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From People to Reefs: Marine Debris and Plastic Pollution in North Queensland

PhD thesis submitted by:

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Publications associated with this thesis

Bauer-Civiello A, Loder J, Hamann M. Using citizen science data to assess the difference in marine debris loads on reefs in Queensland, Australia. *Marine Pollution Bulletin.* 2018; 135: 458-465

Bauer-Civiello A, Critchell K, Hoogenboom M, Hamann M. Input of plastic debris in an urban tropical river system. *Marine Pollution Bulletin*. 2019. 144: 235-242.

Bauer-Civiello A, Hamann M, Benham C. Understanding Public Perception and Awareness of Marine Plastic Pollution in Relation to Littering: A case study in the Great Barrier Reef *in prep*

Bauer-Civiello A, Hamann M, Hoogenboom M. Microplastic loads in an Australian tropical river system *in prep*

Bauer-Civiello A, Paley A, Hoogenboom M. Assessing prospective indicator species of plastic contamination for nearshore coral reefs *in prep*

Other Publications

Critchell K, **Bauer-Civiello A,** Benham C, Berry K, Eagle L, Hamann M, Hussey K, Ridgway T. 2019. Chapter 34-Plastic pollution in the coastal environment: Current Challenges and Future Solutions in: Wolanski E, Day J, Elliot M, and Ramachandran R (Eds.), Coasts and Estuaries. Elsevier, pp. 595-609.

Done T, Roelsema C, Harvey A, Schuller L, Hill J, Schläppy ML, Lea A, **Bauer-Civiello A,** Loder J. 2017. Reliability and utility of citizen science reef monitoring data collected by Reef Check Australia, 2002-2015. *Marine Pollution Bulletin*. 2017. 117: 148-155.

Conference presentations

Bauer-Civiello A, Critchell K, Hoogenboom M, Hamann M. 2018. 'Plastic in a North Queensland River: Quantifying plastic sources in the Great Barrier Reef.' *6th International Marine Debris Conference* San Diego, USA.

Abstract

Marine debris, also known as marine litter, is defined as any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment. Mostly consisting of plastic, marine debris is polluting global oceans at an increasing rate. Plastic items of all shapes and sizes can have detrimental impacts on marine fauna, and increases the stress on marine organisms. Beach clean-ups are one way to reduce plastic pollution but such actions only remove a small fraction of the debris currently present in the ocean, and they will need to occur frequently and indefinitely with existing levels and the current rates of use and production of plastics in society. Instead, identifying preventative techniques for reducing the inputs of debris in the environment or stopping it before it reaches ocean is the key to successfully reducing marine debris pollution in the long-term. Doing this will require multidisciplinary research, including understanding human behaviours, monitoring plastic loads from specific sources, and implementing a wide range of infrastructure and policy to create change.

My overall thesis aim is to provide meaningful insights into plastic pollution management using inter-disciplinary research on marine debris abundance, education and source reduction in Queensland, Australia. To do this, my thesis is split into four research themes. Theme 1 is to understand the distribution patterns of marine debris on Queensland reefs to narrow down potential sources (Chapter 2). Theme 2 is to identify exactly how plastic is entering the aquatic environment (Chapter 3 and 4). Theme 3 is to identify ways to monitor macroplastics (>5mm in size) and microplastics (plastics <5mm in size) to identify impacts, create baselines, and monitor change (Chapter 3, 4 and 5). Lastly, theme 4 is to understand community awareness and concern about marine debris to reduce land based sources, such as that from littering (Chapter 6).

In my first data chapter, I use citizen science data to determine the distribution of subtidal marine debris on reefs in Queensland coastal waters. Using this dataset, I identified the average debris loads collected during reef-health impact surveys completed since 2001. Results showed that debris is present in the highest abundances on the reefs near urban communities, particularly in South East Queensland. Debris loads near the Gold Coast were the highest with a maximum of 27 items per surveys ($400m^2$). There was a wide range of items recorded on surveys, however fishing and

boating related debris were among the highest observed. This suggests that debris effecting subtidal reefs are more likely to be sourced by fishing and boating, and therefore, targeted messaging and source-reduction plans, specifically for recreational fishers and boaters are needed to reduce debris on the reef itself.

In my second data chapter, I monitored debris loads adjacent to and outside stormwater effluents after rainfall events to determine how much plastic was originating from urban sources, using Ross River in Townsville, Queensland as a case study. No seasonal differences in debris abundance were observed, however, I found that even during below-average rainfall years, there was a relatively high and constant flow of debris items entering the river system year-long. In addition, I found that the likely origin of debris items was site dependent. For example, in one of the monitored sites the proportion of the most common plastic debris items in the river matched those found in the nearby park. Whereas, in the other site, the proportion of debris items varied from the types of items found in nearby parks, suggesting that debris may be traveling longer distances via storm drains to enter the river system. These results suggest that the placement of infrastructure, such as drain socks and river booms may be more helpful in some sites, but not others. As a result, this data chapter provides insight into the pathways in how debris can enter aquatic systems, which ultimately flush into the ocean. Most importantly, my chapter suggest relatively small cities, such as Townsville, can contribute to plastic loads in the ocean.

In my third data chapter, I monitored microplastic loads (plastics <5mm) within Ross River, to identify potential sources in local aquatic systems. Sediment and water samples were collected throughout the freshwater section of the river, within the estuary, and within Cleveland Bay both before and after the wet season. Similar to my 2nd data chapter, I did not find any seasonal difference in plastic loads within any section of the river. However, the abundance of plastics within the freshwater sediments was high, with highest concentrations matching levels found in rivers and lakes in Europe. As a result, this data chapter suggests that even in low rainfall years, the Ross River retains a high abundance of plastics in the sediments. Since the rainfall that occurred did not show measurable differences of microplastic abundances within the bay after the wet season, I hypothesise that after heavy rainfall (in excess of the 687 mm that occurred during the sampling period) a proportion of these plastics will be flushed to into sea. In addition, this chapter identifies that the majority of the plastic particles were fragments from degraded larger plastic items, indicating that the reduction of macro debris in the river long term would likely reduce the amount of microplastics in the system.

In my fourth data chapter, I identify ways to monitor microplastic pollution on reef systems by using bioindicators. Currently, there is little information on the degree to which microplastics interact with benthic organisms. Therefore, in this Chapter, I assess new ways to monitor plastic loads by performing experiments using two filter feeders, a sponge, *Carteriospongia foliascens* and a soft coral species, *Lobophytum sp.* In this experiment, I fed two different concentrations of fluorescent microspheres to both species for three days, and determined how much plastic was ingested, how long it was retained, and whether or not the organisms can detect differences in concentration loads. In addition, I observed how plastics interact with the organism, finding that much of the microspheres adhere to the surface of the organism, which is then removed via mucus production. I found that ingestion rates for both species were low, with neither able to detect differences in concentration loads. Sponge species, *C. foliascens* ingestion rates were higher (>1% of the total exposed particles), and able to retain the microspheres up to 7 days. Alternatively, the coral species, *Lobophytum sp*. was low (less than 1% of the total exposed particles), but retained the small amount of ingested particles for the full 14 day experiment. Interestingly, differences in plastic concentrations found on the surface of the organism shed by mucus was detected. Therefore, to monitor microplastic loads on reef systems, it is possible to collect mucus off of benthic species to monitor plastic loads. This has broad implications on potential non-invasive monitoring techniques.

Lastly, my fifth data chapter uses social surveys to understand the community knowledge and perception of marine debris and its sources, again using Townsville, Queensland as a case study. Previous research has shown that the increased awareness, knowledge, concern, and feelings of responsibility for environmental issues have been found to directly link to the likelihood for people to show pro-environmental behaviour such as responsible plastic use and disposal. Therefore, these themes were used to provide information on the current understanding of marine debris and its sources from Townsville residents. Questionnaires distributed online and in-person identified that approximately 70% of Townsville residents had a relatively high awareness of marine debris, and its sources. In addition, a large portion of participants were able to correctly identify that litter occurring inland, such as that from storm drains and within the river system can contribute to marine debris. My results also showed that over 70% of residents believed that individuals had the most responsibility regarding reducing the inputs of marine debris into the environment, and I found a strong connection between people and the Great Barrier Reef. Therefore, in this chapter, I suggest that future messaging to focus on the individual responsibility, pride, and identity to reduce litter in the urban environment, and ultimately, reduce debris from arriving to the ocean.

Overall, in this thesis, I use interdisciplinary research to make a novel contribution to science which can be directly useful to local managing agencies in Australia. For the first time, I collected data of plastic abundances on the Great Barrier Reef, and a local river system, creating baselines for future research, and provided new insights on the possible pathways in which plastic enters the aquatic environment. I identified ways to improve local management, by providing advice on the placement of infrastructure, and identifying the current views and perspectives of marine debris and littering in Townsville.

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I could not have finished this PhD without my strong network of family, friends, and peers, and I cannot in words describe my level of gratitude for the people who have stood by my side for this entire process. I have had nothing but love, support, and encouragement and as a result, this has been one of the best experiences of my life.

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Statement of Contribution of Others

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Publication plan with contributions of co-authors

Chapter Number	Publication details	Extent of the intellectual input of each author, including the candidate
2	Bauer-Civiello A, Loder J, Hamann M. Using citizen science data to assess the difference in marine debris loads on reefs in Queensland, Australia. *Marine Pollution Bulletin.* 2018; 135: 458-465	I developed the research questions. Reef Check Australia volunteers collected the data. I performed the data analysis. I interpreted the data, with guidance from Hamann. I wrote the paper with input and editorial from Hamann and Loder. I developed the figures and tables with GIS support from Kay Critchell
3	Bauer-Civiello A, Critchell K, Hoogenboom M, Hamann M. Input of plastic debris in an urban tropical river system. *Marine Pollution Bulletin*. 2019. 144: 235-242.	I developed the research questions with help from Critchell and Hamann. Critchell, Hamann, and I collected the data. I performed the data analysis. I interpreted the data with guidance from Critchell, Hoogenboom and Hamann. I wrote the paper with input and editorial from Hamann and Critchell. I developed the figures and tables, with GIS support from Kay Critchell.
4	Bauer-Civiello A, Hamann M, Hoogenboom M. Microplastic loads in an Australian tropical river system *in prep*	I developed the research questions. I collected the data and performed all laboratory analysis. I performed the data analysis. I interpreted the data with guidance from Hoogenboom and Hamann. I wrote the paper with editorial from Hamann and Hoogenboom. I developed the figures and tables with GIS support from Kay Critchell
5	Bauer-Civiello A, Paley A, Hoogenboom M. Assessing prospective indicator species of plastic contamination for nearshore coral reefs *in prep*	I developed the research questions. I performed all the field and experiments. I developed laboratory methods with aid from Paley and Hoogenboom. I collected data with aid from paid research staff. I performed all the data analysis, conducted all data interpretation with guidance from Hoogenboom and wrote the paper with input of editorial from Hoogenboom, Paley and Saskia Jurriaans.
6	Bauer-Civiello A, Hamann M, Benham C. Understanding Public Perception and Awareness of Marine Plastic Pollution in Relation to Littering: A case study in the Great Barrier Reef *in prep*	I developed the research questions. I created the questionnaires with help from Benham and Hamann. I organised the human ethics research application. I conducted the surveys and field work with aid from paid research staff. I performed the data analysis with guidance from Benham. I interpreted the results with guidance from Benham. I wrote the paper with input and editorial from Benham and Hamann. I created all figures and tables

Permit approvals and ethics statement

All necessary permits and approvals were used to conduct this work: Fieldwork for organisms collected in data chapter 5 was undertaken under the Great Barrier Reef Marine Park Authority permit number G17/29598.1.

Fieldwork for plankton tows for Cleveland Bay were undertaken under the Great Barrier Reef Marine Park permit number G13/35909.1

The social surveys were carried out in strict accordance with *JCU Human Ethics Committee of James Cook University* approval number H7126.

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Chapter 1
General Introduction

Marine debris, also known as marine litter, is defined as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment" (UN Environment Program, 2009). Marine debris can consist of a wide range of materials including plastic, glass, metal, paper and wood, and is considered to be a prominent, global threat to the marine environment. The use and increased reliance of plastics over the last 50 years has caused plastic-based materials to dominate the majority of marine debris items, and which now up 95% of all marine debris (Ryan, 2015). Consequently, research on plastic pollution has gained momentum now recognized as a pollutant globally.

Marine debris is ubiquitous, occurring in some of the most remote areas of the world (Avio et al., 2017; Gregory, 1999). Persistent items, such as plastics, can be moved large distances, transported by waves, wind and currents and then accumulating in ocean gyres (known as 'garbage patches'), ocean trenches, and uninhabited islands at increasing rates (Lavers and Bond, 2017; Lebreton et al., 2018; Taylor et al., 2016). For example, plastic debris were found to accumulate up to 26.8 new items/m per day on a remote, uninhabited, Pacific island, with an overall density of 671.6 items/m^2 of debris/plastic occurring on the beach (Lavers and Bond, 2017). It is difficult to stem the flow of the debris, as it crosses geographic boundaries and multiple jurisdictions.

Further complicating the difficulties of identifying the source of debris for plastics found in marine environments is that they are often fragmented and comprise numerous material types as well as different sizes and shapes. Plastics items greater than 5mm in size are generally categorised as 'macro plastics' (National Oceanic and Atmospheric Administration (NOAA)). These typically consist of larger fragments, or whole, identifiable, items, such as water bottles, bags, and rope. Due to their synthetic composition and manufacturing process, plastic items remain in the marine environment for unknown periods of time (Moore, 2008). Instead, plastics break into smaller pieces and are termed 'microplastics' when less than 5 mm in size (Vandermeersch et al., 2015). This breakdown occurs when plastic items become increasingly brittle in ultraviolet (UV) radiation, or are damaged by mechanical forces such as waves on beaches (Andrady, 2011). Microplastics can also be manufactured at small sizes, such as resins pellets or microbeads for cosmetic products, facewashes, and toothpaste. Microbeads can enter natural systems because they are small enough to fit through filtering membranes in water treatment plants and thus exit into aquatic systems via sewage effluents (Hartline et al., 2016; Rochman et al., 2015). Synthetic fibres can also be categorised as microplastics, and can be produced a wide range of materials, such as shedding from synthetic clothing in the washing machine or breaking off from ropes, fishing nets, and moorings (Gago et al. 2018).The variety of plastic types, sources, and sizes makes it difficult to quantify plastics in the marine environment, and pinpointing exactly where the plastic originates. As a result, it is difficult to determine the appropriate management strategies to reduce plastic waste before it reaches marine environment.

1.1 Marine debris and plastic pollution as a threat to wildlife

Marine debris and plastic pollution can inflict harm on individuals, species, and habitats. To date over 693 marine species, ranging from plankton to whales, have been recorded to be harmed from plastic alone (Cole and Galloway, 2015; Gall and Thompson, 2015; Gregory, 2009). Harm to species and individuals can take many forms. Derelict fishing and boating gear, for example, has been recorded in the marine environment for hundreds of years by maritime shipping and boating (National Ocean Service, 2019). Discarded (intentionally or not intentionally) rope, nets and fishing line can entangle animals, causing individuals to drown (Sheavly and Register, 2007; Richardson et al. 2019). Furthermore, discarded and lost fishing gear, such as lobster traps, can continue to ghost-fish, unnecessarily entrapping organisms within, eventually leading to starvation or drowning (Matsuoka et al., 2005). Other fishing debris, such as fishing line, can entangle animals or wrap around benthic organisms and substrate (Bauer et al., 2008). In tropical reef systems, fishing line can cause abrasions to coral tissue, increasing the risk of infection from disease (Lamb et al., 2018). Other boating gear, such as derelict anchors, chains, lead sinkers, or other sinking materials discarded from boats and ships have been documented for more than 40 years to crush and damage benthic fauna, which can influence habitat and ecosystems (Davis, 1977).

An increasing number of studies have investigated the potential harm from the ingestion of plastic waste (Ryan, 2015). Plastics pieces of all sizes can become accidentally ingested and trapped in the gut of marine animals, which can lead to harm or starvation (Wright et al., 2013). Soft plastic items such a plastic bags and balloons have been found to be some of the most likely items to be ingested and cause death of marine animals (Roman et al., 2019). If ingested plastics do not cause immediate harm, they can also cause external or internal abrasions, which can have longer term impacts (Gall and Thompson, 2015). For example, microplastics have been found to decrease fecundity in copepods (Cole et al., 2015), and potentially alter hormonal systems in fish (Rochman et al., 2014).

Lastly, plastics or other floating debris items traveling in ocean currents are capable of transporting invasive species, bacteria, disease, and toxins between ecosystems (Carlton 1996; Lobelle and Cunliffe, 201; Rochman et al., 2013; Keswani et al., 2016;;). Due to their synthetic make-up, plastics are able to both carry and absorb toxins around them (Engler, 2012; Gouin et al., 2011). If particles are ingested, the toxic traces are capable of bio-accumulating throughout the food chain (Desforges et al., 2015; Koelmans, 2015). Despite recent evidence and research, the relative threat, concentrations, and harm on species and ecosystems as a whole remains relatively unknown (Beaumont et al., 2019). Further research on quantifying plastic loads, understanding how much enters the environment, and how much interacts with marine species is needed to fully understand the threat of marine debris and plastic pollution to global oceans.

1.2 Sources of marine debris and plastic pollution

Management and mitigation strategies are only effective if the pathways and contributing sources of marine debris and plastic pollution are known. Sources and pathways of marine debris can be complex; arriving in the ocean from different pathways (Figure 1.1). Marine debris can originate from two broad sources: ocean and land ((Rees amd Pond 1995). Land-based items can be littered directly into the marine environment, such as that on beaches, or originate from inland sources, which can be washed from storm water and sewage effluents. Both of which can carry both macro and microplastic loads to the marine environment.

