to distinguish between prey and debris, particularly if debris are similar in size, shape or color to prey items (Day et al., 1985). It has been proposed that vision is the main sense used by seabirds when searching for food (Lovvorn et al., 2001; Martin, 1998). This is supported by the suggestion that if seabirds feed through tactile or chemical cues, they would be less likely to ingest non-food items (Martin and Prince, 2001).

With respect to visual acuity and perception of prey, the retina of the wedge-tailed shearwater (*Puffinus pacificus*), a closely related species, contains five different types of visual pigments in seven different classes of photoreceptors, giving them enhanced color vision (Hart, 2004). It is reasonable to expect that the closely allied short-tailed shearwater shares the same photoreceptors. An important question becomes 'are plastic particles likely mistaken for familiar prey items?' Pursuit or plunge diving birds must cope with the refraction of the position of the underwater prey and also with the reflection of skylight from the surface (Katzir, 1993; Lythgoe, 1979) so it is possible that species with different photoreceptors and/or foraging strategies may be more or less likely to ingest particular types, colors, sizes or shapes of debris.

Like other pursuit diving Procellariformes, short-tailed shearwaters have a narrow passage connecting the proventriculus to the gizzard, which restricts their ability to regurgitate non-digestible material (Carey, 2011). The gizzard is a thick-walled part of a bird's gastrointestinal system, in which food is physically broken down by muscular action and contact with small stones. Indigestible items such as cephalopod beaks, fish otoliths and plastics are often found trapped within the narrow-necked gizzard (Furness, 1985). This can potentially become a problem when chicks are fed by their parents. Because chicks have a reduced ability to regurgitate, debris ingestion can retard growth and development, and debris ingestion has been identified as a source of mortality in some seabirds (Auman et al., 1997; Fry et al., 1987; Priddel et al., 2006; Sileo, 1993).

By understanding the characteristics of the marine debris available in the oceans, we can better understand potential selectivity by marine fauna. This requires comparing what is available in the environment to what is found within the gastrointestinal system of targeted taxa. For example, Schuyler et al. (2012) showed a positive selectivity for soft clear plastics by sea turtles, beyond what was available in the environment.

Our aim was to quantify and describe marine debris ingested by short-tailed shearwaters (*P. tenuirostris*) during two separate stranding incidents in 2010 and 2012 and to ask the following questions: (1) Do *P. tenuirostris* ingest anthropogenic debris? If so, what type(s) of debris do they eat? (2) Is there a difference in the quantity or type of debris ingested between birds of differing ages or sexes? (3) Is there a discernible difference in body condition between birds which had and had not ingested debris? (4) Is debris ingested by *P. tenuirostris* representative of that which we find in the marine environment, or do they select for certain types or colours of debris?

2. Material and methods

2.1. Study area and focal species

North Stradbroke Island is located 40 km east of Brisbane, along the southeast coast of Queensland, Australia (27°20′–27°45′S153°20′–153°33′E). In October 2010 and April 2012, mass-strandings of short-tailed shearwaters occurred along the eastern shore of the island along Main Beach (Fig. 1A). One hundred and two short-tailed shearwaters were collected at random from the estimated 1200 birds washed ashore during the 2010 event. These birds were labeled and frozen for later necropsy. In April 2012, a similar yet smaller stranding event occurred at the same location. As in 2010, weather conditions were rough (wind speeds up to 33 km/h with rainfall in the region of 19–193 mm (Australian Bureau of Meteorology, 2012), which likely contributed to the stranding event. Twenty-seven dead shearwaters were in suitable state to necropsy.

Birds were necropsied using standard techniques (following van Franeker 2004) and stomach, gizzard and intestinal contents were recorded separately. For each of the three sections of the digestive tract, contents were washed in water and strained through a 0.33 mm mesh sieve to separate prey or other solid items ingested. Solid fragments including anthropogenic debris as well as squid beaks, pumice, small rocks and digestion remains, were quantified and identified using a light microscope (Olympus SZ51). The length and width of the ingested contents were measured using electronic calipers and weighed using a high precision digital scale (HM-202). We recorded the type and color of each item. Particles were scraped using a scalpel to determine original colors. All collected items were assessed for positive or negative buoyancy in sea water.

2.2. Trawl sampling

Between November 2011 and May 2012, 41 tows for marine debris in the nearshore environment were collected at different locations in Queensland, Australia (Fig. 1B), using a manta trawl net (mouth size 600 × 200 mm). All trawls were conducted for 30 min at a speed of 1–5 knots. All debris items >0.33 mm were collected and analyzed the same way as for the gut contents.

To compare near-coast debris with oceanic marine debris, a pilot study was conducted using the same type manta trawl net (described above) to sample for floating debris in the high seas. Four tows were conducted along the coast between Yeppoon and Townsville, through the Southern Great Barrier Reef aboard the AIMS (Australian Institute of Marine Science) Research Vessel Cape Ferguson during two days in May 2012 (Fig. 1B). Each tow was conducted for 30 min, at a speed of 3–5 knots. The samples were analyzed the same way as for near-coast trawl samping.

2.3. Statistical analyses

Data were analyzed using R (Studio Version 0.95.263 2009 – 2011 R Studio, Inc.). To check for equal representation of the different classes of debris, we divided debris into the following categories: Hard Plastic, Soft Plastic, Rope/String, Rubber, and Balloon and analyzed using a Chi-Square test. We used generalized linear models (GLM) to estimate whether birds of different ages or genders differ in the quantity, total area, or weight of debris ingested, and whether the quantity, total area, or weight of ingested debris affected the BMI of the birds. Body mass index (BMI) was calculated as the ratio between mass and wing length (Jones et al., 2009). BMI of birds that had and had not ingested debris were also compared using a GLM.

We used the Adonis model (package vegan) (Oksanen et al., 2013) to run permutational multivariate ANOVA (PERMANOVA) tests to determine whether ingestion of different categories and different colours of debris differed for birds of different ages or sexes.