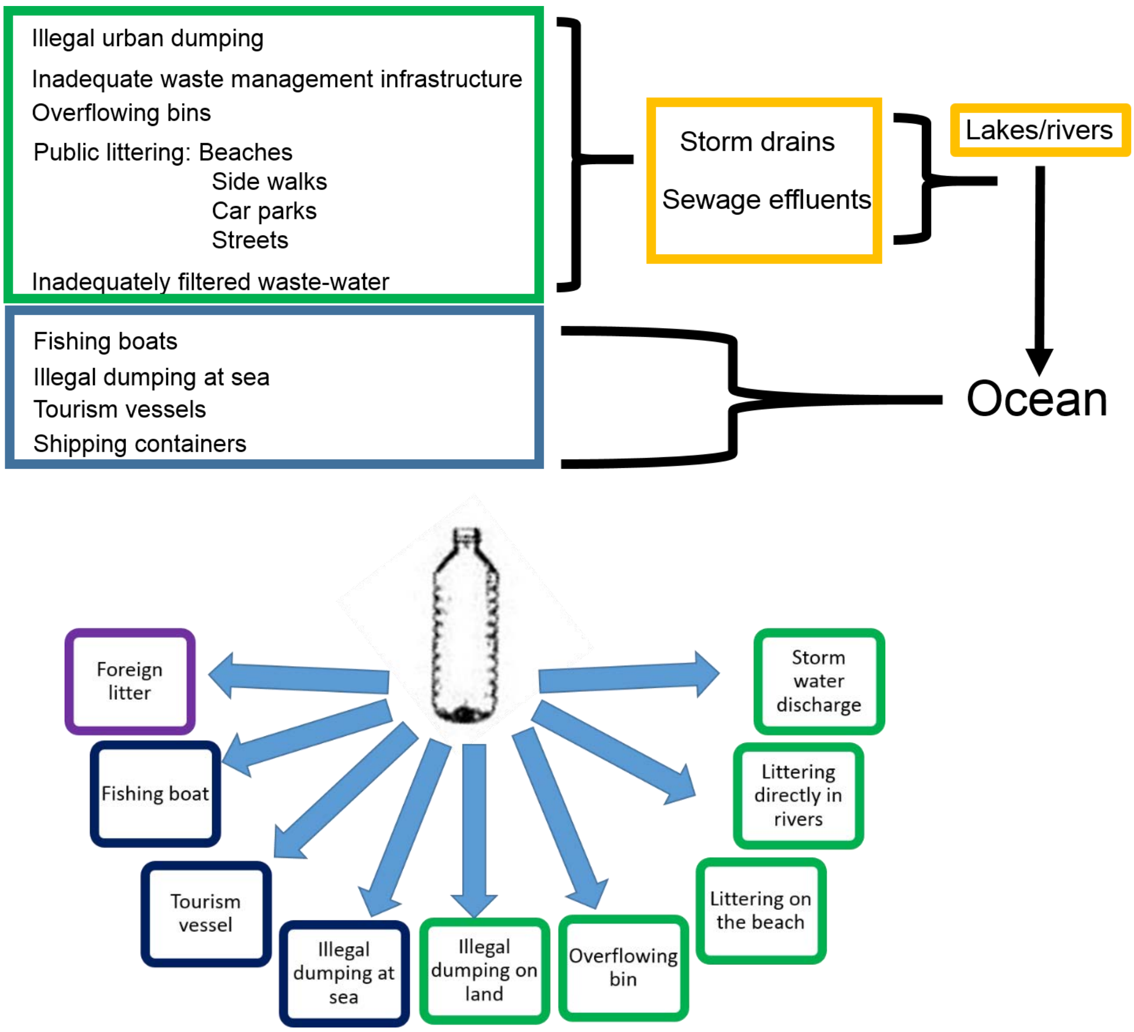


Figure 1.1: *Top: Examples of potential sources and pathways in which marine debris can enter the ocean. Blue outline= marine based litter, green outline = land based litter, and orange outline = potential pathways. Bottom: Quantifying debris items alone is not enough to identify the source. Some items, such as water bottles, can originate from multiple different sources. Blue outline = ocean based, green = land based, and purple = item can originate from land, but carried long distances by sea.*

Although marine based sources, such as derelict boating and fishing gear have been recorded in the literature since the 1980s (Pruter, 1987; Schrey and Vauk, 1987), it is now estimated that a large, generally unquantified amount of debris in the marine environment actually originates from land-based sources (Andrady, 2011; Derraik, 2002; Oosterhuis et al., 2014) although far less is known about this. Recent research suggests in 2010 alone, somewhere between 0.01 to greater than 5 million metric tons of litter and other mismanaged waste was likely to enter the ocean from land based sources per year (Jambeck et al., 2015). If the current use and reliance of plastic items continues to increase, mismanaged waste entering the environment is likely to increase by 20-25% by the year 2050 (Jambeck et al., 2015; Worm et al., 2017). However, once items are in the ocean, it becomes increasingly difficult to identify specific sources to apply effective and targeted management strategies. Therefore, identifying, quantifying, and monitoring of each potential pathway is needed to identify problem areas, and identify where further research is needed.

In addition to understanding the pathways and improving waste management on a local scale, supplementary strategies are needed to reduce plastic pollution in the ocean. Top-down approaches and policies in addition to changing human behaviour regarding plastic use and disposal is essential to reduce marine plastic pollution. Otherwise, maintenance and clean-ups, and the economic costs associated with this will be needed long-term. To use an analogy, mopping the floor around a leaking tap does not fix the leaking tap. To solve the situation, the tap must be turned off, then you may continue to mop up the mess. In other words, mitigation techniques used to capture litter before arriving into the marine environment can never be completely successful. To truly reduce marine debris, managing agencies need to 'turn off the tap' by understanding the underlying human behaviours of plastic use and disposal to effectively redirect actions to reduce or remove the threat.

1.3 Rivers as transport mechanisms for land-based debris

Within the last decade, research has found that a large proportion of land-based debris and plastics from inland sources are capable of flowing into freshwater systems, which eventually lead to the ocean (Lebreton et al., 2017; Moore et al., 2011). This is because any mismanaged litter from urban sources, such as any of the pathways in Figure 1.1 (e.g. littering, over flowing bins, litter from trucks etc.) can be washed into storm water drains, which then can enter directly into river systems. Large quantities of plastic debris within an urban river system was first extensively described by Moore et al. (2011), where both macro and microplastic particles were recorded in high concentrations in two Southern Californian river systems, coastal waters, and beaches.

Later, research showed a high abundance of microplastic particles in the surface water of The Great Lakes and later extended throughout the St. Lawrence River system in Canada, where up to 1.4×10^5 microplastic particles were recorded within the sediment (Castaneda et al., 2014; Eriksen et al., 2013). Research on plastic loads has continued to grow in freshwater systems in areas with lower human populations, such as the lakes in Tibet (Zhang et al., 2016). Overall, it is now estimated that is somewhere between 0.41 to 4 million tonnes of plastic waste per year being washed into the ocean via river systems per year world-wide (Lebreton et al., 2017; Schmidt et al., 2017).

Despite this estimation of high loads of plastic contributed by river systems around the world, the plastic pollution load of many of the world's river systems remain unquantified, and the exact pathways of debris and plastic pollution remain unknown (Brennholt et al., 2018). For example, some countries, such as Australia, have large quantities of debris washing ashore, but many of the land based sources from river systems, have yet to be quantified (Cunningham and Wilson, 2003; Hardesty and Wilcox, 2011; Kiessling and Hamilton, 2001; Smith, 2010). This provides a level of uncertainty regarding local and urban contributions of debris and plastics to the marine environment, and how to appropriately implement intervention techniques, such as implementing infrastructure, improving waste management, and engaging the community. Therefore, fine scale monitoring of river systems at local levels can better inform local and national legislation to mitigate debris from entering the ocean system (Carpenter and Wolverton, 2017).

One pathway in which mismanaged waste can enter the ocean is through the act of littering (Law 2017). As such, the behavioural intentions of plastic disposal is an important aspect of marine debris that needs to be examined to reduce plastic and debris loads before it arrives in the ocean. Both accidental and active littering in urban and coastal communities are the underlining source of the litter that arrives from storm water systems that enter river systems or littered directly in the ocean. The factors that drive littering behaviours have been well documented in literature (Campbell et al., 2014; Madhani et al., 2009; Robinson, 1976; Spehr and Curnow, 2015), however, this is rarely examined in relation to marine debris (Hartley et al., 2018). Consequently, it is unknown if people in coastal communities identify that the litter occurring in and around their local areas, and not just that on beaches, can contribute to marine debris. Based on relevant theories of pro-environmental behaviours and intentions, knowledge and awareness of the issues are likely to influence action and behaviours. Conversely, a lack of overall awareness can be important information for local policy governing structures to fuel education and awareness campaigns in combination of other management and mitigation techniques (Slavin et al. 2012; Vince and Hardesty 2016; Campbell et al. 2016).

1.4 Marine debris and plastic pollution in Australia

Over the last few decades, there has been increasing evidence that marine debris and plastic pollution is a threat to the Australian marine environment (e.g. Bauer-Civiello et al., 2018; Cunningham and Wilson, 2003; Frost and Cullen, 1997; Verlis et al., 2014). Marine debris and plastic waste have been recorded on many, if not most Australian beaches, with as much as 2,094,768 plastic items collected around coastal areas of Australia in 2018 alone (Australian Marine Debris Database-2018). In addition, microplastic particles have been recorded to be present around the entire coastline of the country, likely originating from a combination of domestic and international sources (Reisser et al., 2013). As a result, the latest 2009 report by the Canberra Department of Environment identifies that 77 Australian marine species were impacted by plastic, including turtles, cetaceans, seabirds, dugongs, pinnipeds, sharks, and rays (Ceccarelli, 2009). Despite the growing number of studies documenting debris ingestion and interaction with Australian marine species (e.g. Kroon et al., 2018; Roman et al., 2019; Verlis et al., 2013, 2014; Wilcox et al., 2018), there is very little information quantifying how much debris is in the environment, where it is coming from, how much debris is interacting with species, and exactly how much of a threat it poses to marine habitats. Therefore, understanding the extent and contribution of potential pathways and sources of marine debris in coastal waters is essential for mitigation and litter management on a national scale. The state of Queensland, Australia, neighbouring state to the Great Barrier Reef, has the highest measured litter incidence in Australia; 1.4 times higher than the national average according to litter data from a nation-wide clean-up initiative (Boomerang Alliance, 2015). Yet, the pathways through which inland urban litter can enter the marine environment, such as that through river systems have yet to be examined in peer reviewed literature in Australia. Furthermore, there is little information regarding the act or behavioural intentions of littering and the level of community awareness of marine debris, particularly in regional areas of Australia. Previous research has shown that the Great Barrier Reef and coastal environment are held with high regard among Australian residents (Goldberg et al., 2018), however, litter remains a problem (Great Barrier Reef Marine Authority 2019

Outlook Report). Identifying this connection between litter and marine debris can provide further information as to why litter occurs, and how to reduce it from arriving in the ocean and provide further information for one of the many pathways toward the complex problem of land-based marine debris.

1.5 Knowledge gaps and information needed for management of marine debris

Management of marine debris is complex and requires a combination of science, policy, and litter management to mitigate the input of marine debris (Rochman, 2016; Rochman et al., 2016). Since there is a wide range of factors that influence the input of litter and plastic into the environment, interdisciplinary research, including environmental science, biological science, and social science is required to understand the whole picture of marine debris and plastic pollution (Pahl and Wyles, 2017). Interdisciplinary research has been previously used on a wide range of coastal issues, for example, a combination of understanding human behaviour and ecological monitoring are needed for reducing light pollution that impacts turtle nests, and other marine related issues, such as illegal fishing (Kamrowski, 2014; Kamrowski et al., 2014; Riskas 2017; Riskas et al., 2018). Although this need for interdisciplinary research, particularly for coastal issues, is acknowledged in recent literature on coastal and litter management (e.g. Benham and Daniell, 2016; Christie, 2011; Ciannelli et al., 2014), this rarely occurs, particularly in graduate level studies (Ciannelli et al., 2014). Therefore, in my thesis I will make a novel contribution to the science by using a cross-disciplinary approach across multiple knowledge gaps to provide management-relevant information for Townsville and Queensland. This thesis uses these overarching themes to provide meaningful insights to marine debris management, education, and source reduction in Queensland, Australia, using Townsville Queensland, as a case study (Box 1).

- **Theme 1: Understand distribution patterns to narrow down potential sources** (Chapter 2)
- **Theme 2: Identify exactly how plastic is entering the aquatic environments and why** (Chapters 3 & 4)
- **Theme 3: Identify ways to monitor macro and microplastic loads to identify impacts, create baselines, and monitor change.** (Chapters 4 & 5)

- **Theme 4: Understand community awareness and concern about marine debris to reduce land based sources, such as that from littering.** (Chapter 6)

1.6 Thesis Outline

In light of the knowledge gaps described above, this thesis aims to understand the sources of marine debris and plastic pollution in Queensland, Australia, and provide a holistic approach to marine debris management. This thesis contains seven chapters, with five stand-alone data chapters which address the overall themes described above.

Chapter 1: Provides an overview of marine debris as a pollutant and identifies gaps in knowledge that are needed to effectively manage and reduce marine debris.

Chapter 2: Aims to understand the current distribution and types of subtidal debris on the reefs along the Queensland coast. This information provides a baseline dataset to monitor debris loads and provides insights to: 1) the relative threat to subtidal debris on the reef, 2) identify the most common items found on Queensland Reefs, and 3) identify the likely sources.

Chapter 3: Aims to monitor debris loads entering freshwater systems using Townsville as a case study. This chapter focuses on: 1) debris inputs via storm drains into the river through time, 2) debris inputs from rainfall, and 3) identifying common items and their likely sources.

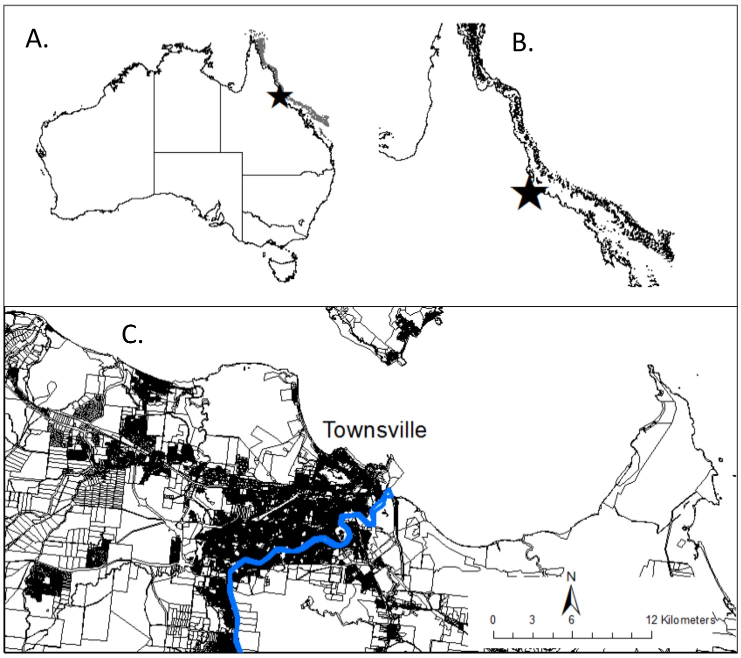
Chapter 4: Aims to identify microplastic loads within Ross River as a source of microplastic in the Great Barrier Reef. Furthermore, it aims to quantify storm drains as a source of microplastic loads by quantifying microplastic within the sediment and water surface before and after the wet season.

Chapter 5: Aims to identify a novel indicator species that can be used to monitor microplastic loads and relative impact on reefs and monitor acute events, such as those from monsoonal regions, where rainfall can influence rainfall microplastic loads.

Chapter 6: Aims to identify the community perception and awareness of plastic marine debris in the Great Barrier Reef. Specifically, I aim to answer the following questions: 1) What is the current state of knowledge and awareness of marine debris and its sources, and what are the attitudes and values regarding littering and marine debris? 2) How does the level of knowledge or responsibility to care for the local marine environment predict the level of concern for marine plastic pollution? And lastly, 3) how can this information be used to engage the local community in Townsville and shape local policy measures and future research to reduce plastic?

Chapter 7: Provides an overview of thesis results, and what this means for management of marine debris in the Great Barrier Reef, and Queensland coast.

Box 1.1: Case-site description: Townsville and Ross River



Townsville is the largest neighbouring city to the Great Barrier Reef World Heritage Area (Panel B), and is home to approximately 229,000 people (Australian Bureau of Statistics 2016 Census). A river and associated creek system, Ross River, flows through the urban community, discharging into Cleveland Bay (Panel C). Cleveland Bay contains sensitive habitats, including nearshore reefs and seagrass meadows important to dugong and marine turtle species (Waycott et al., 2005; GBRMPA 2004).

Townsville has an average annual rainfall of 1,143 mm per year (Australia Bureau of Meteorology), 86% of which occurs between the months of September and March, making it susceptible to large monsoon rainfall flushes, carrying inland litter to the river system and ocean. To regulate river flow through the city, three weir systems are built within the river. During the dry season (April through October), these weirs act as dams, impeding river flow. The basin size of the river is about 1,340 km^2 with annual discharge varying year to year, depending on rainfall (unpublished Townsville City Council data). After a large rain event or during a wet season, these weirs can overflow (unpublished Townsville City Council data). This means that any debris entering the system is retained until there is enough rain for the debris to flow over the weirs and out to the bay. Storm water drains are situated throughout the city, with multiple effluents leading directly to the river. No other effluents (such as treated sewage) enter the river at any locations.

Chapter 2
Using citizen science data to assess the difference in marine debris loads on reefs in Queensland, Australia

Abstract

The prevalence of marine debris in global oceans is negatively impacting the marine environment. In Australia, marine debris has been an increasing concern for sensitive marine environments, such as coral reefs. Citizen science can contribute data to explore patterns of subtidal marine debris loads. This study uses data from Reef Check Australia to describe patterns of debris abundance on reef tourism sites in two Queensland regions, the Great Barrier Reef (GBR) and Southeast Queensland (SEQ). Debris was categorised into three groups, fishing line, fishing net, and general rubbish. Overall, debris abundance across reefs was relatively low (average 0.5-3.3 items per survey ($400m^2$)), but not absent on remote reefs surveyed in the GBR region. Highest debris loads were recorded in SEQ near cities and high use areas. These results indicate the presence of marine debris on remote and urban reefs, and the applicability of using citizen science to monitor debris abundance.

Citation: Bauer-Civiello A, Loder J, Hamann M. Using citizen science data to assess the difference in marine debris loads on reefs in Queensland, Australia. *Marine Pollution Bulletin.* 2018; 135: 458-465

2.1 Introduction

In recent years, the growing prevalence of marine debris in world oceans is gaining attention as a critical issue in marine conservation (Currie et al., 2017; Darmon et al., 2017; Eriksen et al., 2014; Hardesty et al., 2017; Lavers and Bond, 2017). In particular, there is an increasing volume of literature from across the world indicating impacts to marine wildlife through either the entanglement or ingestion of plastic, suggesting that the problem is more ubiquitous than previously thought (Courtene-Jones et al., 2017; Denuncio et al., 2017; Law, 2017; Worm et al., 2017). Debris is even being recognised as a threat in more remote areas without human populations, for example, large amounts (53.1 to 4,492 pieces per m^2) of plastic debris were found on Henderson Island, a remote island in the South Pacific (as reviewed by Lavers and Bond, 2017). Despite the extent and magnitude of the problem, there is still very little knowledge about the abundance of marine debris in sub-tidal marine environments, how it gets there, how it moves, and the degree to which it may threaten marine wildlife and their habitats (Ryan, 2015).

In Australia, the impact of debris on local marine ecosystems has been an increasing concern for marine scientists, conservationists and governing agencies (Derraik, 2002; Gall and Thompson, 2015; Vince and Hardesty, 2017; Willis et al., 2017). Due to the increasing records of debris impacts on marine wildlife, the Australian government identified marine debris as a "key threatening process" in coastal Australian waters (Smith and Edgar, 2014; Slavin et al. 2012; Willis et al., 2017). In 2009, the Australian government prepared a 'Threat Abatement Plan for the Impacts of Marine Debris on Vertebrate Marine Life' to further recognise the threat of marine pollution on marine wildlife and coordinate abatement strategies. In addition, scientists and conservation agencies have started to provide mechanisms to better manage fishing debris, such as the use of T*Angler* bins and initiating 'Sealing the loop' programs around public fishing spaces (Pearson et al., 2014). Despite this nation-wide plan and increased political attention, the sale and disposal of single use plastics and the volume of marine litter is expected to grow (Jambeck et al., 2015). Furthermore, while marine debris on shorelines are well quantified, there is still relatively little information on debris loads within the sub-tidal waters of Australia. A further understanding of the abundance of debris, debris type, and accumulation is needed to provide a robust platform for legislation or incentives to mitigate marine debris.

Survey data from beach-based clean ups indicates that Queensland beaches can accumulate between 439 and 2806 plastic items per km per year (Clark and Johnston, 2016). These items include a variety of plastic products from fishing debris to everyday household items (Taylor and Smith, 2009) and they could come from a variety of marine and/or land-based sources (Critchell et al., 2015). This load of plastic items accumulating on beaches could have strong implications for the potential impact of sensitive marine habitats, such as the ecological and social values of important natural and cultural heritage areas such as the Great Barrier Reef World Heritage Area (Great Barrier Reef Marine Park Authority, 2019).

In addition, it is likely that most of the impacts to marine species arises from debris within the water column or in benthic habitats, but unlike beach clean ups, it is exceptionally hard to quantify either the existing load of debris in marine habitats, or the volume of inputs into the marine system. Therefore, there is relatively little publically available information about the level of debris in subtidal Queensland coastal waters. Essentially, because quantifying patterns or abundances of debris in subtidal benthic habitats is more difficult and less cost effective debris loads are not well documented. Obtaining an estimate of the level of debris in benthic habitats is essential if we are to further understand how marine debris interacts and potentially alters the state and value of marine species and habitats.

Volunteer organisations and citizen science groups are able to implement replicable and cost-effective monitoring across broad areas (Jambeck and Johnsen, 2015; Dickinson et al., 2010; van der Velde et al., 2017), and have been successful in monitoring ecosystem health (Done et al., 2017; Marshall et al., 2012), tracking wildlife (Jaine et al., 2012; Marshall and Pierce, 2012), and providing information on invasive species (López-Gómez et al., 2014). In Australia, subtidal marine debris has been recorded by citizen science groups such as Tangaroa Blue Foundation (https://www.tangaroablue.org), PADI Project Aware (projectaware.org/diveagainstdebris), and the New South Wales Underwater Marine Debris database (https://www.uvnsw.net.au/marine-debris-surveys). However, these volunteer diving programs often visit known debris prone areas, and thus their data does not provide means of quantifying overall patterns of subtidal debris abundance.

Reef Check Australia (RCA) is a non-profit, citizen science organisation that has been monitoring reef health on Queensland reefs using a globally-standardised protocol since 2001. Specifically, RCA conducts regular surveys of long-term monitoring sites to provide a robust baseline dataset that can document changes in reef condition over time (Done et al., 2017), and contributes to the knowledge of reef scale health and condition assessments (GBRMPA 2014). During RCA reef surveys, volunteer divers record data on coral reef habitat, wildlife and condition. As part of the surveys they also record information on sub-tidal debris, providing an opportunity to quantify marine debris loads across regularly monitored reefs.

To provide insights of patterns of benthic debris, I use RCA's long term reef survey dataset to examine large scale patterns of marine debris occurring on Queensland sub-tidal reefs. With this dataset, I aim to describe state-wide patterns of debris abundance located at RCA monitoring sites. In addition, since Queensland reefs are intrinsically separated geographically, I compare patterns of debris types among the two main surveyed regions: Southeast Queensland (SEQ) and the Great Barrier Reef (GBR). Due to differences in nearby population density, and ease of access, I predict that there will be more sub-tidal debris within SEQ reefs. In addition, I predict there will be differences in overall debris type between the two regions, suggesting different targeted management strategies for the relevant area's managing agencies.

2.2 Methods

2.2.1 Reef Check Surveys

RCA conducts annual standardised coral reef health surveys, using point intercept transects to measure substrate composition and belt surveys for reef impacts, and share information with stakeholders (Hodgson, 1999). In Queensland, surveys were conducted in two regions defined by RCA: the Great Barrier Reef (GBR) and Southeast Queensland (SEQ) (Figure 2.1). The GBR sites have been surveyed regularly since 2001, and range from Heron Island in the south to Osprey Reef in the Coral Sea. SEQ surveys began in 2007 and occur on reefs from Fraser Island south to the Gold Coast. GBR and SEQ survey sites include both coastal and off-shore reefs. Sites occur in both

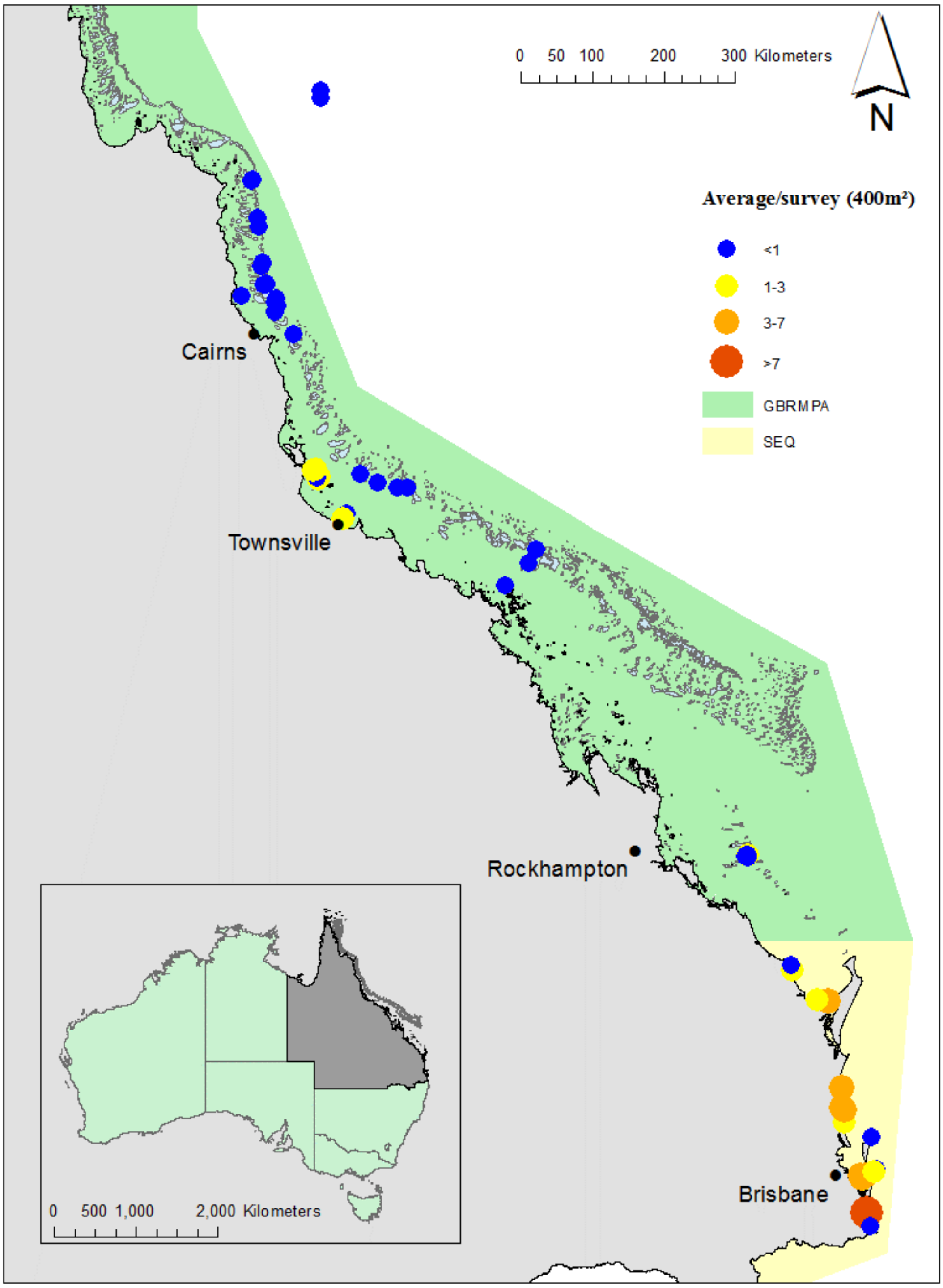


Figure 2.1: *Average debris per survey (400m^2) along the Queensland coast. Note: Osprey Reef is not located in the GBRMPA, however for the purpose of this paper, it was considered in the GBR analysis. Data was set to the boundaries using the natural jenks method of ArcGIS. These Categories were then rounded to the nearest whole number. Averages lower than 1, but > 0 were combined for a single 'low' category.*

protected and non-protected zones, with the majority (76%) of GBR sites occurring in no-take, in which recreational and commercial line fishing is not allowed. In comparison, only 33% of SEQ sites are located in no-take zones.

Most reef surveys were conducted within a five month survey period that occurred from February to June in the GBR, and August to December in SEQ. For the purpose of this paper, reef surveys were examined based on annual surveys, from 2001 to 2016 in the GBR, and 2007-2016 in SEQ. There is a concerted effort taken to conduct surveys at each location within the same month each year to minimise seasonal variation. However, because RCA relies on the availability of trained volunteers and dive operators offering their services in-kind or at a reduced cost, there can be variation in survey timing. Other constraints, such as unfavourable weather or budget limitations, also restrict the ability to reach certain sites each year, or at the same time every year. Therefore, sites that were newly implemented or not surveyed more than two times were not included in this analysis.

Reef check surveys were conducted on SCUBA or snorkel and carried out using measurement tapes to mark four, 20m transects, with five meters between each replicate transect (Hill and Loder, 2013). Sites were located with GPS coordinates, and detailed maps that were regularly updated to relocate sites. Surveyors use these coordinates and maps to haphazardly place transects in the same area each year, following the natural outline of the reef, and avoiding non reef building substrate, such as sand. Reef health surveys were made up of four parts, substrate percent cover, and abundance of reef impacts (such as bleaching, disease, and scaring), invertebrates, and fish. Debris was recorded as a part of the reef impact survey, where one to two divers performed a series of five meter wide, 20m long belt transects (2.5 meters on either side of the transect line) with 5 meters between transects (Figure 2.2), recording any debris item present within the belt area. This covers an area of 400m^2. These surveys are repeated once a year, unless interrupted by unforeseen circumstances, such as poor weather or if site was no longer accessible.

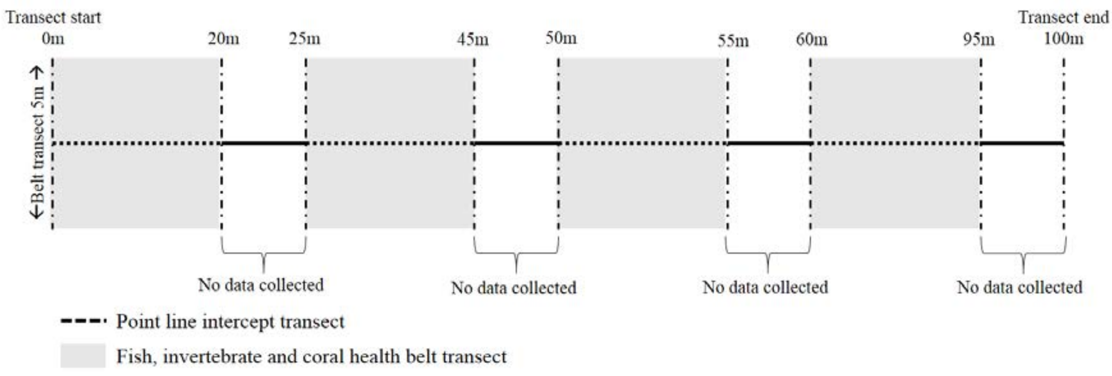


Figure 2.2: *Standardised Reef Check protocol, using the point line intercept and belt transect method. Figure modified from Hill and Loder (2013). In order to show debris abundance, debris items were summed across all transects to obtain debris abundance per survey area (400m^2).*

2.2.2 Debris categorisation and quantification

Within RCA impact surveys, debris items were categorised into; fishing line, fishing net, and general rubbish (any debris that does not fall within the previous categories). This included any visible items in any size range. Since the debris surveys were part of a larger site survey, the debris items were counted but not weighed or measured. Instead, once the items were observed they were recorded in one of the three categories, and if a camera was available, a picture was taken for documentation and further identification. Photographs were later cross-referenced to survey data, to provide more information on debris type. If safe for the surveyors, debris items were removed from the site, whenever possible. However, sometimes the debris items such as fishing line were tangled with reef structure, and attempting to remove them could cause damage.

Due to low debris densities, the four twenty meter replicate transects were treated as a single eighty meter transect rather than as replicates (Figure 2.2). Therefore, the total debris items were summed across all transects to obtain debris abundance per survey area (400m^2). The total debris abundance per survey was then averaged over multiple surveys to account for any double counting over time. Any site visited three or more times between 2001 and 2016 was included in the analysis.

2.2.3 Statistical analysis

The average debris abundance per survey area (400 m^2) was analysed in ArcGIS (ESRI) to determine patterns of debris along the Queensland coast. To compare the difference of debris abundance and type between the two regions (SEQ and GBR), average number of debris items over time was used. Since data did not meet parametric assumptions, a non-parametric Man-Whitney test was performed in IBM SPSS Statistics version 25.

2.3 Results

Across a 15 year time span, a total of 79 locations were surveyed along the Queensland coast, ranging from Osprey Reef to the Gold Coast. This included 54 sites within the GBR, and 24 within SEQ (Appendix 1). Within the two regions, a total of 622 surveys were conducted from 2001 to 2016 (n= 437 in GBR, and n=185 in SEQ). Overall, debris was present in 32% of the surveys completed in the GBR, averaging less than one item per survey. Conversely, debris was recorded in over half (56%) of the surveys in SEQ, with an average of 3.2 items per survey.

When comparing between regions, SEQ survey sites had more fishing line, fishing net, and overall debris abundance (Mann-Whitney $p < 0.001$, $p=0.033$, $p<0.001$, respectively). However, there was no significant difference found in the general debris abundance between the two regions (Mann-Whitney $p=0.08$) (Figure 2.3). The highest overall debris abundance (including all categories) were recorded at SEQ sites from the Gold Coast, with an average of 27 pieces of debris were recorded per survey (400m^2) (Figure 2.4). In comparison, the highest abundance of debris in the GBR was recorded in the Palm Islands and Magnetic Island with an average of 3 and 2 items of debris per survey, respectively (Figure 2.4). In both regions, across all sites, the number of items recorded on surveys remained relatively consistent over time (Figure 2.5).

The type of debris was highly variable over the two regions. Fishing line and net made up over half of the debris items (72% and 7% respectively) in SEQ, but only 17% of the items recorded in the GBR (9% fishing line, 8% fishing net). Instead, in the GBR, approximately 82% of the items were recorded as 'general rubbish.' Unfortunately, only 6% of the general rubbish items could be further classified by analysing photos. Either due to the lack of camera availability in earlier surveys, or low prioritisation of photography. Photographed items included one item of plastic packaging, one item of fabric, two items of rope (>2m), one cardboard packaging, metal fishing items, and other boating related items such as anchors. On Heron Island in the GBR, a total of seven items of abandoned or lost scientific sampling gear was also recorded on surveys. In the SEQ sites, approximately half (47%) of the items labelled in the general rubbish category were able to be further identified from photographs. From the photographs, metal items were the most abundant (40% of the identified items) (Figure 2.6), including metal piping, metal fishing items such as rods and reels, foil, bottle caps, and aluminium cans. Plastic items made up approximately 32% of the photographed items in SEQ, and included rope, plastic film remnants, rubber and elastic straps, bait and tackle packing, and plastic food packaging (Figure 2.7). The rest of the items consisted of glass (18%), paper and cardboard packaging (3%), sanitary (3%), and other (3%).