To discern whether there was a difference between anthropogenic debris in high seas and near-shore environments we used a PERMANOVA test. We then compared anthropogenic debris

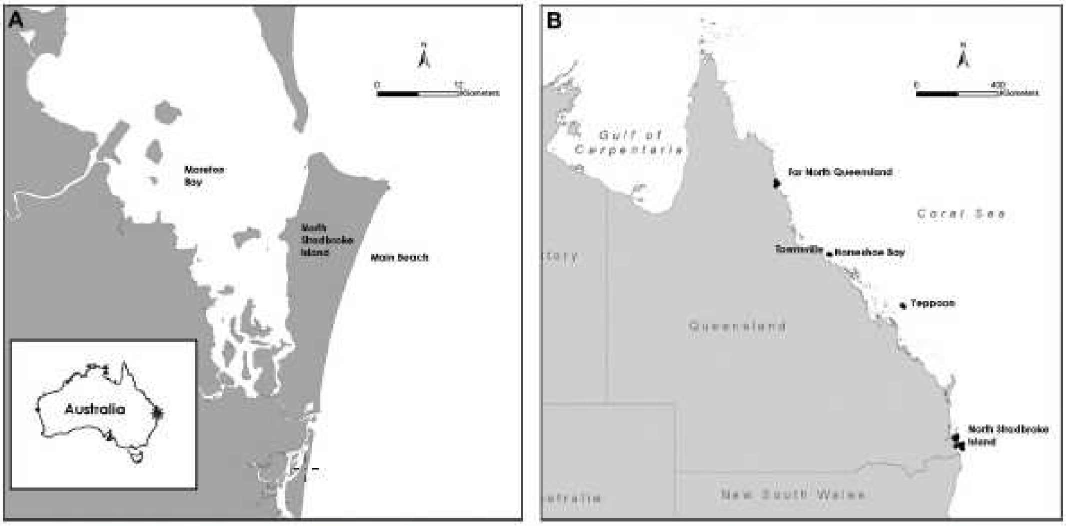

Fig. 1. (A) North Stradbroke Island including Main Beach where stranded birds were surveyed and collected for necropsy and (B) trawl sampling zones.

ingested by beach washed birds to debris available in the marine environment as sampled from our surface trawls. We employed the same procedures as above to test for color preference.

3. Results

A total of 129 birds were sampled during the two stranding events: 102 adult birds in 2010 and 27 juvenile birds in 2012. Given that stranding event in 2010 took place when adults are likely completing migration to their breeding grounds in southern Australia, we expected that stranded birds were adults. Gonad state and plumage characteristics supported this assumption. Birds in the 2012 stranding event were identified as juveniles based on plumage, time of year and gonad state.

66 Birds were females, 49 were males and 14 were of unknown sex. 67% of our total birds sampled had ingested a total of 399 pieces of anthropogenic debris. Anthropogenic debris items averaged 11.36 mm in length (range of 0.97–80.79, ±5.57), 3.98 mm in width (range of 0.24–44.07 + 2.85) and 3.86 g in mass (range of 0.01–58.06 + 0.10).

Of the 102 adult birds, 63% ($N = 64$) had ingested debris. Gender was approximately even: 52% of sampled birds were females. The average weight was 360 g (310–400 g) and the mean BMI was 13.0 (range = 10.5–16.2). In the second stranding event, 85% of the necropsied birds had ingested anthropogenic debris. Of these juvenile birds (as determined by plumage and moult) 48% were females. The average weight was 291 g (range of 208–538 g) with a BMI of 12.6 (range = 9.0–19.5).

In total, we found 305 pieces of ingested anthropogenic litter from the 2010 stranding event. Of these, 261 pieces were plastic, accounting for 48% of the total of solid items found in the guts of adult birds. Other debris items including rubber, string and balloon were also recorded. Among the non-anthropogenic dietary items were squid beaks, pumices and small rocks, small gastropods, bits of wood and seeds (Table 1).

In 2012, plastic accounted for 50% of items found in gut by quantity with a total of 129 particles out of 168 pieces of anthropogenic debris. Hard plastic, rubber, string, balloons, foam and an intact glowstick are examples of anthropogenic debris that were consumed by birds sampled in this study. Other dietary items included squid beaks, pumice, wood, seeds and gastropods, as well as algae, pieces of clay, insects, fish vertebrae and teeth (Table 1).

Most anthropogenic debris was found in the gizzard (51% and 67% respectively for 2010 and 2012), followed by the stomach with 37% and 23%, respectively (Fig. 2). The average number of particles per birds was 4.5 for adult birds and 7.14 for juveniles. Overall, 70% and 72% (2010, 2012 respectively) of particles were positively buoyant.

Near-coast trawls and offshore trawls showed no significant difference in color categories ($p = 0.415$), so they were combined for all color analyses. Significant differences were observed when comparing color of debris ingested by birds and that available in the marine environment from our trawl samples ($p = 0.001$, Fig. 3). Near-coast and ocean trawls differed, however, when we compared the presence of different categories of debris ($p = 0.021$), which may be due to the small number of ocean trawl samples. For this reason, we used only near-coast trawls in our analyses of selectivity of debris categories.

Table 1
Breakdown of items ingested by short-tailed shearwaters (by count) from stranding events in 2010 and 2012.

Items	2010 (Adults)	2012 (Juveniles)	Total proportion (%)
Anthropogenic			
Plastic	261	129	48.99
Rubber	33	3	4.52
Foam	0	21	2.64
Balloon	7	13	2.51
String	4	2	0.75
Natural			
Pumice	103	18	15.20
Squid beak	60	41	12.69
Small rock	41	10	6.41
Gastropod	21	4	3.14
Seed	2	7	1.13
Wood	3	2	0.63
Feather/fur	3	0	0.38
Algae	0	3	0.38
Fish vertebrae	0	1	0.13
Fish tooth	0	1	0.13
Clay	0	1	0.13
Insect	0	2	0.25

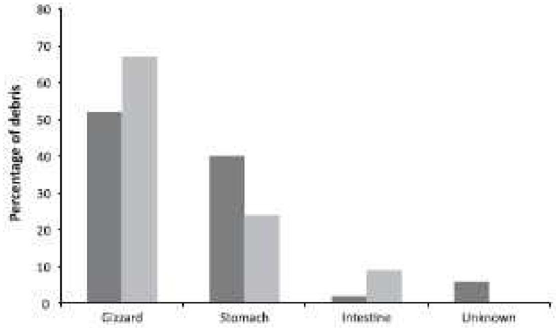

Fig. 2. The percentage of debris in the various sections of the gastrointestinal system of stranded short-tailed shearwaters in 2010 (dark grey) and 2012 (light grey).

We found a significant difference in the proportion of debris categories ingested by the shearwaters as compared to trawl samples ($p = 0.001$), suggesting birds were selecting for certain types of debris (Fig. 4). However, juveniles and adults showed no difference in ingestion of debris types ($p = 0.204$) nor was there a difference between males and females ($p = 0.866$). Overall 48 and 50% of all items found to be ingested by shearwaters in 2010 and 2012 were plastic. This was followed by pumice (19%) and squid beaks (11%) for 2010 birds, and squid beaks (15%), foam (8%) and pumice (6%) by 2012 birds.

There was no significant difference in the size (area), weight or number of pieces of debris ingested between males and females ($p > 0.2$ in all cases). Juveniles did not differ from adults in the size or weight of debris pieces they ingested; however they did ingest significantly higher numbers of pieces of debris ($p < 0.0001$).