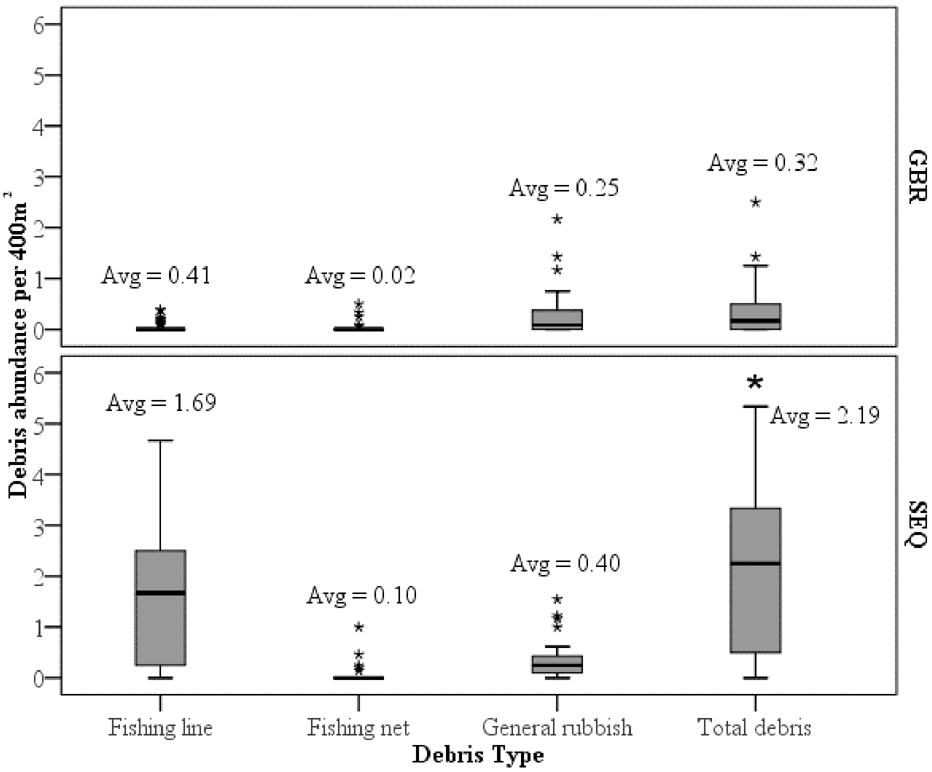


Figure 2.3 *Comparison of average debris abundance and type per survey (400m²) across the two regions (as described by Reef Check Australia) along the Queensland coast: the Great Barrier Reef, and Southeast Queensland. Box plots represent median and interquartile (25th and 75th). Asterisk indicate outliers. Outliers were identified by larger asterisks was removed since it was greater than the provided scale: 27 items/400m², Gold Coast (see Fig. 2.4)*

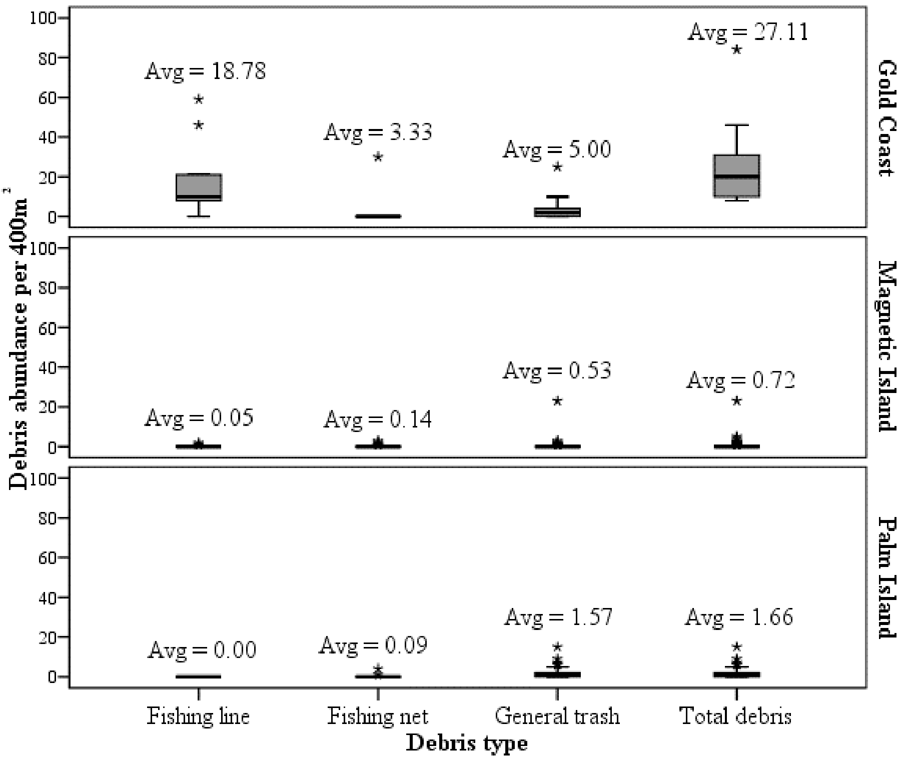


Figure 2.4 *Comparison of average debris abundance and type in 'hotspots'. The Gold Coast is located in Southeast Queensland Region, whereas Magnetic Island and Palm Island sites are located in the Great Barrier Reef region. Box plots represent median and interquartile (25th and 75th). * Indicate outliers.*

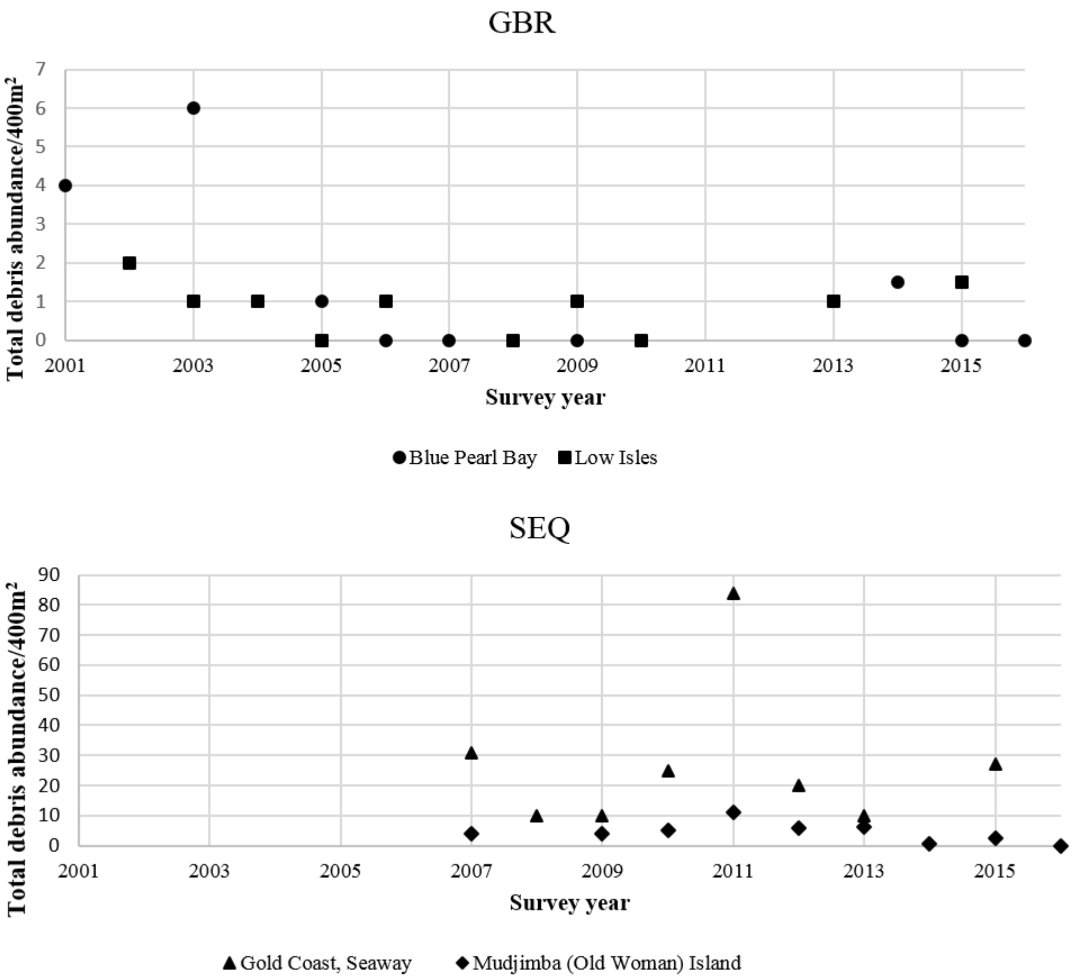


Figure 2.5 *Total debris abundance on most consistently surveyed reefs, two examples of GBR sites (Blue Pearl Bay and Low Isles), and two examples of SEQ sites (Gold Coast, Seaway and Mudjimba (Old Woman) Island). GBR surveys began in 2001, and SEQ surveys in 2007. Some reefs were not surveyed every ear, therefore absent markers indicate no survey performed that year. Data included multiple sites surveyed in the same reef.*

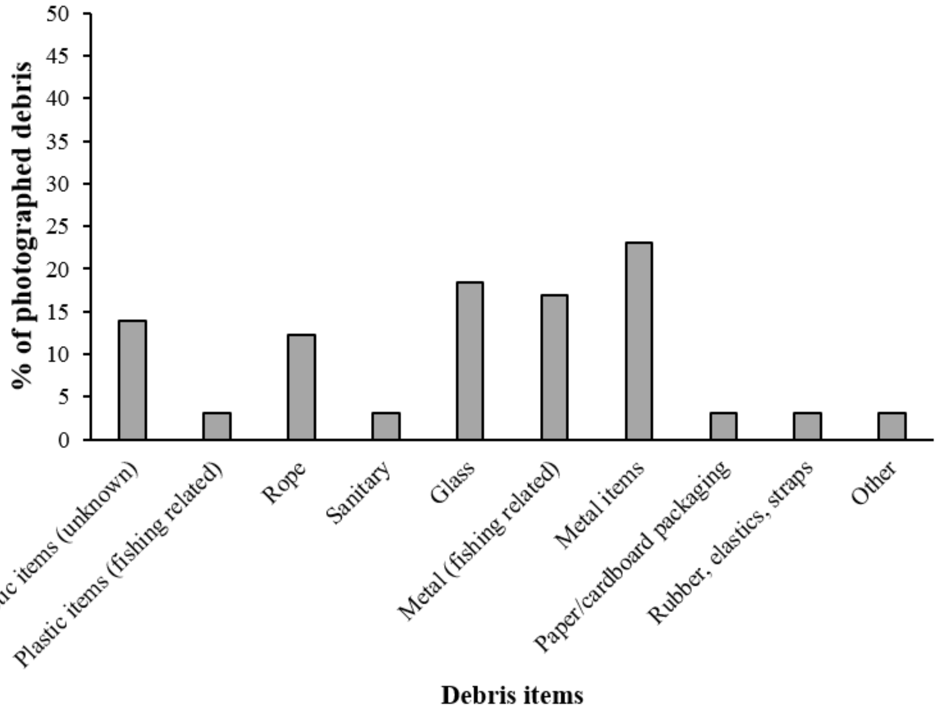


Figure 2.6 *Percent of debris categories identified in photographs in Southeast Queensland. Items only represent approximately half of the items labelled in 'general rubbish' category. The remaining items were unidentified.*

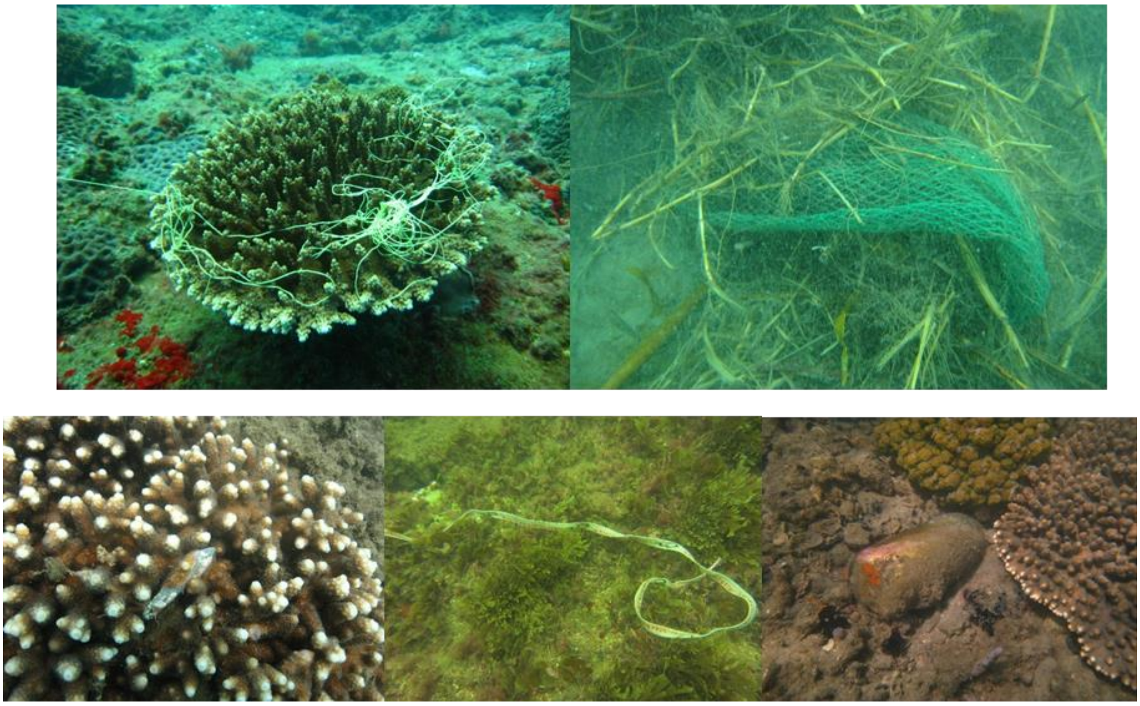


Figure 2.7 *Examples of photos of debris recorded on surveys. Photos were used for cross referencing with data collection. Top row: fishing line (left) and net (right). Bottom row: a fishing lure categorised in general rubbish (left), a strapping band categorised in general rubbish (middle) and a glass bottle (right).*

2.4 Discussion

Overall, the amassed data from RCA surveys suggest that subtidal marine debris abundance across Queensland reefs were relatively low but became higher on reefs closer to high-use recreational areas such as Brisbane, the Gold Coast, Magnetic Island and the Palm Islands. This pattern of relatively high debris densities around cities are commonly found among other shoreline and subtidal research around Australia (Hardesty et al., 2017; Smith and Edgar, 2014), and around the world (Coe and Rogers, 2012; Galgani et al., 2000; Jambeck et al., 2015; Rosevelt et al., 2013). More specifically, in Queensland's neighbouring state, New South Wales, marine debris surveys recorded lower densities of debris in offshore reefs, but higher densities closer to estuaries and nearshore reefs (Smith and Edgar, 2014). This pattern of higher debris densities surrounding areas with large populations add weight to a growing body of evidence that most waste enters the marine system from areas adjacent to high human populations and high use.

Importantly, debris items were also found in remote areas of the Great Barrier Reef and offshore sites such as Osprey Reef, suggesting the relatively pristine reefs also do not escape the threat of marine debris. This is not unexpected, as debris has been recorded in some of the more remote and untouched areas in the world (Lavers and Bond, 2017). Specifically in Australia, debris has been found on remote beaches throughout northern Queensland, and sand cays located within the GBR (Smith and Edgar, 2014; Verlis et al., 2013, 2014; Wilson and Verlis, 2017). Although in low abundance, the very presence of debris on these more remote reefs suggests that their habitats and species could be subject to the relative impacts, such as coral damage, smothering, and entanglement, especially if deposition rates increase as projected (Chiappone et al., 2005; Sheavly and Register, 2007). In addition, the presence of plastic items on reefs, such as fishing line, net rope, and soft plastics, has recently been associated with other coral impacts, such as increased levels of coral disease (Lamb et al., 2018). This dataset provides valuable data to identify the presence of marine debris, and supports a further understanding of debris abundance patterns, which is useful for identifying how marine debris may influence marine systems and target relevant management actions.

Fishing line debris was found to be the dominant debris type, and occurred in significantly greater amounts in reefs within SEQ than in the GBR. On the whole, the

SEQ region is smaller and more accessible to people than the GBR, and has higher coastal populations, therefore it is likely that the sites surveyed in SEQ are used more often by fishers and boaters than surveyed sites in the GBR (Department of Agriculture and Fisheries, 2017). Based on the latest Department of Agriculture and Fisheries surveys from 2013-2014, there was approximately 236,000 +/- 13,000 recreational fishers in Brisbane alone, in comparison to the 36,000 +/-3,400 in Townsville (the two largest cities in each region) (Webley et al. 2015). For both cities, approximately 50% of the fishermen own and use boats. Fishing gear has been recorded as one of the dominant marine debris items in other reef habitats both in Australia and around the world (Edyvane et al., 2004, Donohue et al., 2001), but its abundance is heavily dependent on the degree to which the surveyed area is used by fishers (Bauer et al., 2008) and the type of fising conducted. For example, in Gray's Reef National Marine Sanctuary in Southeast USA, 75% of the debris in areas of high boat density was fishing line, compared to 23% in area with lower boat densities (Bauer et al., 2008). Similarly, significant abundances of fishing and other debris were recorded in South Australia due to heavy boating and fishing (commercial and recreational) activities in the Great Australian Bight (Edyvane et al., 2004). Proportionally, fishing line abundance was similar to those found on other underwater debris surveys in Australia, where approximately 82% of debris items were found to be fishing monofilament, occurring most commonly on nearshore sites (Smith and Edgar, 2014). This is slightly higher than the 67% found within SEQ region, suggesting relatively consistent debris loads across states. It is clear that strategic initiatives are needed to reduce fishing line debris is needed to reduce these loads on local reefs.

The difference in debris abundance and type across the two regions, is also likely influenced by regional artefacts such as differences in site placement. The majority (76%) of GBR sites occurred in no-take zones in which recreational and commercial line fishing is not allowed. In comparison, only 33% of SEQ sites are located in no-take zones (Appendix 1). This is because there are fewer areas in SEQ in which fishing activity is regulated (in comparison to the GBR), with the only marine park located in Moreton Bay. In addition, RCA relies heavily on the in-kind services of the tourism industry, and most survey locations are popular tourist destinations, and are thus typically within protected, no fishing zones. Despite this, 64% of the fishing line and net were recorded on surveys occurring within protected areas in the GBR.

Therefore, it is likely that my data under-estimate the degree to which fishing line items accumulate in benthic habitats of the GBR.

Unfortunately, due to the lack of photographs, I was unable to further identify debris type found within the GBR, beyond the 6% that were identifiable. In comparison, items on SEQ reefs had a greater diversity of general rubbish, consisting plastic, metals, paper, rubber and glass, likely due to the nearness of large urban sources. In both regions, observed items were similar to those commonly found on beaches throughout the Queensland coast (Hardesty et al., 2017; Hardesty and Wilcox, 2011; Wilson and Verlis 2017). Again, due to the nature of RCA, most surveys sites are also popular tourist destinations, in both regions of the Queensland coast. As such, I can assume a "dirty reef" would be less desirable to tourists (Bauer et al., 2008; Derraik, 2002), and vessel operators that visit these sites daily are likely to maintain them (Personal Observation). Regardless, general debris items were still observed at many sites.

One of the key pieces of information required to underpin initiatives to reduce the future load of marine debris is to understand the source of the debris. It is important to identify specific sources because different strategies are required to reduce inputs from debris arising from boating and fishing activities than strategies used to minimise inputs from general litter and the urban storm water systems. It is likely that many items volunteers observed on the surveyed reefs are from boating based activities, either from fishing or tourism vessels or shore-based recreation fishing (Wilson and Verlis, 2017). Heavier items such as glass and metal are likely to sink near-immediately to the bottom, and are thus unlikely to move great distances from where they were discarded. However, plastic and rubber items are generally lighter and can more easily be shifted by wave action or water circulation, hence it is more challenging to determine the origin of plastic products because they may have been discarded elsewhere and been transported to the site (Critchell et al., 2015). Overall, the data suggests that litter education and/or waste management actions targeted at recreational boat users and island visitors in and around the sites that were surveyed could contribute to efforts to reduce future marine debris loads. Working with fishers directly, creating incentives, and encouraging fishers to participate in citizen science clean ups may also provide an important avenue for outreach, and offer people the chance to view the potential impacts of littering while on the reef. In addition, there should be a concerted effort for future surveys to refine techniques to improve identification of debris items – such as photography, more detailed survey categories, or item removal to allow a stronger understanding about marine debris types and sources, particularly in the GBR.

The data I analysed in this paper were collected during a structured component of a broader survey to monitor various aspects of reef health. Therefore, it is difficult to directly compare this data with other subtidal debris studies. Similarly, most studies on sub-tidal debris use different methods, or seek to answer different questions, so comparisons are challenging. For example, in another GBR study, benthic surveys found fishing line abundance to be as high as 18 items per 400m^2 in the Palm Islands (Williamson et al., 2014). In comparison, RCA surveys recorded 0 items per 400m^2 surveyed within the same region by Reef Check Australia. The differences in results could arise because Reef Check Australia transects were not always occurring in areas of high fishing line hotspots and the Williamson et al. (2014) field work was assessing a larger scale project comparing protected and non-protected reefs so some of their transects where in heavily fished areas. While a survey design solely focused on benthic marine debris in reef systems might provide a more detailed analysis, the survey design has enabled a structured and comparative survey of benthic marine debris on reefs and could be used as a baseline for future surveys or refined sampling. In addition, it is important to note that due to internationally recognised standardised and replicable methods, these results could be used to directly compare debris abundances using other Reef Check data around the world.

Adaptations to the data collection methods could add to considerable strength to future sub-tidal marine debris surveys. For example, double counting of durable debris items over time is possible because not all items were photographed and thus it is not always known how many of the items were removed from the sites during the surveys. An improved photography protocol could therefore aid in the data analysis by reducing the likelihood of double counting of heavy or entangled debris.

2.5 Conclusion & Monitoring initiatives

In summary, this study provides a baseline dataset for subtidal marine debris abundances along both urban and remote Queensland reefs, and highlights the importance of citizen science to identify patterns and monitor marine debris on the reef systems. Debris on reefs can have a direct influence on the state of reef health, and can be a threat to inhabiting wildlife. To help reduce this threat, citizen science programs can be designed in a robust manner to help develop and implement more rigorous continuous debris monitoring, which aid understanding of marine debris and plastic pollution at targeted spatial and temporal scales. Long-term debris trends are highly relevant to agencies responsible for waste management or litter regulations, such as local municipal areas or management authorities and can provide a pathway for communities to contribute to science-based management approaches.

Chapter 3
Input of plastic debris in an urban tropical river system

Land-based sources can contribute approximately 80% of anthropogenic debris in marine environments. A main pathway is believed to be rivers and storm-water systems, yet this input is rarely quantified. I aimed to quantify the abundance of land-based debris entering a river system through storm drains in an urban area of tropical Australia. To account for seasonal variability, debris was quantified pre, post and during the wet season from 2014-2017. Plastic items within the river were compared to those in adjacent parks to assess similarities in debris composition. A total of 27,943 items were collected (92% plastic). Debris loads in the post-wet seasons were significantly higher than the wet-season. Furthermore, variability in the portion of debris found in nearby parks compared to the river suggests that factors other than rainfall, play a role in debris abundance. These results can be used to identify targeted management strategies to reduce debris loads.

Citation: Bauer-Civiello A, Critchell K, Hoogenboom M, Hamann M. Input of plastic debris in an urban tropical river system. *Marine Pollution Bulletin*. 2019. 144: 235-242.

3.1 Introduction

Anthropogenic debris has become a ubiquitous problem threatening global waterbodies (Law, 2017; Moore, 2008; Worm et al., 2017). Consisting of up to 95% plastic, anthropogenic debris has been recorded in nearly every aquatic ecosystem (Auta et al., 2017), in addition to many freshwater rivers and lakes (Eerkes-Medrano et al., 2015). Once in aquatic ecosystems, many debris items remain buoyant, and can easily be transported across vast distances via currents and winds (Maximenko et al., 2015). As a result, anthropogenic debris has been recorded in some of the most remote (from human settlements) aquatic locations in the world (Lavers and Bond, 2017; Munari et al., 2017; Ribic et al., 2012). Most importantly, anthropogenic debris in the marine environment is being increasingly found to not only negatively impact species, but the function of ecosystems (Lamb et al., 2018), and the health of fauna through entanglement, ingestion and habitat change (Gall and Thompson, 2015; Nunes et al., 2018; Ryan, 2018). In response, many countries, and inter-governmental organisations have been working to understand the issue and develop management interventions to mitigate the growing problem of debris in marine environments (Critchell et al., 2019; Niaounakis, 2017; Vince and Hardesty, 2017).

Oceans act as a sink for anthropogenic debris, however, managing the removal, and reducing impacts, of debris in the ocean is challenging. The vast expanse of the oceans, the sheer scale of abundance and variability of input sources of debris makes removal costly and time consuming (Islam and Tanaka, 2004). Currently, most strategies for *in situ* removal include beach clean-ups, and innovative pilot projects such as ‘marine bins’ (seabinproject.com) in semi-enclosed marine habitats, or the ocean clean up (theoceancleanup.com) (Vince and Hardesty, 2017). However, mismanaged waste from urban areas moving into freshwater and marine systems has been predicted to increase (Jambeck et al., 2015), and ongoing beach clean-ups will continue to be time and labour intensive, and at times highly reliant on volunteers or citizen science programs (Bauer-Civiello et al., 2018; Duckett and Repaci, 2015). Moreover, deploying and maintaining equipment in the marine environment is expensive and only provide short-term solutions (Critchell et al., 2019). Therefore, establish more effective means of mitigation directly at debris sources is a step forward the reduction of debris, in addition to removal of debris already in the ocean and on beaches.

Freshwater systems are a common pathway for land-based anthropogenic debris to reach the marine environment, as they connect coastal and inland urban communities to the ocean (Castaneda et al., 2014; Lima et al., 2014; Mani et al., 2015; Schmidt et al., 2017; Zhao et al., 2014). The input from freshwater systems is not well known, however Lebreton et al. (2017) estimate that there is somewhere between 1.15-2.41 million tonnes of plastic are transported to the ocean from rivers per year. Debris items enter freshwater systems through various sources, including sewage effluents, storm drains, and through recreational and commercial activities such as water-sports and fishing (Kooi et al., 2018). Once items are in a freshwater system they can accumulate over time, and the flow of water ultimately flushes the debris into the coastal and ocean habitats (Browne et al., 2010; Eerkes-Medrano et al., 2015). Unlike research of marine debris on beaches, there is relatively little known about patterns of debris abundance in freshwater systems. Monitoring debris type and abundance can provide a better understanding as to how debris enters the system, and its most likely source. Knowing each of these can improve mitigation strategies to inform management agencies to target problem areas and likely sources of debris in the environment.

In Australia, land-based debris is a commonly speculated source of anthropogenic debris found in the coastal and marine environment (Critchell et al., 2015; Hardesty and Wilcox, 2011; Willis et al., 2017), however, the amount of debris that originates from river systems remains understudied (Willis et al., 2017). Tropical areas, such as northern Australia, undergo seasonal monsoonal rain flushes that commonly contribute to litter and other pollution loads in freshwater habitats (Li et al., 2015; Moore et al., 2011). Litter originating from sidewalks, streets, highways, parklands, and carparks are collected by water flowing throughout the catchments and become washed into storm drains leading to river systems and eventually the sea (Armitage and Rooseboom, 2000; Marais et al., 2004; Moore et al., 2011; Rech et al., 2014). Other environmental factors, such as wind, can also play an important role in the transportation of anthropogenic debris (Kooi et al., 2018), such as moving items from adjacent parks and recreational areas into aquatic systems. However, sources such as these are rarely examined in peer reviewed literature, particularly with monsoonal seasonal flow in monsoonal regions. Understanding these aspects provides insight into debris loads in a local river system and as well as information on specific sources that help management target local initiatives.

To establish effective ways to stop anthropogenic debris before it enters the marine system, it is important to understand the how the debris arrives into the river system to identify sources. . Thus, the overall aim of this study is to quantify the amount of anthropogenic debris entering a freshwater river system, and identify likely sources, using the Ross River in the tropical city of Townsville, Queensland, Australia as a case study. Since I expect to see higher debris abundances within the river after rainfall events, I aim to investigate the following questions: 1) How does the rainfall season influence the abundance of anthropogenic debris, specifically before, during, and after the wet season? 2) Is there consistent input of debris through time? 3) How much does litter in nearby parks influence debris loads in the river? With these data, I hope to provide some practical solutions to the debris problem in river systems, and therefore mitigate debris at the source before it arrives to the ocean.

3.2 Methods

3.2.1 Site description

All data collection took place in the city of Townsville, North Queensland, Australia, home to approximately 229,000 people (Australian Bureau of Statistics 2016 Census). The Ross River and associated creek system flows through the urban community, discharging into Cleveland Bay, which is part of the Great Barrier Reef World Heritage Area (Figure 3.1). Cleveland Bay contains sensitive habitats, including nearshore reefs and seagrass meadows important to dugong and marine turtle species (Waycott et al., 2005; GBRMPA 2004). The region has an average annual rainfall of 1,143 mm per year (Australia Bureau of Meteorology), 86% of which occurs between the months of September and March. However, in the duration of my study the city has experienced rainfall levels lower than the average annual total; 1027.2 mm in 2014, 398 mm in 2015, 951 mm in 2016, and 657 mm in 2017 (Bureau of Meteorology). Ross River has an impoundment that is used as a reservoir to supply the freshwater to the urban areas of Townsville, with a basin size of about 1,340km^2. There are also three smaller, artificial weirs throughout the river, that impede water flow until large rainfall events provide enough local input for them to overflow (Figure 3.1). This means that any debris entering the system is retained until there is enough rain for the debris to flow over the weirs and out to the bay. Annual discharge varies, depending on the amount of rainfall, which may result in the weirs and dam overflowing. For example, the most recent public report in 2010 suggests that peak flow occurred between 378 m^3/s to 418 m^3/s, but after 150 mm of rain occurred within 12 hours, discharge increased to over 1000 m^3/s (Townsville City Council, 2010). During the sampling time period, the weirs had periods over overflow in the 2014 and 2016-2017 wet season.

3.2.2 Collection methods- River

Prior to 2014 surveys, unstructured clean-ups (meaning not based on quadrat or distance sampling) took place to test site location and note areas of high densities of debris. These unstructured clean-ups occurred just before the river's dam reached capacity and flushed the entire river in April of 2014. At this time, the majority of the debris around the river was removed, providing a baseline for the study. It should be noted that the riparian area of the river was cleaned haphazardly by council, local community groups and clean-up events. However, these events often cover small sections of the river and often has no formal data collection methods.

Anthropogenic debris was subsequently collected from Ross River over three consecutive wet seasons, with collections occurring from October 2014 to June 2017. Since rainfall is likely to wash debris items into storm drains or directly into the river (Lattin et al., 2004; Moore et al., 2002; Rech et al., 2014), all data were collected over three sampling periods; before, after, and during the wet season, hereafter referred to pre-, post, and during. Pre-wet season sampling occurred from October to November of 2014, 2015 and 2017 and post-wet season sampling occurred between January and March of 2015 and 2016. Each site was visited at least once in each season (Appendix 2). To explore the effects of an individual rainfall event, sampling efforts intensified during the 2016-2017 wet season. Debris collections happened after every rain event over 5 mm (Bureau of Meteorology), hereafter described as the 'during' time period.

Anthropogenic debris was collected at the mouth of storm drain effluents from two sites separated by weirs (Figure 3.1). All clean-ups were conducted by two or three people on kayaks, visiting the same two sites, and covering the same area each visit. Surveyors aimed to remove all of the debris items by hand within the specified area during each clean-up. However, it was noted that much of the debris items were obscured by surface vegetation, which could be more visible depending on the number of surveyors. No other equipment except gloves, bags, and sharps containers, were used. Site 1 is enclosed by weirs, approximately 0.09 km^2 in area. The area between weirs around site 2 was 0.75 km^2 and therefore impossible to clean the entire area in a single clean-up event in a manageable time period. As such, clean-ups were concentrated outside storm drains where the density of the debris had been found to be the highest (based on pilot expeditions), approximately 0.08km^2 area (shown by blue lines in Figure 3.1). The number of people and the time spent sampling was recorded after each clean-up to quantify sampling effort. Dates of clean-ups for both sites were paired where possible and dependent upon time, volunteer availability, and weather conditions. . However, due to time constraints this could not happen for every clean-up event. For example, during the 2016-2017 wet season, a clean-up did not occur in January for site 2 due to unforeseen circumstances. In addition, site 2 was visited twice in the post-wet season sampling, because we did not complete the site during a rainfall event, and I was not able to return to the site until after the event, due to safety of volunteers.

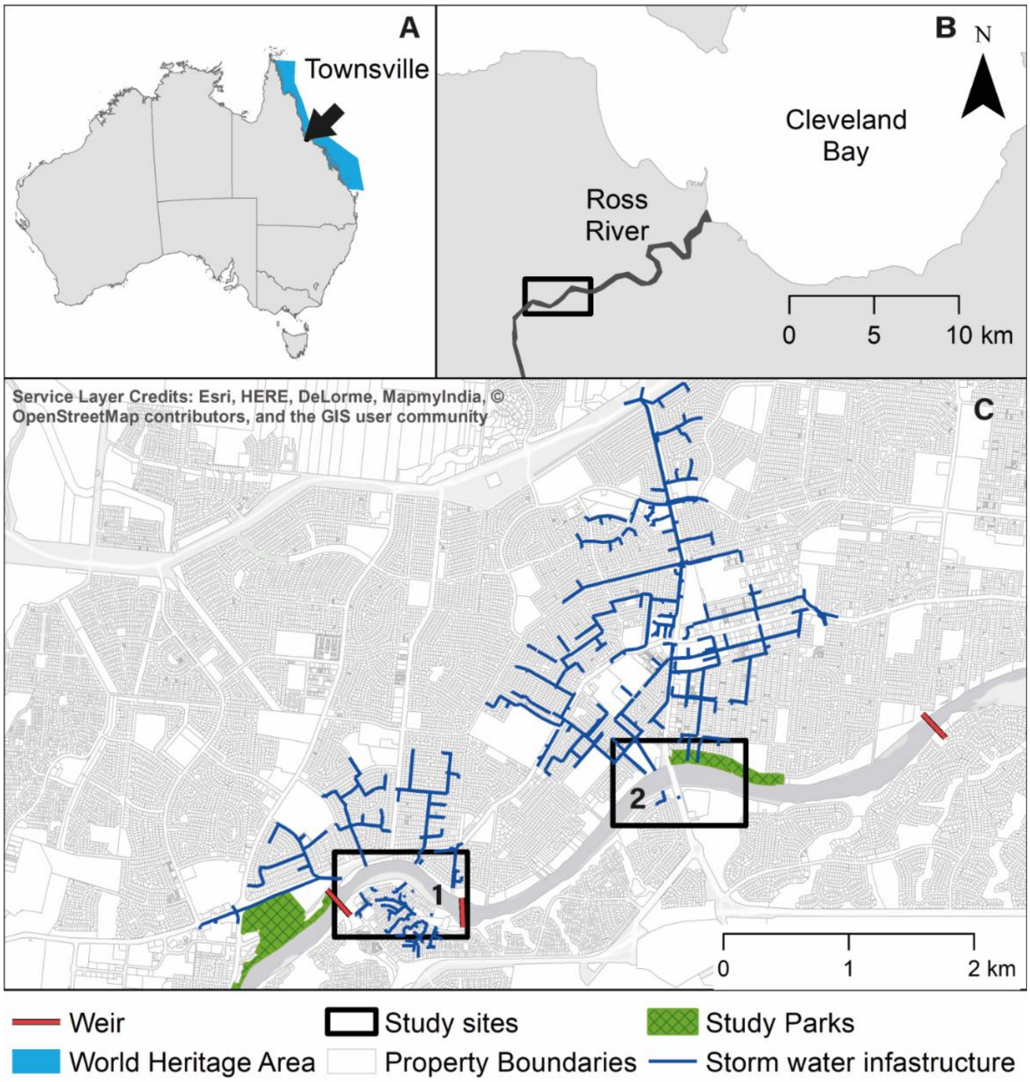


Figure 3.1: *Map of site locations. Items were collected in areas enclosed by black box, with the left as site 1, and the right as site 2. Blue lines indicate channels along streets for each storm drain. Map layers provided by Queensland Spatial Catalogue: http://qldspatial.information.qld.gov.au, and Townsville City Council.*

3.2.3 Collection methods- Park

To determine how much of the anthropogenic debris was originating from the surrounding areas and parklands adjacent to the study sites at any given point of time, clean-up data were opportunistically used from Clean-up Australia Day (CUAD), and clean-ups organised by the non-profit, citizen science organisation, Tangaroa Blue at two separate dates collected during the 2016-2017 wet season. CUAD is a nation-wide clean-up event and campaign, where volunteers around the country pick up debris in public parks and beaches (https://www.cleanupaustraliaday.org.au). . Likewise, Tangaroa Blue is also a volunteer organisation that regularly organises clean ups around the country (https://www.tangaroablue.org/database.html). I worked with Townsville City Council to set aside CUAD bags of collected waste from river-side parks to sort, using the same methods as I used for my in-river clean-up data (see below). Parklands chosen were situated as close to the river cleaning sites as possible (Figure 3.1). The park near site 1 is approximately 200m from the edge of the river site, whereas the park near site 2 is approximately 50m away. All parkland clean-ups occurred within the 2017 wet season, in the same time period as the 'during' wet season river sampling. Unfortunately, the land-based were organised separately to the kayak-based clean-ups, and only the data during the 2017-2017 time period could be obtained. The debris type and abundance found in the river can be compared to the adjacent parklands to provide additional information regarding how much of the debris was originating from the storm drains, or nearby parks along the river.