The BMI was not affected by either the total weight or number of pieces of debris that were ingested. The BMI was significantly lower in birds that had ingested a larger total size of debris ($p = 0.00188$); however this was due to one outlier. When the outlier was removed, there was no correlation between BMI and number of pieces of debris ingested. Also, there was no significant difference in BMI between birds that had and had not ingested debris. Birds sampled in 2010 (adults) had a higher BMI ($p = 0.00188$) than birds sampled in 2012 (juveniles). Overall, birds were underweight compared to the known average mass for short-tailed shearwaters (see discussion).

4. Discussion

We found that 67% of stranded *P. tenuirostris* had marine debris in their gastrointestinal system (GIS), with the majority of the debris being plastic in composition. This is comparable to other studies which have shown that among all seabirds, Procellariiformes (especially shearwaters) are most likely to ingest plastic, with at least 80% of Procellariiformes recorded to contain plastic in their GIS (Colabuono et al., 2009; Robards et al., 1995; Ryan, 2008). For that reason, *Fulmarus glacialis* (Northern Fulmar) has been used in the North Atlantic and North Pacific Oceans as a monitoring tool for the health of the environment regarding marine debris trends (van Franeker et al., 2011). Other researchers have also observed that plastic debris found on the beach contains peck marks made by birds, suggested that birds could be mistaking plastic fragments for natural prey items such as cuttlebones, which are commonly and intentionally ingested by birds (Cadée, 2002).

We found significant differences in the amount and type of marine debris consumed by juvenile and adult birds. Substantially more juvenile than adult birds were found to have ingested marine debris in our study (85% vs. 62.7%), and the juveniles ingested more debris by count than adults ingested. Young birds may be more prone to ingesting marine debris because they are naïve consumers. Additionally, these birds might still be carrying particles fed to them by their parents before fledging, (Carey 2011; Rodriguez et al. 2012). Adults would have been foraging in Australian waters during the breeding season and may have picked up plastic debris they subsequently fed to their young. Therefore, juveniles would have ingested debris coming from Australian waters in either case, whether through direct feeding or receiving food from adults prior to fledging. Conversely, adult short-tailed shearwaters maintain an annual cycle in the offloading of plastics when they feed debris to their chicks (Ryan et al., 1988). Perhaps this is why Skira (1986) noticed a reduction in plastic load in adult birds when they were in their southern breeding season compared to the Northern hemisphere.

The birds in 2010 (adults on their southward migration) had consumed plastic particles comprised of primarily clear and dark colors and fledging birds in 2012 consumed mostly clear particles (Fig. 3). Perhaps the slight differences in colours consumed by the

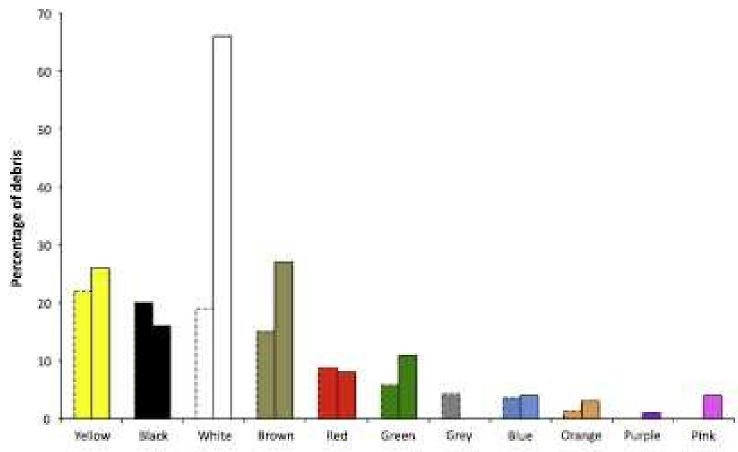

Fig. 3. The percentage of different colored anthropogenic debris found in various sections of the gastrointestinal system of short-tailed shearwaters in 2010 (dashed columns) and 2012 (solid columns).

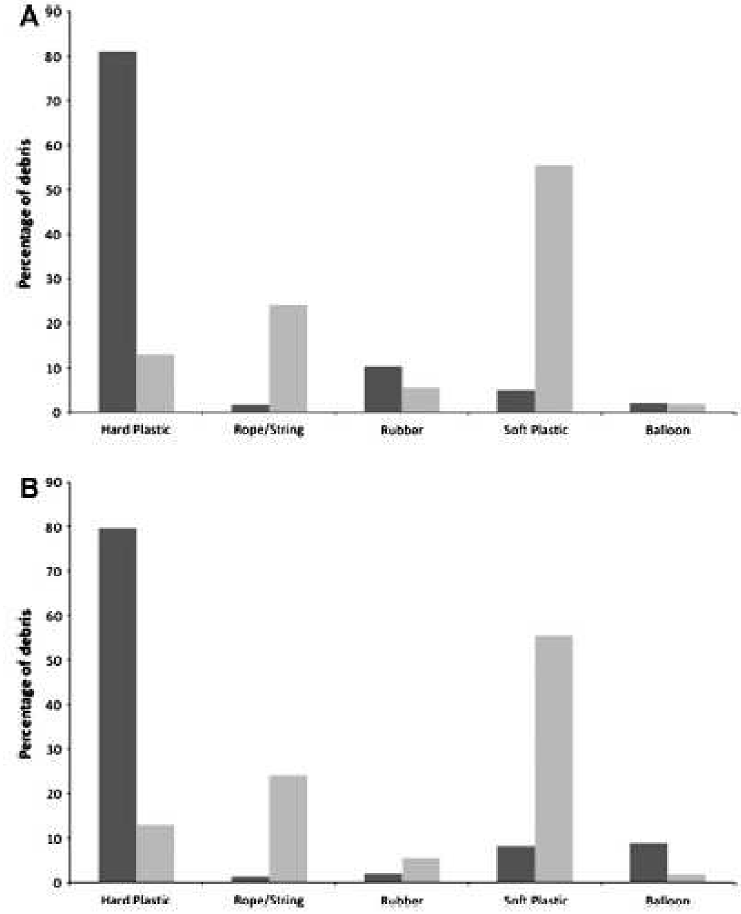

Fig. 4. Types of debris ingested by shearwaters (dark bars) compared to debris observed in surface trawls (light bars) in (A) 2010 and (B) 2012.

two age classed birds sampled in two different years reflects the different foraging grounds and the colours of plastics available in these regions. Carey (2011) found a prevalence of clear plastics ingested by juvenile short-tailed shearwaters, although grey, black and red plastics were also recorded. Other recent studies indicate that short- tailed shearwaters have a preference for light colors (Vlietstra and Parga, 2002), while Skira (1986) reported that short-tailed shearwaters in Tasmania selected bright colors such as yellow, green and red. In contrast, Day (1980) suggested that shearwaters show no color preference and that the ingestion of particular colors might reflect regional patterns or that starving birds might pick anything when they are in poor body condition.