3.2.4 Sorting methods

Anthropogenic debris collected from clean-ups were sorted into categories based on the Australian Marine Debris Database (https://www.tangaroablue.org/resources.html) to standardise identification to other studies across Australia. Using this format I focused on the broader categories of debris, including plastic packaging (such as plastic drink bottles, plastic bags, plastic cups, and straws), food containers (such as paper/waxed packaging, and drink cartons), Styrofoam, toys (including balloons), cigarette items, personal care items, clothes and footwear, and fishing related items.

3.2.5 Data analysis

Since clean-ups occurred in a fluid, aquatic environment, where the number of people and time taken to search for debris influenced the ability to detect and collect items, all clean-up data were standardised to the number of debris items per unit of effort (number of surveyors multiplied by the number of hours the group spent sampling, as per (Hardesty et al., 2017; Maunder and Punt, 2004; Nelms et al., 2017). All statistical analyses were performed using SPSS.

To compare the abundance of anthropogenic debris across sampling seasons and across sites, a two-way ANOVA was used, with a Tukey's HSD post hoc. Data were found to be normally distributed with a Shapiro-Wilk normality test, and Levene's test of homogeneity. Since some of the seasonal observations did not occur across all years, a separate one-way ANOVA was used to compare abundances of debris items across sampling years to determine if there was consistent input of debris within the river system through time (2015-2017). The same test was performed among the most common debris types, collected across seasons. This was to further identify if there were any changes in patterns for specific debris items. Items that were evident across multiple sampling times were compared, with items that were singletons or not presented in all sampling times were excluded from analysis. A complete list of debris items can be found in Appendix 2. Most common debris items were identified as the top 10 most abundant items collected. Since some item abundances differed among years, a ranking system was used to identify overall top items across all sampling periods.

Lastly, to compare the abundance of anthropogenic debris collected in the parklands to that collected in the river, the percent abundance of individual plastic items were calculated for in river and park sites. Since it was not known how much effort (person hours) was given during the clean-ups performed by volunteers in Clean-up Australia Day, and other larger scale events, I analysed the proportional abundance of debris. Debris abundance on land was only compared to the data collected during the 2017-2017 wet season since this only occurred once during the sampling period. I then analysed the top 10 most abundant items to compare the abundance of specific debris types between the river and parklands.

3.3 Results

A total of 27,943 items of anthropogenic debris were collected from the two study sites of the Ross River adjacent to storm drains over three consecutive wet seasons. A large proportion of the collected debris was plastics, 91% in site 1 and 93% in site 2. Metal items made up 5% of the total debris, and all other materials (glass, cloth/footwear, paper, wood, and unknown) collectively made up the remaining 2% of the total debris items. In a single wet season (September 2016- June 2017), a total of 2,766 plastic food packing items, 1,089 straws, 1,028 foam insulation remnants, 804 soft plastic remnants, 990 plastic bottle tops, and 458 plastic bags were collected from both river sites.

3.3.1 Debris trends through time

Over the course of three years, the average abundance of anthropogenic debris decreased, with the highest amount of debris collected in 2015, with a total of 395 items per unit effort (Figure 3.2). This was significantly greater than the debris collected in 2016 ($F(3,24) = 9.451$, $p = 0.006$), and 2017 ($p < 0.000$). Overall, the abundance of debris differed among seasons ($F(2,22) = 5.226$, $p = 0.014$), where the debris collected in the post-wet season was significantly greater than during the wet season ($F(2,22) = 5.226$, $p = 0.023$, Figure 3.3). No significant difference was found between the total debris collected in the pre- and during-wet season ($p = 0.894$), or pre- and post-wet ($p=0.171$). In addition, there was no significant interaction between site and season ($F(1, 2) = 3.322$, $p = 0.055$), however, when only looking at the most common items, there was a significant interaction detected ($F(1, 2) = 2.265$, p-value = 0.026, Figure 3.4). That is, at site 1, the most common items such as straws, drink bottles, plastic bottle caps, plastic cups, hard plastic pieces, and metal cans were significantly more abundant in the post-wet season sampling period than either the pre-wet or during. However, this same pattern did not occur in site 2, with only plastic bottles being significantly greater in abundance in the post-wet season.

The number of anthropogenic items entering the system after every rain event varied from 23 items per unit of effort to 188 items per unit effort in site 1 (average of 102 items/effort per rainfall event), and 70 to 287 at site 2 (average of 185 items/effort per rainfall event). Fewer items were collected in May through to June (dry season), after heavier rainfall (Figure 3.5). During the 2017 wet season, the number of items entering site 1 appeared to decrease after January sampling, but remained high until March at site 2. During the 2017 intensive sampling there was an average input of 23 (+/- 7) items per day at the site 1, and 32 (+/- 9) items per day at site 2.

3.3.2 Comparison of parkland and river debris

In comparison to the anthropogenic debris collected in the river, 82% of the items collected in the park area near site 1 were plastic, and 69% in the park near to site 2 were plastic. Among the most common items, there was a greater disparity of plastic food packaging abundance in the parklands compared to the river near site 2 than that found near site 1. Plastic food packaging in parklands made up 19% near site 1, and 7% near site 2, compared to the 22% in both river sites (Figure 3.6). However, there was a higher percentage of specific plastic items, such as utensils, plastic remnants and aluminium cans in site 1 parks. The same pattern did not occur in site 2, instead, only the relative abundance of plastic remnants and unknown plastics was higher in nearby parklands near site 2 than in the river.

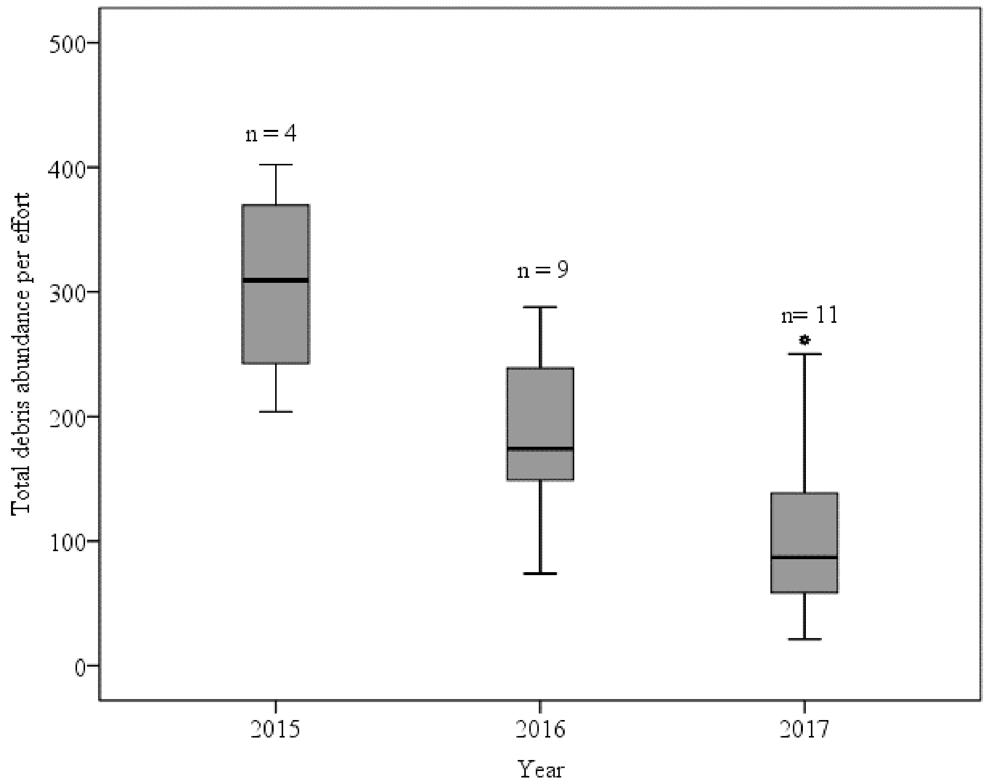


Figure 3.2: *Average abundance of anthropogenic debris per effort (number of samplers multiplied by the total hours spent sampling) collected from the river, across years sampled. Note that 2014 clean-up was not included as only one clean up occurred at each site (n=2). Boxes represent the median, with the upper and lower quartiles. Whiskers represent maximum value, or a 95% confidence if outlier occurs. * indicates outliers (1.5 x Inter-Quartile-Range).*

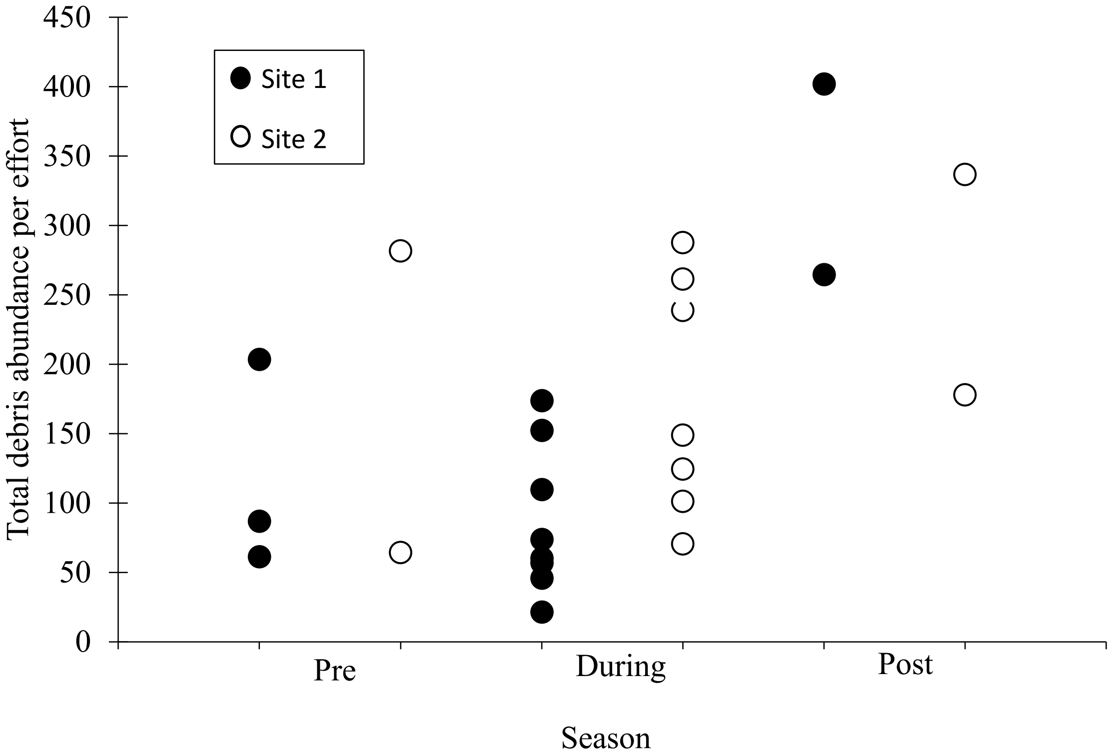


Figure 3.3: *Range of debris items per unit of effort collected on each clean up across all seasons. Each dot represents a clean-up effort.*

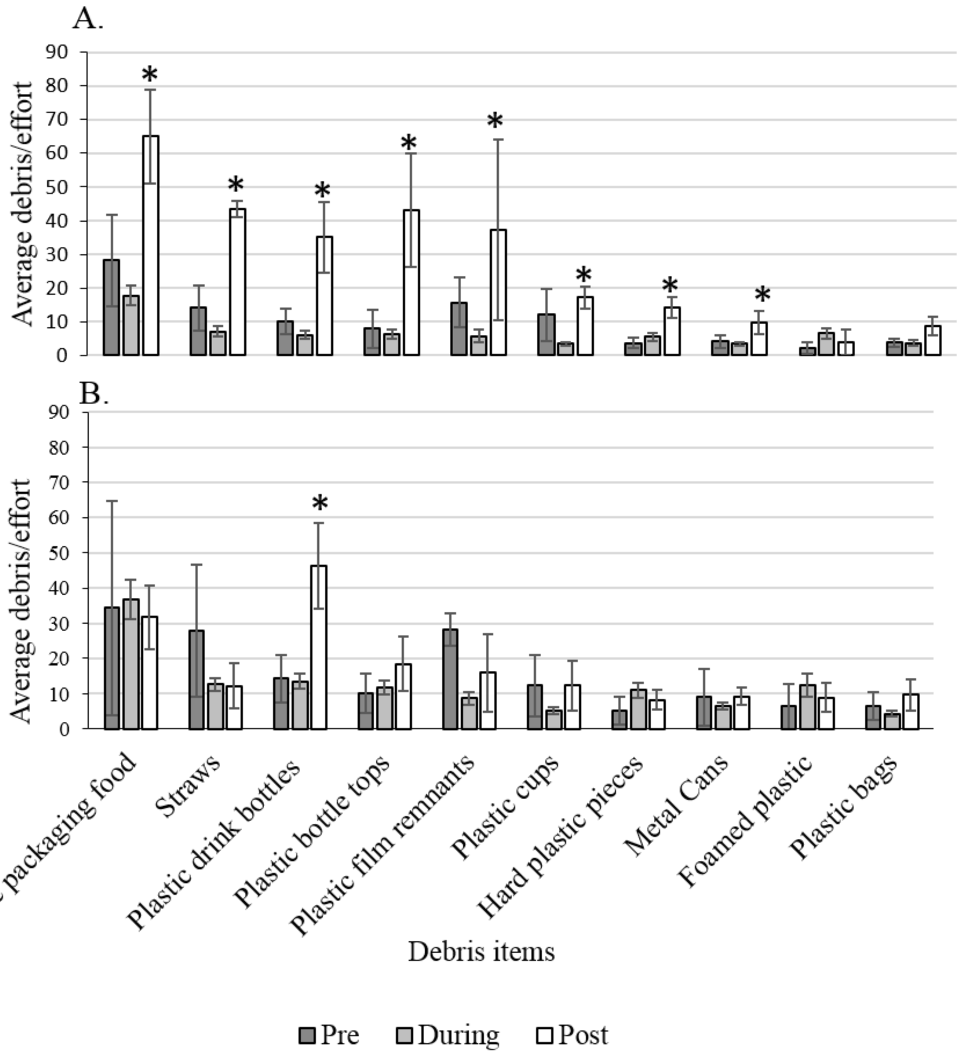


Figure 3.4: *A comparison of the average abundance of debris for site 1 (A.) and site 2 (B.) per unit of effort (+/-SE) of the top ten most abundant items recorded in the pre-, post-, and during the wet season. * Signifies a significant difference between sites.*

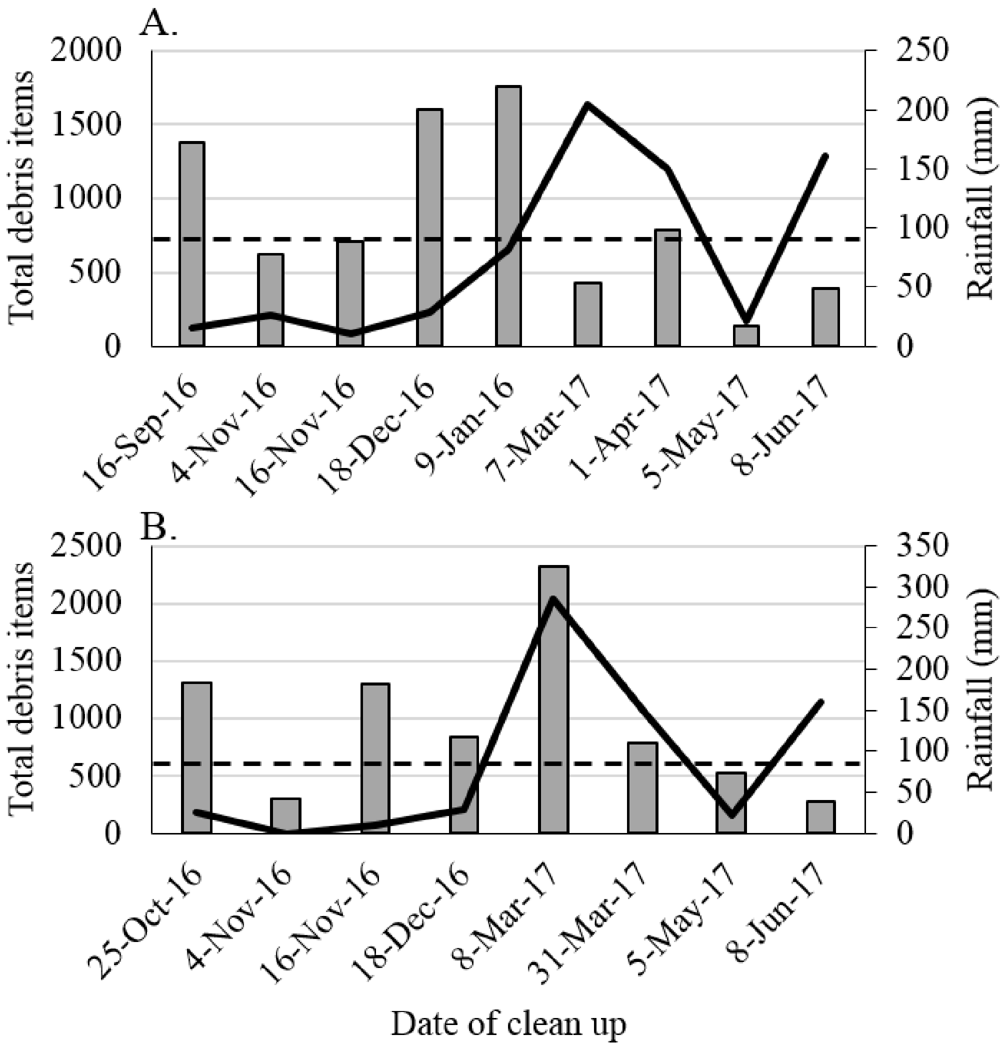


Figure 3.5: *Number anthropogenic debris items collected over the 2016-2017 wet season in comparison to the amount of rainfall since the last clean up (solid black line), with A as site 1 and B as site 2. The dotted line denotes the average rainfall over the year (1134mm/12 months), anything above the dotted line indicates relatively heavy rainfall. Note, sampling days differ slightly between sites. Note that differences in y-axis range occurs.*

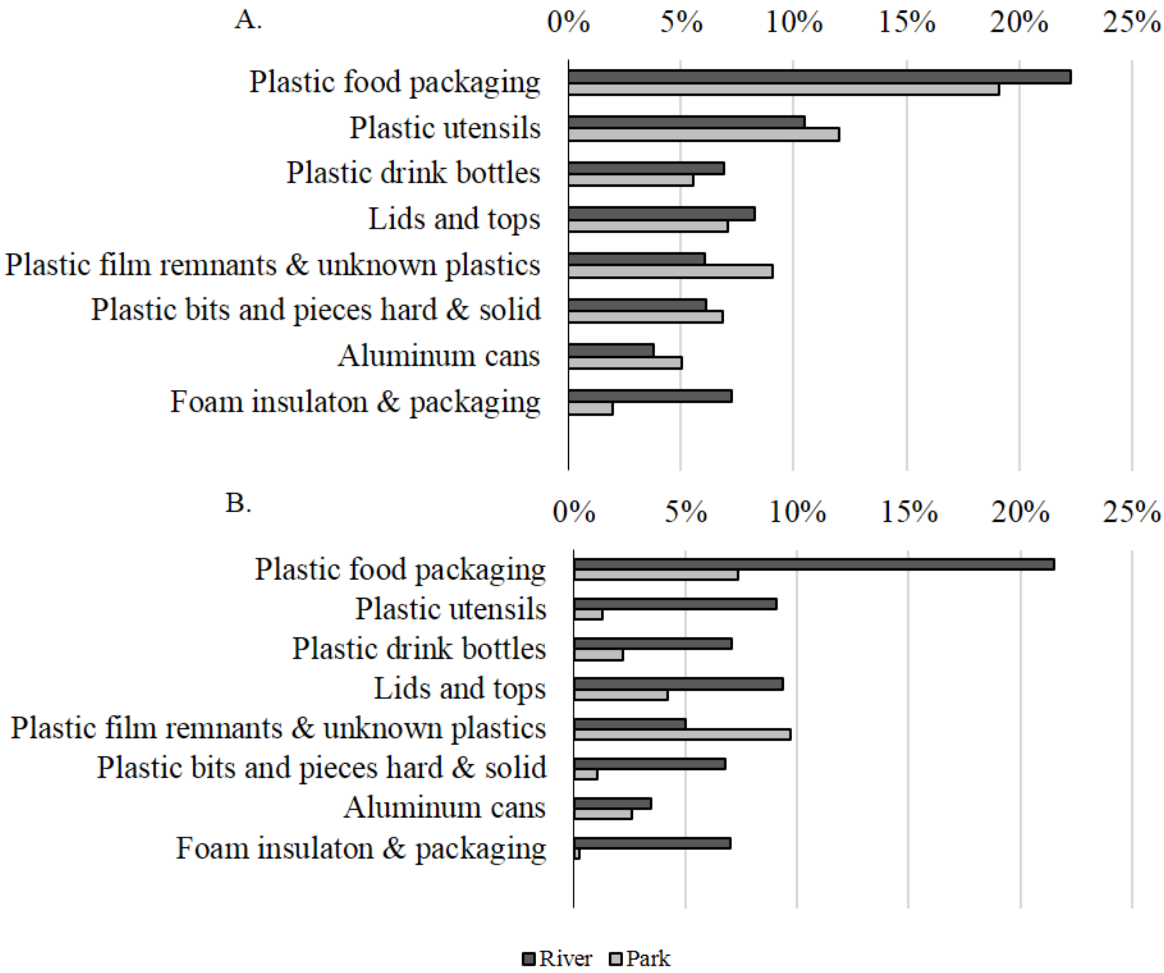


Figure 3.6: *The percent of most common anthropogenic debris collected from the river compared to that adjacent parks cleaned in two separate occasions during the 2016-2017 wet season for site 1 (A), and site 2 (B).*

3.4 Discussion

This research shows that large quantities of anthropogenic debris, primarily single-use plastics, are found in tropical Queensland river systems, and can ultimately flow into the ocean after monsoonal flushes. Furthermore, my results suggest that, in low rainfall years, there is a relatively consistent input of anthropogenic debris that accumulates in the river. Results of this study showed no significant difference between the abundance of items collected during the wet season and the pre-wet season, suggesting that wind or direct littering into the river from nearby parks, schools or public spaces, may be as large a source of debris as the storm water discharge during rainfall events. It is also possible that small rainfall events that occur haphazardly outside the wet-season contribute to debris deposited in the river between the post-wet and the next pre-wet sampling periods. Other studies have identified storm drains as a likely source of anthropogenic debris. For example, Duckett and Repaci (2015) found correlations of the overall abundance of anthropogenic debris and number of storm water effluents emptying onto beaches (Cunningham and Wilson, 2003; Duckett and Repaci, 2015).

My results are similar to what has been found by council reports in in Mackay, a city 388km south of Townsville and approximately 1/5th the population size. Here, a total of 8,281 anthropogenic debris items were recorded from 35 gross pollutant traps placed outside of the storm drains effluents at six sites between March 2014 and June 2015 (Mackay Regional Council, 2015). In comparison, I collected a total of 10,440 items in the same time frame from two sites in Townsville, but this is likely an underestimate due to missed items that sink or those which were obscured from view (Morritt et al., 2014). While these numbers are relatively small compared to studies in large cities in populated areas of Europe, Chile, and California, where up to millions of items flow out of large scale rivers per day (e.g. up to 36 tons of plastic debris in the Seine River in one year) (Gasperi et al., 2014; Morritt et al., 2014; Rech et al., 2014; Schmidt et al., 2017)., my results suggests that a considerable amount of litter is capable of flowing from relatively small cities in North Queensland.

The variation in rainfall totals across the sampling period (2014-2017) was likely to have influenced the accumulation of anthropogenic debris items in the river (Figure 3.5). Low rainfall in 2015 led to restricted water flow, and as a result, any items blown or washed into the river were likely to be retained. In addition, any anthropogenic debris entering the system following heavier rainfall in 2014 could have accumulated in the time between the weirs overflowing and my sampling. Moreover, after heavy rainfall events (heavy being greater than monthly average of 95mm), for example, when over 200 mm of rainfall occurred in March of 2017 (Figure 3.5), it is possible that debris items were washed away or submerged before they were able to be collected (especially at site 2, where the collection site did not cover the entire area between the weirs), creating the illusion of less debris in the system (Kooi et al., 2018; Moore et al., 2011). This pattern is illustrated on a smaller scale during the 2016-2017 wet season, where more debris items were collected during multiple lower volume rainfall events, rather than after a heavier rainfall event (as shown in Figure 3.5). Therefore, it is likely that the fluctuations between light and heavy localised rainfall in addition to the catchment area influences the dispersal and distribution of debris located within the river.

Unexpectedly, I did not cumulatively collect more anthropogenic debris items during the wet season than I did in the post-wet. This is in contrast to previous research where debris loads increased after rainfall events (e.g. Moore et al., 2011). Originally, I thought I would be able to capture more of the debris before it washed away, or sank, but instead I found that that frequency in which debris enters the river system is more likely to be due to variance in rainfall and wind patterns. Regardless, I collected 1,656 pieces of litter in the river immediately after rainfall events (a total of 724mm of rain), which suggests that large amounts of anthropogenic debris is entering the system after each rainfall. It is also important to highlight that during times of river flow (which occurred during the 2016-2017 wet season), the surface vegetation often becomes concentrated by wind and river flow, and sometimes covered the entire river surface making it difficult to navigate and access. This surface vegetation traps debris and prevents it from flowing downstream, and therefore could obscure the actual timing of debris input. Moreover, heavy surface vegetation could also have obscured the anthropogenic debris from view and this would influence the amount of debris visible to surveyors and thus reduce the amounts collected. Unfortunately, the surface vegetation was too thick and heavy to remove with such a small team of surveyors on kayaks.

Our study was able to identify inland sources of litter, outside river systems directly contributing to the abundance found in the river. The strongest evidence for this comes from the proportion of plastic debris found in the park near site 1 is nearly identical to that found in the river, and therefore may be one of the primary sources of debris abundance in that area. However, there seemed to be a disparity in the proportion of the most abundant littered items in parks near site 2 and those found within the river. These results were similar to that found in Carpenter and Wolverton (2017), where anthropogenic debris within streams depended on the context and use of the surrounding area. I stress that future research examining the sources and inputs of debris into aquatic systems should be expanded to include surveys of adjacent or nearby parklands to help pinpoint exact debris sources for source reduction management.

3.4.1 Potential solutions

Over the course of a single wet season, it took 108 person hours to clean approximately two square kilometres of the Ross River. Using average wages in Townsville (approximately $26 per hour) (estimated via Payscale.com), this effort is worth AUD$2,700 per year to clean these sections of the river, and therefore hypothetically, AUD$66,150 per year to clean the entire 49 km length of Ross River. These figures are estimates as this data has not been published in literature, to my knowledge. This does not include volunteer hours of people cleaning parklands and beaches individually and through other citizen science or community events. Regular clean-ups are costly for local councils, and therefore, unlikely to be sustained across the entire river. Instead, I recommend the following strategies be considered in relation to the local socio-economic context to reduce debris loads entering local river systems:

1. **Implementing infrastructure**, such as river booms, gross pollutant traps and Sea Bins, is useful to reduce anthropogenic debris loads entering into rivers and creeks (Gasperi et al., 2014). River booms used to capture floating debris have been implemented in other areas of Australia, such as Adelaide, Melbourne, Sydney and Cairns. Gross pollutant traps have been implemented in Mackay. Furthermore, floating 'Sea Bins' have been recently implemented in Perth marinas to remove littered items within marinas. The cost in Australia for a small scale river booms (15-30 meters) is between AUD$200 and AUD$5,000 depending on type and size (via Spillpro.com.au). These costs increase for larger infrastructure (such as those that cross entire river estuaries). For example, in the United States, large booms can cost up to USD$36,000 with USD$16,000 in annual maintenance fees (Santa Clara Valley Urban Runoff Pollution Prevention Program). To reduce maintenance costs such as regular debris removal and equipment repairs, the river boom in Townsville could be strategically placed only during the wet seasons, downstream to avoid capturing the bulk of the surface vegetation and directly outside storm drain effluents. However, the efficiency of this infrastructure is not well understood (Gasperi et al., 2014), and cannot act alone. In addition, it should be noted that the cheap inflatable booms can also degrade in the sun over time. Therefore, I stress that this infrastructure should be used in combination with the suggestions below.

2. **Anti-littering campaigns** are popular management tools and may be more effective in sites that are more driven by wind, whereas storm drain socks or river booms may be most beneficial for sites influenced by rain events. This includes targeted debris management for the most common items may also be necessary to reduce debris loads in and around the river. For example, 22% and 19% of the items at site 1 and the nearby park, respectively, were snack-sized food packaging items. I also found more pens, highlighters, and markers, at site 1 than site 2 (Appendix 2). These items may originate from the school grounds that border site 1, and/or from the school-age children that frequent the surrounding park and bike paths in transit from other neighbourhood schools or shopping centres. Therefore, providing focused efforts, initiatives and educational material to the children that attend Townsville schools, could be a solution to reducing litter in the area. Other management strategies, such as ensuring that bins in nearby parks are regularly maintained and emptied, in addition to educational signage would benefit these areas. Straws made up a significant proportion of the debris in the river (7% at both sites) therefore targeted action to eliminate unnecessary straws from local shops and cafes could reduce total debris in the environment.

3. **Collaboration between scientists, community groups, local government**, **and industry** is important for debris monitoring programs and initiatives. A significant challenge of this study was finding the many small scale, informal data collection efforts done by local councils on litter and debris abundance in local river systems, as well as in Australia. Moreover, the issue of plastic pollution currently has the public's attention, and thus some parks and public spaces are cleaned in informal ways. These small and informal collections could be a useful resource for management, however, these data are not often collected, shared, or publicly available. Improved collaboration between scientists, community groups and councils (or other organisations collecting data) would provide an improved picture of small scale debris patterns. This could be achieved through standardised data collection, such as the Australian Marine Debris Initiative (Tangaroa Blue).To help this issue, all data was uploaded in the Australian Marine Debris Initiative database in effort to make a collaborative approach to reduce the litter issue in Townsville. Further

coordinated approaches would be valuable to compare anthropogenic debris types, abundances, and patterns between regions, and share information on effective mitigation strategies.

3.5 Conclusion

My research identifies that there is large and consistent supply of anthropogenic debris entering a small Australian river system that has the potential to enter the Great Barrier Reef World Heritage Area from a small city in North Queensland. The monitoring of these debris loads within this river system provides information on a management relevant scale to reduce debris before it enters the ocean. Furthermore, this dataset provides the unique opportunity to test for the effect of local and state government legislation, such as the recent plastic bag bans and container deposit scheme, as well as, local scale anti-straw campaigns. I stress that continuously monitoring the river in a systematic way is important to further identify sources and therefore help reduce anthropogenic debris in aquatic environments.

Chapter 4
Microplastic loads in an Australian tropical river system

Around the world, river systems can carry large abundances of microplastics (plastic <5mm in size) from inland communities to the ocean. To determine plastic loads within an Australian river system, sediment and water samples were collected outside storm water effluents in the Ross River in Townsville, North Queensland. Since the river system is located in the monsoonal tropics, samples were collected before and after the wet season to assess the seasonal input of microplastic in aquatic systems. Samples were also collected within the estuary and bay to determine if plastic abundance in coastal waters increases after rainfall. Results showed a 16% increase of microplastic abundance within the water samples of the freshwater section of the river after a heavy rainfall event, but no differences in any other location throughout the estuary and bay. However, high variability within and among locations means that no significant difference in microplastic loads was detected between seasons in either the water or sediment samples. There was also no significant increase of microplastics in water or sediment after the wet season outside of storm drains. The results of this study indicate that microplastics are always present even in a relatively small tropical river system, but heavy rainfall (in excess of 687mm) is likely needed to contribute to ocean concentrations of microplastic pollution. Overall, this dataset provides a baseline against which plastic loads can be compared over time, and suggests the reduction of macroplastics is likely to be a more effective method for reducing microplastic loads within urban rivers than managing inputs of microplastics directly.

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4.1 Introduction

It is recently estimated that there are somewhere between 5 to 51 trillion particles of plastic in the global oceans, a number which is predicted to increase in future years (Eriksen et al., 2014; Jambeck et al., 2015; van Sebille et al., 2015). The high uncertainty in these estimates is associated with a lack of knowledge of the breakdown rates of large plastic items into microplastics (plastic < 5 mm in size) and the scarcity of data quantifying inputs of plastic into the ocean from different sources (Auta et al., 2017; Critchell et al., 2019). In addition to a lack of knowledge of plastic inputs into the ocean, the relative threat to marine, terrestrial, and freshwater habitats from microplastic pollution is not fully understood (Eerkes-Medrano et al., 2015). As a result, research regarding microplastic quantity, fate, and impacts is increasingly important to determine management strategies at local, national, and global scales.

Microplastic particles in river systems have been found in sediment, water, bivalves and fish (Castaneda et al., 2014; Mani et al., 2015; Sanchez et al., 2014). In some cases, the abundance of microplastic particles in the water column outnumbers fish larvae (Lechner et al., 2014). Studies conducted in the last five years have shown that plastic can enter freshwater systems through numerous sources, such as atmospheric fall out (plastic in dust and air), industrial spills, storm water run-off, and sewage effluents (Dris et al., 2018). Furthermore, the debris from these sources can accumulate, especially if the river passes through multiple urban communities (Dris et al., 2018; Koutsodendris et al., 2008; Lechner et al., 2014). Accumulation of microplastic particles within river systems can potentially have severe impacts on the freshwater systems themselves, as well as act as a major source of microplastic particles to the marine environment (Lebreton et al., 2017; Lechner et al., 2014). However, the abundance and sources of plastics and microplastics in freshwater systems is likely to vary depending on local contexts. Therefore, further research is needed to understand microplastic abundances and sources in freshwater systems to help manage loads entering the marine system.

Microplastic pollution, and its dispersal from freshwater to marine systems can be heavily influenced by rainfall events or seasonal inflow of water (Dris et al., 2018). Similar to macro plastics, this is likely to occur because microplastics from the surrounding urban communities can be washed into storm drains and are then expelled directly into the river system (Baldwin et al., 2016; Horton et al., 2017b; Peng et al., 2018). Recent research has identified an increased abundance of plastic in estuaries after periods of rainfall (e.g. Cheung et al. 2016). However, few studies have attempted to quantify how many microplastics enter marine and freshwater environments from specific sources (such as storm drains), or compared the abundance of microplastic loads in the environment after seasonal rainfall (Dris et al., 2018). Furthermore, identifying and monitoring specific sources of microplastics in freshwater systems can be easier than waiting until the plastics have dispersed into the marine environment, as particles likely occur at higher densities, are often less degraded, and biofouling is minimal (Eriksen et al. 2018). Therefore, monitoring plastic loads directly after rain events, and outside specific point sources, can help quantify exactly where and how plastic enters aquatic systems. Such location-specific knowledge could thus help identify more cost-effective means of clean-up or prevention.

In Australian coastal waters, there is an estimated oceanic concentration of approximately 4200-9000 microplastic particles per km^2 (Reisser et al., 2013). However, it is unknown how much of the microplastic loads in Australia's oceans are derived from local sources. River systems pass through all of the coastal cities of Australia, but there is currently no peer reviewed literature identifying or monitoring microplastic loads in freshwater or estuarine systems of Australia (Critchell et al., 2019). Furthermore, there has yet to be an attempt to quantify plastic loads from specific sources, such storm water drains. Therefore, this study aims to quantify loads of microplastic pollution in a freshwater system of Australia and in doing so, create a baseline assessment of plastic loads and identification of potential sources. Since higher pollution rates within storm water effluents has been correlated with rainfall volume, particularly in monsoonal areas of the Australian tropics (Dris et al., 2018; Kim et al., 2007), I here assess microplastic abundance in a river system that flows through the largest city of tropical north Queensland as a case study. To do this, I aimed to answer the following specific questions: 1) what are the microplastic loads in a Queensland river system; 2) are microplastic concentrations close to storm drains elevated after rainfall events; 3) are microplastic concentrations in coastal waters adjacent to the river mouth elevated after seasonal rainfall flushes?