Stranding events are common in shearwaters perhaps because they travel long distances between their breeding and feeding grounds. Such events also appear to occur more frequently in inexperienced immature birds (Work and Rameyer, 1999; Gould et al., 2000). This may simply be a function of weather during fledgling periods or may also be associated with naivety in searching for food. We did not find a significant relationship between the quantity of debris consumed and the body condition of the birds, a finding consistent with those of other authors who also did not detect clear evidence of an impact on the body condition of birds that had ingested plastics (Carey 2011; Rodriguez et al. 2012). In contrast, Connors and Smith (1982) found a negative correlation between the amount of plastic ingested and fat deposits in Red Phalaropes (*Phalaropus fulicarius*); however phalaropes are coastal feeding birds. Spear et al. (1995) found that heavier seabirds had higher plastic loads and he hypothesized that birds in better physical condition are more prone to ingesting plastics because they are more fit and they feed in different areas. However, among the birds that had consumed plastics, the number of particles were negatively correlated with body condition indicators (Spear et al., 1995). While ideally we would have ideally sampled adult and juvenile birds during the same year, stranding events are serendipitous and we did not have this opportunity.

Adult birds had a significantly higher BMI and were heavier than juveniles (mean mass of 360 and 291 g, respectively). We attributed this difference to age. Overall, however, birds sampled in this study were notably underweight: the average weight for an adult short-tailed shearwater should range from 480 to 800 g (Onley and Scofield, 2007). Given that beached washed birds were often wet and/or covered in sand, BMI results should be taken with caution. While studies often find that pre-fledging chicks weigh more than adults, it is worth noting that in both sampling years birds typically had no fat or only a trace of fat and likely would have been in poor health prior to stranding.

Our work suggests that birds select anthropogenic debris in different proportions to that which is available in the marine environment, with short-tailed shearwaters disproportionately consuming hard plastic, rubber and balloons (Fig. 4). Perhaps some of these items are more conspicuous in the marine environment or birds may be selecting them for some other currently unknown reason. It has been suggested that balloons may be mistaken for cephalopods, a common prey item of shearwaters (Weimerskirch and Cherel, 1998). Keeping consistent, detailed records of ingested debris type and comparing ingested debris to that available in the environment will increase our understanding of the role that choice plays in ingestion of anthropogenic debris.

This study adds to a growing body of literature quantifying the types and amounts of anthropogenic debris ingested by marine taxa. Importantly, we also compared types of debris ingested to that available in the marine environment which is a relevant addition that we hope other studies can also include. Seabirds have been shown to be good indicators of marine health (Furness and Camphuysen, 1997). Monitoring the occurrence of plastic in marine taxa and understanding where marine fauna are encountering and ingesting debris demonstrates the utility of using wildlife as indicators of environmental health.

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References

Auman, H.L., Ludwig, J.P., Giesy, J.P., Colborn, T., 1997. Plastic Ingestion by Laysan Albatross Chicks on Sand Island, Midway Atroll, in 1994 and 1995. Surry Beatty & Sons, Albatross Biology and Conservation.

Australian Bureau of Meteorology, 2012. Climate Data Online, accessed 25 May 2012, <http://www.bom.gov.au/climate/data/>.

Azzarello, M.V.V., Van Vleet, E.S., 1987. Marine birds and plastic pollution. Mar. Ecol. Prog. Ser. 37, 295–303.

Balazs, G., 1985. Impact of ocean debris on marine turtles: entanglement and ingestion. NOAA–Technical Manuscripts–NMFS–SWFC, pp. 387–429.

Cadée, G.C., 2002. Seabirds and floating plastic debris. Mar. Pollut. Bull. 44, 1294–1295.

Carey, M.J., 2011. Intergenerational transfer of plastic debris by short-tailed shearwaters (*Ardenna tenuirostris*). Emu 111, 229–234.

Colabuono, F.I., Barquete, V., Domingues, B.S., Montone, R.C., 2009. Plastic ingestion by Procellariiformes in Southern Brazil. Mar. Pollut. Bull. 58, 93–96.

Connors, P.G., Smith, K.G., 1982. Oceanic plastic particle pollution: suspected effect on fat deposition in red phalaropes. Mar. Pollut. Bull. 13, 18–20.

Day, R., 1980. The Occurrence and Characteristics of Plastic Pollution in Alaska's marine birds. Thesis (M.S.). University of Alaska.

Day, R.H., Wehle, D.H.S, Coleman, F.C., 1985. In: Ingestion of plastic pollutants by marine birds. Proceedings of the Workshop on the Fate and Impact of Marine Debris, Honolulu, Hawaii, pp. 344–386.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852.

Fry, M.D., Fefer, S.I., Sileo, L., 1987. Ingestion of plastic debris by Laysan Albatrosses and wedge-tailed shearwaters in the Hawaiian Islands. Mar. Pollut. Bull. 18, 339–343.

Furness, R.W., 1985. Ingestion of plastic particles by seabirds at Gough Island, South Atlantic Ocean. Environ. Pollut. A, Ecol. Biol. 38, 261–272.

Furness, R.W., Camphuysen, K., 1997. Seabirds as monitors of the marine environment. ICES J. Mar. Sci.: J. du Conseil 54, 726–737.

Gorman, M., 1993. Environmental hazards : marine pollution/Martha Gorman. ABC-CLIO, Santa Barbara, Calif.

Gould, P., Ostrom, P., Walker, W., 2000. Foods, trophic relationships, and migration of sooty and short-tailed shearwaters associated with squid and large-mesh driftnet fisheries in the North Pacific Ocean. Waterbirds 23, 165–186.

Gregory, M.R., 1978. Accumulation and distribution of virgin plastic granules on New Zealand beaches. New Zealand J. Mar. Freshwater Res. 12, 399–414.

Hart, N.S., 2004. Microspectrophotometry of visual pigments and oil droplets in a marine bird, the wedge-tailed shearwater *Puffinus pacificus*: topographic variations in photoreceptor spectral characteristics. J. Experiment. Biol., 1229–1240.

Hunt, G.L., Coyle, K.O., Hoffman, S., Decker, M.B., Flint, E.N., 1996. Foraging ecology of short-tailed shearwaters near the Pribilof Islands, Bering Sea. Mar. Ecol. Prog. Ser. 141, 1–11.

Hutton, I., Carlile, N., Priddel, D., 2008. Plastic ingestion by flesh-footed shearwaters, *Puffinus carneipes* and wedge-tailed shearwaters *Puffinus pacificus*. Papers Proc. Royal Soc Tasmania 142 (1).

Jones, K., Krebs, J., Whittingham, M., 2009. Heavier birds react faster to predators: individual differences in the detection of stalking and ambush predators. Behav. Ecol. Sociobiol. 63, 1319–1329.

Katzir, G., 1993. Visual Mechanisms of Prey Capture in Water Birds. MIT Press, Cambridge, Massachusetts, pp. 301–315.

Laist, D.W., 1987. Overview of the biological effects of lost and discarded plastic debris in the marine-environment. Mar. Pollut. Bull. 18, 319–326.

Lebreton, L.C.M., Greer, S.D., Borrero, J.C., 2012. Numerical modelling of floating debris in the world's oceans. Mar. Pollut. Bull. 64, 653–661.

Lovvorn, J.R., Baduini, C.L., Hunt, G.L., 2001. Modeling Underwater Visual and Filter Feeding by Planktivorous shearwaters in Unusual Sea Conditions. Ecological Society of America, Washington, DC, ETATS-UNIS, pp. 2342–2356.

Lythgoe, J.N., 1979. The Ecology of Vision. Oxford University Press, Oxford.

Martin, G.R., 1998. Eye structure and amphibious foraging in albatrosses. Proc. Roy. Soc. Lond. Ser. B: Biol. Sci. 265, 665–671.

Martin, G., Prince, P., 2001. Visual fields and foraging in procellariiform seabirds: sensory aspects of dietary segregation. Brain, Behav. Evol. 57, 33–38.

Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environ. Res. 108, 131–139.

Morgan, W.L., 1982. Feeding methods of the short-tailed shearwater *Puffinus tenuirostris*. Emu 82, 226–227.

Moser, M.L., Lee, D.S., 1992. A fourteen-year survey of plastic ingestion by western north atlantic seabirds. Colonial Waterbirds 15, 83–94.

Mrosovsky, N., Ryan, G.D., James, M.C., 2009. Leatherback turtles: the menace of plastic. Mar. Pollut. Bull. 58, 287–289.

Ogi, H., 1990. Ingestion of plastic particles by sooty and short-tailed shearwaters in the North Pacific. In: Shomura, R.S., Godfrey, M.L. (Eds.), Proceeding of the Second International Conference on Marine Debris, Honolulu, Hawaii, pp. 635–652.

Oksanen, J., et al., 2013. Vegan: Community Ecology Package. R Package version 2.0-8. <http://CRAN.R-project.org/package=vegan>.

Onley, D., Scofield, P., 2007. Albatrosses, Petrels and Shearwaters of the World. A&C Black Publishers Ltd., London.

Priddel, D., Carlile, N., Fullagar, P., Hutton, I., O'Neill, L., 2006. Decline in the distribution and abundance of flesh-footed shearwaters (*Puffinus carneipes*) on Lord Howe Island, Australia. Biol. Conserv. 128, 412–424.

Robards, M.D.P., John, F., Wohl, Kenton.D., 1995. Increasing frequency of plastic particles ingested by seabirds in the subarctic North Pacific. Mar. Pollut. Bull. 30, 151–157.

Rodriguez, A., Rodriguez, B., Carrasco, M., 2012. High prevalence of parental delivery of plastic debris in cory's shearwaters (*Calonectris diomedea*). Mar. Pollut. Bull. 64, 2219–2223.

Ryan, P.G., 2008. Seabirds indicate changes in the composition of plastic litter in the Atlantic and south-western Indian oceans. Mar. Pollut. Bull. 56, 1406–1409.

Ryan, P.C., AD; Gardner, B.D., 1988. Plastic ingestion and PCBs in seabirds: is there a relationship? Mar. Pollut. Bull. 19, 174–176.

Schuyler, Q., Townsend, K., Wilcox, C., Hardesty, B.D., 2012. To eat or not to eat? debris selectivity by marine turtles. PLoS ONE 7 (7), e40884. http://dx.doi.org/10.1371/journal.pone.0040884.

Schuyler, Q., Hardesty, B., Wilcox, C., Townsend, K., 2013. Global analysis of anthropogenic debris ingestion by sea turtles. Conserv. Biol. 1–11. http://dx.doi.org/10.1111/cobi.12126.

Sileo, P.R.S.L., 1993. The effects of ingested plastic on growth and survival of albatross chicks. In: Vernner, K., Briggs, K.T., Morgan, K.H., Siegal-Causey, D. (Eds.), The Status, Ecology and Conservation of Marine Birds of the North Pacific. Canadian Wildlife Service. Special Publication, Ottawa, pp. 212–217.

Skira, I.J., 1986. Food of the short-tailed shearwater, *Puffinus-Tenuirostris*, in Tasmania. Wildlife Res. 13, 481–488.

Spear, L.B., Ainley, D.G., Ribic, C.A., 1995. Incidence of plastic in seabirds from the tropical pacific, 1984–1991: relation with distribution of species, sex, age, season, year and body weight. Mar. Environ. Res. 40, 123–146.

van Franeker, J.A., 2004. Save the north sea Fulmar-Litter-EcoQO manual: collection and dissection procedures. Wageningen, Alterra.

van Franeker, J.A., Blaize, C., Danielsen, J., Fairclough, K., Gollan, J., Guse, N., Hansen, P.L., Heubeck, M., Jensen, J.K., Le Guillou, G., Olsen, B., Olsen, K.O., Pedersen, J., Stienen, E.W.M., Turner, D.M., 2011. Monitoring plastic ingestion by the northern fulmar *Fulmarus glacialis* in the north sea. Environ. Pollut. 159, 2609–2615.

Vlietstra, L.S., Parga, J.A., 2002. Long-term changes in the type, but not amount, of ingested plastic particles in short-tailed shearwaters in the southeastern bering sea. Mar. Pollut. Bull. 44, 945–955.

Weimerskirch, H., Cherel, Y., 1998. Feeding ecology of short-tailed shearwaters: breeding in Tasmania and foraging in the Antarctic? Mar. Ecol. Prog. Ser. 167, 261–274.

Work, T., Rameyer, R., 1999. Mass stranding of wedge-tailed shearwater chicks in Hawaii. J Wildlife Dis. 35, 487–495.

Appendix N. CSIRO information flyer – Understanding the effects of marine debris on wildlife.

WEALTH FROM OCEANS
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CSIRO

Understanding the effects of marine debris on wildlife

CSIRO scientists are working with colleagues at the University of Queensland, the University of Tasmania and the University of Western Australia to provide knowledge that can underpin management decisions relating to the effects of marine debris on wildlife.

They are involved in a survey and education project with Earthwatch Australia; research on abandoned fishing nets with GhostNets Australia; and studies of marine turtles with the University of Queensland. The work addresses issues identified in Australia's National Threat Abatement Plan.

GhostNets

Research in association with GhostNets Australia has shown that combining models of marine debris with species occurrence data could pinpoint areas where prevention and clean-ups could make a difference to biodiversity. The work has also highlighted cost-effective areas for surveillance and/or interdiction of derelict fishing gear.

A model simulation of the likely paths ghostnets take to get to their landing spots on beaches in the Gulf of Carpentaria found that entanglement risk for turtles is concentrated in an area along the eastern margin of the Gulf and in a wide section in the southwest extending up the west coast.

Marine turtles

Surveys of marine debris composition and ingestion by 115 sea turtles stranded in Queensland in 2006–2011 highlighted increasing amounts of plastic in the marine environment and provided evidence for the disproportionate ingestion of balloons by marine turtles.

The study found differences between ingestion in the turtles' benthic and pelagic phases, and that most ingested items were plastic and were positively buoyant.

TeachWild

TeachWild is a national three-year marine debris research and education program developed by Earthwatch Australia in partnership with CSIRO and funding Partner Shell to understand the extent of the global issue of marine debris and its impacts on Australian wildlife.

The program engages Australian teachers and students, and employees of Earthwatch, Shell and CSIRO in research activities including ocean trawls for debris, beach surveys, oceanography experiments, marine observations, and seabird, turtle and marine mammal research.

So far, scientists have engaged with more than 2700 students from some 45 schools Australia-wide, conducting 29 school beach surveys.

They have conducted ocean surface trawls from 78 sites around the continent collecting 235 surface trawl samples and surveyed 161 coastal sites from Cape Tribulation clockwise around Australia to Darwin.

Five satellite tags on green sea turtles to monitor their movement, and breeding site surveys have been completed for more than 15 seabird species.

National Marine Debris Database

Data from citizen volunteers and scientists are entered into the National Marine Debris Database online via the *Atlas of Living Australia*. The database is intended to assist the formulation of waste management policies and practices by state governments and coastal councils, and to contribute to a global marine debris database.

Working together

Groups such as Tangaroa Blue, The Surfrider Foundation, Clean Up Australia other coast care groups and volunteer organisations conduct beach clean-ups around the country. Efforts are made to coordinate with these activities and complement their work where appropriate.

Surveys, data analyses, modelling and visualisation

CSIRO provides research expertise in survey design and data collection, oceanographic and ecological modelling, and statistical analysis, as well as supporting data handling, analysis and visualisation. The activities include:

- collecting consistent coastal and offshore data relating to the sources, distribution, and ultimate fate of marine debris,
- collecting data on the distribution of vulnerable wildlife;
- investigating factors affecting the ingestion and entanglement of debris by wildlife;
- using oceanographic models to predict the distribution of debris in the ocean, and compare this with wildlife distributions to identify key areas and species of concern;
- identifying factors (such as ocean currents, population densities and waste management policies) that influence the volume and distribution of marine debris; and
- identifying low-cost, long-term monitoring sites for marine rubbish and its impacts on wildlife; and
- providing analyses to help governments and the public tackle the problem of marine debris.

Publications

Butler JRA, Gunn R, Berry HL, Wagey GA, Hardesty BD and Wilcox, CV (2013) Value chain analysis of ghost nets in the Arafura Sea: identifying trans-boundary Stakeholders, intervention points and livelihood trade-offs. Accepted, *Journal of Environmental Management*.

Schuyler Q, Hardesty BD, Wilcox CV and Townsend K (2013) Are turtles eating more debris? A global analysis since 1900. Accepted, *Conservation Biology*.

Wilcox CV, Hardest BD, Sharples R, Griffin DA, Lawson TJ and Gunn R (2013) Ghost net impacts on globally threatened turtles, a spatial risk analysis for northern Australia. *Conservation Letters*, DOI: 10.1111/conl.12001.

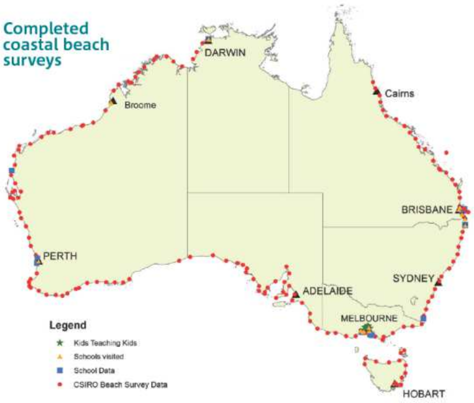
Schuyler Q, Townsend K, Hardesty BD and Wilcox CV (2012) To eat or not to eat: debris selectivity by marine turtles. *PLOS One* 7(7): e40884. DOI:10.1371/journal.pone.0040884.

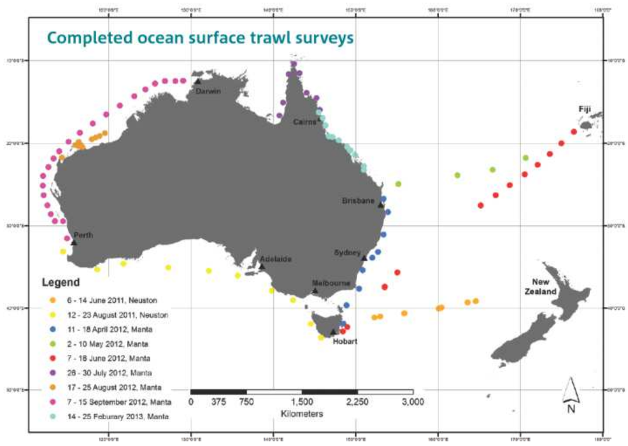
Gunn R, Hardesty BD and Butler J (2010) Tackling 'ghost nets': Local solutions to a global issue in northern Australia. *Ecological Management and Restoration*, 11: 88–98.

Hardesty BD and Wilcox CV (2013) Ghostnets fish on: marine rubbish threatens northern Australian turtles. *The Conversation*. 31 January 2013.

Hardesty BD and Wilcox CV (2011) Marine debris: biodiversity impacts and potential solutions. *The Conversation*. 23 August 2011.

Hardesty BD and Wilcox CV (2011) *Understanding the types, sources and at-sea distribution of marine debris in Australian Waters*. Final report to the Department of Sustainability, Environment, Water, Health, Population and Communities.





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School enquires: teachwild@earthwatch.org.au

WEBLINKS

Teachwild: teachwild.org.au/

Marine Debris Database on *Atlas of Living Australia*: teachwild.ala.org.au/bdrs-core/portal/17/home.htm

Citizen science training: www.ala.org.au/blogs-news/fielddata-software-citizen-science-training-course/

facebook: www.facebook.com/pages/Marine-Debris-Australia/233284236732809

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Appendix O. CSIRO information flyer – Tackling Marine Debris

WEALTH FROM OCEANS
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CSIRO

Tackling marine debris

CSIRO scientists are working to provide knowledge that can underpin management decisions relating to marine debris and its effects on wildlife.

They are involved in a survey and education project with Earthwatch Australia; research on abandoned fishing nets with GhostNets Australia; and studies of marine turtles with the University of Queensland. The work addresses issues identified in Australia's National Threat Abatement Plan.

GhostNets

Research in association with GhostNets Australia has shown that combining models of marine debris with species occurrence data could pinpoint areas where prevention and clean-ups could make a difference to biodiversity. The work has also highlighted cost-effective areas for surveillance and/or interdiction of derelict fishing gear.

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The study found differences between ingestion in the turtles' benthic and pelagic phases, and that most ingested items were plastic and were positively buoyant.

TeachWild

So far, scientists have engaged with more than 3000 students from 50 schools Australia-wide, completing 35 school beach surveys. They have conducted ocean surface trawls from 78 sites around the continent collecting 235 surface trawl samples and surveyed some 200 coastal sites from Cape Tribulation clockwise around Australia to Darwin.

Distant waste

Cox Bight and New River Lagoon on Tasmania's south-western coast are hundreds of kilometres from human settlements.

From the air they appear as pristine sands amid wilderness greens and Southern Ocean blues.

Up close it's a different story. Despite their isolation, the beaches here are littered with buoys, bottles, nets, boxes, gumboots, packing straps and ropes.

CSIRO scientists took a float plane from Hobart to five of Tasmania's most remote beaches in May 2013 during the final stage of the national marine debris survey. They landed on flat water near the coast, and hiked to the survey sites.

Other far-flung locations, such as Cape Queen Elizabeth on Bruny Island, were reached after hours of driving and walking.

This was a milestone in a marathon journey: a continent away from the first survey at Cape Tribulation, Queensland, 18 months earlier.

Some 200 beaches were surveyed; not one was rubbish-free.

Giblin River, Tasmania

Publications

Butler JRA, Gunn R, Berry HL, Wagey GA, Hardesty BD and Wilcox, CV (2013) Value chain analysis of ghost nets in the Arafura Sea: identifying trans-boundary Stakeholders, intervention points and livelihood trade-offs. Accepted, *Journal of Environmental Management.*

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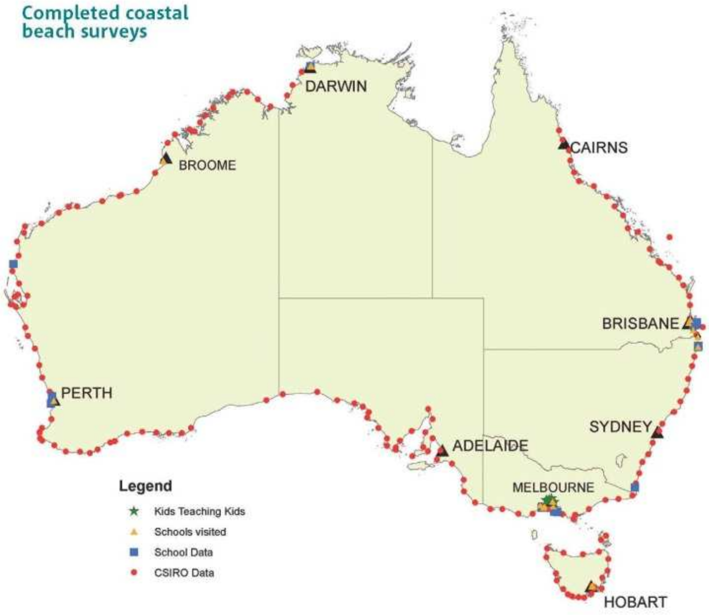
National Marine Debris Database

Data from citizen volunteers and scientists are entered online into the National Marine Debris Database. The database is intended to assist the formulation of waste management policies and practices by state governments and coastal councils, and to contribute to a global database of marine debris.

Working together

Groups such as Tangaroa Blue, The Surfrider Foundation, Clean Up Australia other coast care groups and volunteer organisations conduct beach clean-ups around the country. Efforts are made to coordinate with these activities and complement their work where appropriate.

Completed coastal beach surveys



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Citizen science training: www.ala.org.au/blogs-news/fielddata-software-citizen-science-training-course/
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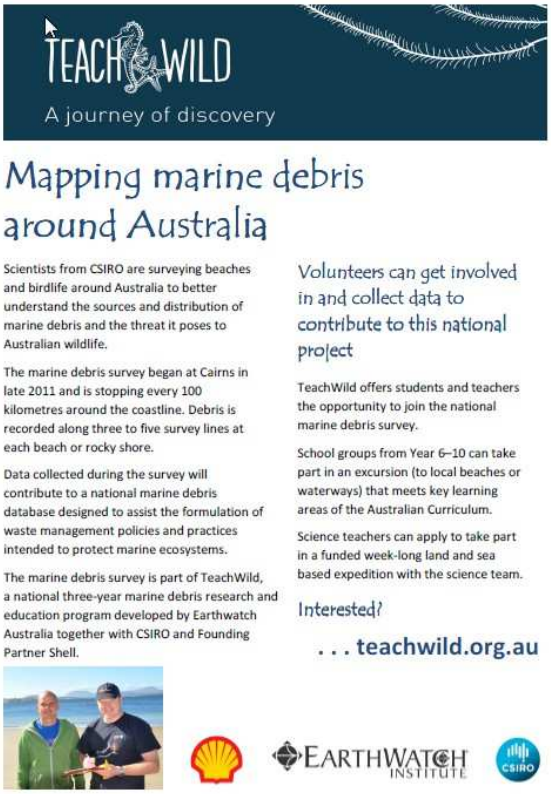
Appendix P. TeachWild handout developed by CSIRO to share with interested citizens encountered during coastal debris surveys.



TEACH WILD

A journey of discovery

Mapping marine debris around Australia

Scientists from CSIRO are surveying beaches and birdlife around Australia to better understand the sources and distribution of marine debris and the threat it poses to Australian wildlife.

The marine debris survey began at Cairns in late 2011 and is stopping every 100 kilometres around the coastline. Debris is recorded along three to five survey lines at each beach or rocky shore.

Data collected during the survey will contribute to a national marine debris database designed to assist the formulation of waste management policies and practices intended to protect marine ecosystems.

The marine debris survey is part of TeachWild, a national three-year marine debris research and education program developed by Earthwatch Australia together with CSIRO and Founding Partner Shell.

Volunteers can get involved in and collect data to contribute to this national project

TeachWild offers students and teachers the opportunity to join the national marine debris survey.

School groups from Year 6–10 can take part in an excursion (to local beaches or waterways) that meets key learning areas of the Australian Curriculum.

Science teachers can apply to take part in a funded week-long land and sea based expedition with the science team.

Interested?

. . . teachwild.org.au

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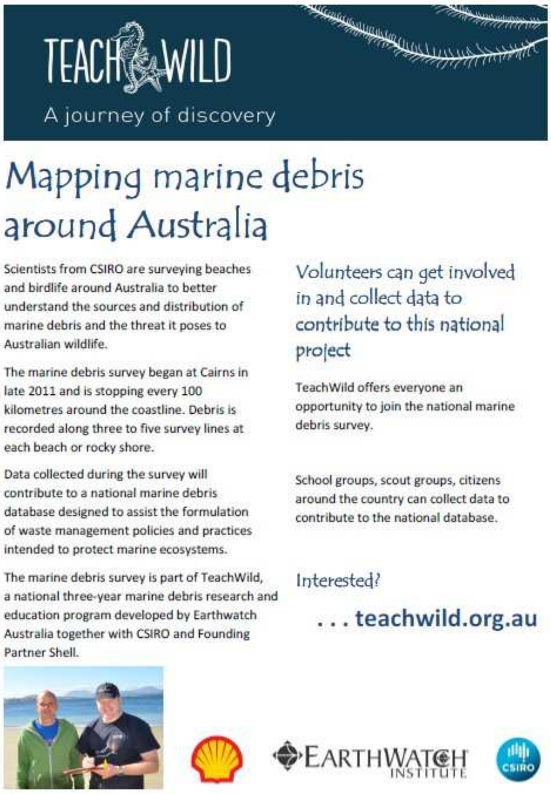

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Volunteers can get involved in and collect data to contribute to this national project

TeachWild offers everyone an opportunity to join the national marine debris survey.

School groups, scout groups, citizens around the country can collect data to contribute to the national database.

Interested?

. . . teachwild.org.au

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Appendix Q. CSIRO marine debris project selected for prime minister's science update.

PRIME MINISTER'S SCIENCE UPDATE - DRAFT 2013

Marine biodiversity – CSIRO targets abandoned fishing gear to save threatened turtles

CSIRO research is identifying hot spots for abandoned fishing gear, estimating the impact on biodiversity, particularly threatened marine turtles, and providing information needed to intervene.

Approximately 640,000 tonnes of fishing gear is abandoned worldwide each year. Abandoned fish nets, known as ghost nets, are carried by the currents and tides before washing ashore, entangling seabirds, marine mammals and sea turtles throughout the oceans for many years and causing significant loss of biodiversity.

Ghost fishing is harmful to all marine species including threatened species, commercially viable species and undersized fish.

Australia is home to six of the world's seven threatened species of marine turtle. During a recent Gulf of Carpentaria beach cleanup 80 per cent of the species recorded in nets were marine turtles.

Research identifiying ghost net hot spots

In collaboration with GhostNets Australia and Indigenous rangers, CSIRO researchers have identified hot spots where abandoned fish nets are having an impact.

Using ocean current models and data collected by Indigenous rangers on ghost nets being washed ashore, researchers are able to simulate the paths ghost nets take to get to beaches in the Gulf of Carpentaria, and estimate the impact on biodiversity, particularly threatened marine turtles.

Ghost nets on Australia's shores come mainly from Indonesia, Japan, Korea, Taiwan and Thailand.

> Ninety per cent of marine debris is of a fishing nature and originates from all parts of South East Asia
Photo: Alistair Dermer

A global biodiversity problem being targeted

With the knowledge gained from this research, the ocean paths ghost nets take can be targeted for prevention, intercepting the ghost netting before it reaches high density turtle populations.

This research is also helping to understand the global threat from marine debris and making predictions that can guide regulation, enforcement and conservation action.

Identifying the global hot spots where marine debris meets commercially valuable or threatened marine species enables researchers to understand where prevention and clean-ups could really make a difference.

Further Information
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Appendix R. CSIRO participation in international marine debris meeting in South Africa highlighted. CSIRO team member led field trip with >40 participants to demonstrate methodology and carry out beach surveys and coastal clean up efforts as part of international delegate.

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- Numerical modelling used to understand violent fluid
- CSIR data acquisition and communication protocol for mines ready for uptake

Natural Environment

CSIR participates in first African Marine Debris Summit

The first African Marine Debris Summit was held from 6 to 8 June 2013 at the South African National Biodiversity Institute (SANBI), Cape Town. Attended by delegates from across the African continent and as a far afield as Australia, the Summit coincided with World Environment Day on 5 June, and World Oceans Day on 8 June. The theme of the summit was 'African Lessons to Inspire Local Actions'. Dr Linda Godfrey, CSIR principal scientist, was invited to present a paper on the work of the CSIR's pollution and waste group, focussing on job creation opportunities in the South African waste sector. Her paper, *Resource-intensive local job creation opportunities in waste cleansing and collection*, explored opportunities for local, community-based employment in the avoidance and collection of marine debris along the South African coastline.

Undertaking a marine debris survey under the guidance of Tonya van der Velde, CSIRO Australia

Organised by the United Nations Environment Programme, Plastics SA, the Department of Environmental Affairs, and SANBI, the summit was aimed at bringing together marine debris researchers, natural resource managers, policy-makers, industry representatives, and the non-governmental community; to highlight research advances, allow sharing of strategies and best practices to assess, reduce, and prevent the impacts of marine debris, and provide an opportunity for the development of specific bilateral or multi-country strategies.

The final day of the Summit, on World Ocean Day, included a field training session with Tonya van der Velde of the CSIRO Australia, on the methodology adopted in the national Australian Marine Debris Survey (for more information see http://www.csiro.au/science/marine-debris). The summit was rounded off with a beach cleanup along the Milnerton Beach. "It's very sad to see the amount and types of waste washing up along our coastline, which we know is directly impacting marine life," says Godfrey. "When you see plastic straws, ear buds, bottle tops, and shopping bags (amongst other things) lying on the beach and you see the shocking photos of what these objects do to our birds, penguins, turtles, and seals, it's really a wake-up call to think about what we do with our rubbish."

The group was joined by Ray Chaplin, adventurer, who is currently undertaking a 2 300 km riverboarding source-to-sea expedition along the Orange River, to raise awareness of the pollution within and along our rivers (for more information see http://raychaplin.com/orangeriver).

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