4.2 Materials and Methods

4.2.1 Field methods

Site Description. All samples were collected from Ross River in Townsville, Queensland, Australia. Ross River is 49 kilometres in length and runs through Townsville in close proximity to the urban environment, and empties into Cleveland Bay which is part of the Great Barrier Reef World Heritage Area (GBRWHA) (Bauer-Civiello Ch. 3, Fig. 3.1). The river is dammed as the primary water source for the city of Townsville, and three weirs exist within the river to help regulate river flow. These weirs can overflow after a large rain event, particularly during the wet season. Storm water drains are situated throughout the city, with multiple drainage channels leading directly to the river (See Chapter 3 Figure 3.1 and 4.1 below). No other effluents (such as treated sewage) directly enter the river.

To determine whether storm drains are a source for microplastic pollution, sediment and water samples were collected from the Ross River directly adjacent to effluents (see below for more details).. Since rainfall is likely to influence the amount of water flowing from storm drains into the river, sampling was completed both before and after the wet season. This sampling design allowed me to determine how much plastic is present in the sampled portion of the river system, whether plastic abundance is elevated after rainfall, and potentially, whether microplastic exits the river system into the GBRWHA. For this study, I focussed on a total of seven storm drains, six of which occur in the freshwater section of the river, and the other located in the estuary. Drain locations were chosen based on known locations of high debris abundance as identified in Chapter 3. Furthermore, drains within the freshwater section were seperated by two artificial weirs that impeed water flow during the dry season (as described in Chapter 1, Box 1; Figure 1.1 and Chapter 3, Figure 3.1). This divides the river into four sections, and sampling occurred in three of these sections.

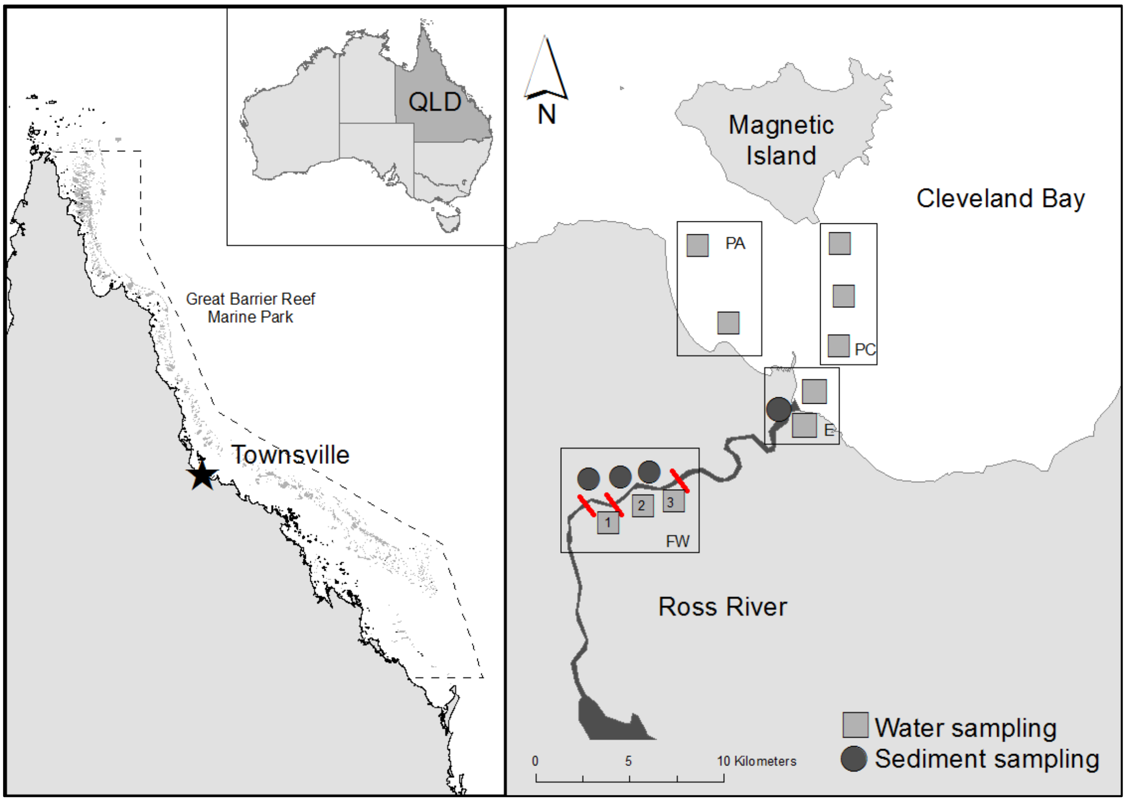

Figure 4.1: *Map of sampling sites on Ross River. Water sampling sites are indicated with squares, and sediment sampling sites are indicated with circles. Red lines indicate placement of artificial weirs. Box outline indicate grouped locations, Freshwater (FW), Estuary and River mouth (E), Port channel (PC), and Pallarenda (PA). Paired sediment and water sampling occurred 1) Downstream, 2) Mid-stream, and 3) Upstream. During rainfall events, water flow from Ross River is likely to flow north past Pallarenda, or along the east side of Magnetic island and around (Critchell et. al. 2015).*

Water Sampling. Water samples were collected adjacent to specific storm drain effluents within the four different sections of the river (Figure 4.1). To detect whether plastic was exiting the river, water samples were also collected within the river mouth (at high and low tide) and at six sites in Cleveland Bay, before the wet season in November of 2016, and once after the wet season in May 2017. Sampling sites located in Cleveland Bay were chosen based on hydrodynamic models that predict the most likely dispersal path of particles exiting the river during flood (Critchell et al., 2015).

Plastic on the water surface was sampled by performing plankton tows with a 63 µm mesh net and a 1 L mesh cod end (Sea-Gear Corporation, USA). Since some areas of the freshwater section of the river were shallow and narrow (particularly during the dry season), a relatively small net was used for all of sampling (2 m long, 0.5 m diameter). Each tow was performed for 5 minutes at a speed of approximately 3-6 knots, and the net was pulled behind the boat, away from the engine flow (Hall et al., 2015). Three replicate tows were performed at each site and GPS coordinates were collected at the start and end of each tow to determine exact distance travelled and water volume sampled. Objects captured in the net were transferred into a glass jar at the end of the tow for laboratory processing. All jars and equipment were washed with detergent and rinsed three times with tap water before sampling, and were also rinsed (with river or ocean water) three times *in situ* to reduce plastic contamination from outside sources (Barrows et al., 2017).

Sediment Sampling. To quantify plastic abundance within the sediments of the river, a pilot study was first performed to determine the number of samples needed to account for within-site variation, and to refine laboratory methods for extracting microplastics from fine sediments. Sediments were collected using a 5 L Van Veen sediment grab (432 cm^2 sampling area) deployed from a small vessel adjacent to each of the seven storm drains selected for sampling. A gradient sampling design was used to determine plastic accumulation outside of the storm drains (Ellis and Schneider, 1997), in which sediment samples were taken along three replicate transect lines which fanned out from each drainage point. Since the majority of the effluents led directly into the river, difficult to access, or surrounded by rocks or concrete, the banks of the river were not sampled in this study. The pilot study indicated no statistically significant relationship between plastic abundance and the distance from the drain a sample was collected ($K\text{-}W(1, 6) = 0.549$, $p = 0.459$). Therefore, subsequent sediment grabs were taken at distances of 1 m and 27 m away from the mouth of each storm drain along three transect lines from each drain ($n = 6$ per drain), which were both pooled and kept separately depending on analysis (see data analysis below). For storm drains that had rocky or cement areas along the river edge, the starting point of all three transect lines was the closet area with soft sediment adjacent to this rock/cement. Despite this, some sampling points were too rocky to collect sediment. Collected sediment samples were transferred from the grab into an aluminium tin and covered with aluminium foil. Before use, each tin was rinsed with tap water, then rinsed (with river water) 3 times *in situ*, before placing sediment in the tin (Barrows et al., 2017). This was to remove any potential outside contaminates from storing and transporting the containers. It was assumed that any microplastics occurring on the surface of the water would be similar to that found in the sediments.

4.2.2 Laboratory plastic extraction methods

Plastic extraction & quantification - water samples. Entire samples were vacuum filtered onto Macro Science MS GA (porosity 1.6 μm) glass filter papers. If significant amounts of organic material was present (which largely occurred in salt water/brine samples), samples were left to settle for at least 0.5 h and the supernatant of the sample was vacuum filtered. For a subset of these samples from the pre-wet season sampling event (n = 8), the organic matter was retained and visually inspected. For these samples, no plastic particles were observed to be trapped in the organic material. However, due to difficulties in extracting and examining this organic matter, which often contained gelatinous matter that formed thick flocs, microplastic particle loads in samples with high organic matter content may be underestimated (see Discussion section). Filter papers containing microplastics and other material filtered from the samples, were immediately placed in a fume hood, or on the bench, and covered by clean aluminium foil for drying. Once dried, filter papers were transferred into aluminium foil envelopes and stored in a refrigerator prior to visual inspection to count microplastic abundance.

Microplastic particles on the filter papers were counted using a dissecting microscope under 4x magnification. Items were identified as plastic based on colour, shape, texture, and brittleness, and were classified as either particles or fibres (Wu et al., 2018). Counted particles were also tallied under categories based on level of certainty that it was plastic: high certainty plastic particles and fibres, low certainty plastic particles and fibres, and non-plastic particles. The colour of all items was noted during counting. Items that were considered not plastic consisted of organic material, glass, or metal fragments. Particles were randomly selected and retained to account as the most common particle types, and were placed in small plastic vials for subsequent analysis using Fourier-Transform-Infrared (FTIR) spectroscopy (see section 4.2.5 below).

Plastic extraction & quantification - sediment samples. The river sediment collected had a wide range of base-substrate types, from rocky material to leaf litter and detritus. The majority of the sediment was fine silts and clays with a high organic matter content. As such, many of the protocols previously used to extract microplastic from sediments resulted in low plastic recovery during pilot trials (Appendix 3).

Consequently, several extraction protocols were tested to improve recovery (as noted in Appendix 3) before analysis of the full sample set commenced. These pilot trials revealed that sieving dried sediment into 2 mm and 1 mm size grain size fractions resulted in the highest recovery rates. Consequently, to extract microplastic from sediments, all samples were dried under a fume hood for 1 to 3 days (fine clay-like sediment typically took longer to dry than other sediment types). Sediments were then sieved through a set of metal geological sieves with mesh diameters of 2 mm and 1 mm, and both size classes were weighed. Sediments and other material retained in the 2 mm sieve were visually inspected, and plastics in this size fraction were removed with forceps, counted, and retained for subsequent FTIR analysis. Any macro plastics (plastics > 5 mm) or other anthropogenic debris items also collected within the grab were counted and categorised. Since the plastics within the 1-1.99 mm size range were too difficult to see without a microscope, and were numerically more abundant, sediment from this size category was subsampled for counting. To do so, sediments were mixed using a wooden or metal spoon and three replicate subsamples, each 10% of the sediment weight, were taken. Each subsample was placed in a petri dish and examined under a dissecting microscope using 1 x magnification. Plastic particles for both size ranges were identified, removed, and categorised as per particles from the water samples. Categories including high certainty plastic fragments, high certainty plastic fibres, low certainty plastics particles, low certainty plastics fibres, and non-plastic particles, were retained and placed into plastic vials for subsequent FTIR analysis. Sediments in the <1 mm size fraction were not analysed due to difficulties associated with confidently distinguishing plastic from other particle types within this size range.

4.2.3 Accounting for potential sample contamination

To account for potential contamination of samples during both sample collection and laboratory analysis, I assessed contamination from fibres dislodging from the plankton net, fibres and particles from materials present within the boat used during sampling, and fibres and particles from materials used in the laboratory during sample processing.

Net contamination. To understand how fibres from the net could contribute to contamination I tested the plankton net used for sampling (Straight conical net, model 9000, Sea Gear Corporation, mesh 60 or 64 µm, opening diameter 50 cm). Before testing the net the hose was flushed for three minutes. Each net was then suspended from a frame and sprayed with freshwater from a hose three times, for three minutes, with the spray nozzle set to 'full'. Water samples were retained with the same mesh cod end which was used for water sampling. The water samples were transferred into a pre-washed and rinsed glass jars, transported to the lab, and processed using the same protocol as for the other water samples. To test whether the hose could also contribute additional contamination, three replicate 1L water samples from the hose were also placed into glass jars and analysed. The volume of water used in the trial was calculated by using the same hose setting and recording the time taken to fill a 10 L bucket, 3 times.

Boat contamination. The carpet on the flooring of the boat used for all but freshwater sampling was noted as another potential source of fibre contamination of the water samples. To assess this, carpet fibres were removed via tweezers, and placed into a plastic vial to be observed under a dissecting microscope and then these were compared to particles commonly found in samples. This was possible because the colour, shape, and size of these fibres were consistent and easily detected (Figure 4.2C).

Laboratory contamination. Based on previous research, airborne contamination of samples with microplastics is a common occurrence (Torre et al., 2016). To account for airborne plastic contamination while samples were being dried, a total of 18 control samples were created using 100 ml of tap water. These samples were vacuum filtered onto filter paper, and half were placed under a standard laboratory fume hood, and half were placed under a rinsed aluminium tin to dry for 1-3 days. These were the same methods used to dry the filter papers from the samples. The number of plastic particles occurring on the filter papers were counted before and after placing them out to dry.

4.2.4 FTIR analysis.

A sub-sample of all suspected plastic particles observed in both water and sediment samples were identified using a Nicolet Continuum FT-IR spectrometer

(Thermo Fisher, USA). A total of 170 high certainty plastic fibres and particles and 130 low certainty plastic fibres and particles were scanned and their spectra compared to the Nicolet plastic library for polymer identification. This included 20-30 examples from each season (half fibres, half particles). In addition, a total of 38 particles categorised as 'not plastic' were also scanned (18 from water samples, and 20 from sediment). In total 338 particles were scanned. This provided me with an approximate accuracy percentage for the counted plastics. For the majority of particles the ATR reflectance mode with germanium crystal was used (Wu et al., 2018). For fibres and particles too small for reliable results in ATR mode, transmission mode was used. Since many of these particles extracted from sediments were commonly coated with organic material, particles were rinsed with Milli-Q water prior to analysis. If the FTIR reads remained unclear, particles were then soaked in hydrogen peroxide until the organic material was removed, which took approximately 0.5 to 1 hour, depending on how heavily the particles were soiled. Scanned particles were considered to be definitely plastic if there was at least a 50% match to a polymer in the library, and at least 5 out of 10 of the match options provided by the software were of plastic (example in Figure 4.2). Unfortunately, the FTIR machine that was used was not consistent with detecting the material of plastic, rather more consistent with where or not it was plastic. Therefore, type of polymer was not recorded. Accuracy percentages for each plastic identification category are depicted in Table 4.1.

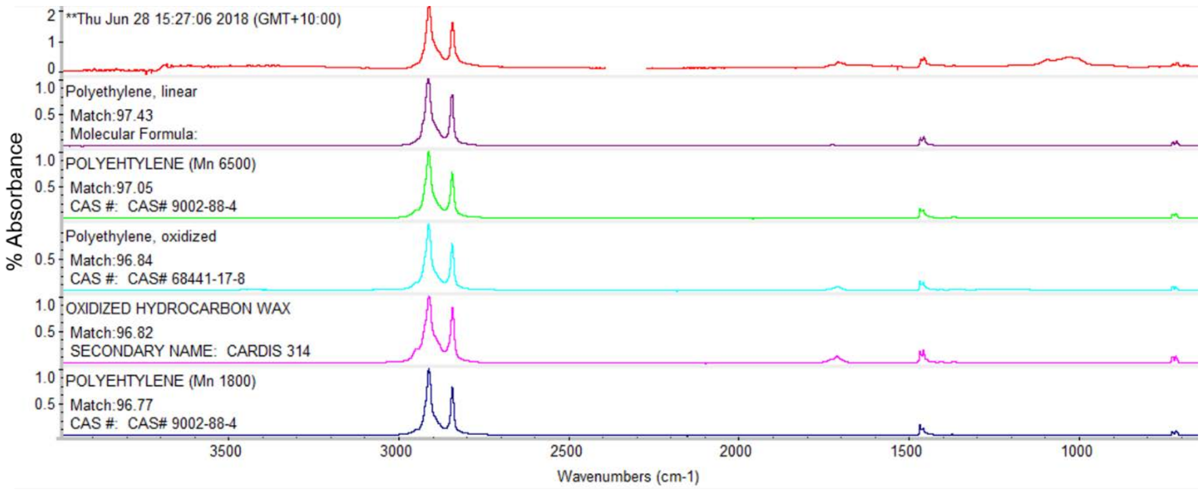

Figure 4.2: *Example of a microplastic scan results using the FT-IR, included in analysis. The top red, is the particle scan, with the top 5 matches provided by the software program below.*

4.2.5 Data analysis

Correction of data for contamination and plastic identification. Assessment of potential contamination of samples by external microplastics revealed ubiquitous contamination from several sources. Contamination of samples by fibres from the boat carpet was detected (Figure 4.3C), as was contamination of samples by fibres present in tap water and airborne in the laboratory (1.78 ± 0.46 SE) fibres were observed settling on each blank filter paper after drying them under an aluminium tin, and an average of 3.78 (±0.72 SE) fibres were observed on the filter paper after drying under the fume hood). Contamination of samples by fibres from sampling nets was also detected, with an average of 28 fibres (largely blue and pink) from host control test, plus an additional 5 particles, likely to be contaminated from previous sampling (Figure 4.3D). In addition, FTIR analysis showed very low accuracy of identifying fibres from the water samples as plastics (17 – 22% accuracy, Table 4.1). Consequently, all fibres were removed from counts of microplastics in the water samples. Fibres found in sediments were more accurately identified as plastics (60 – 66%, Table 4.1), and were visually different from the boat carpet and net fibres. Therefore, fibres were retained in counts of microplastics in the sediment samples. In addition to removing the fibres, particle counts were corrected according to the proportion of particles analysed with FTIR that were confirmed to be plastics. Counts of microplastic particles, as distinct from fibres, were not corrected for contamination because no particle contamination was detected.

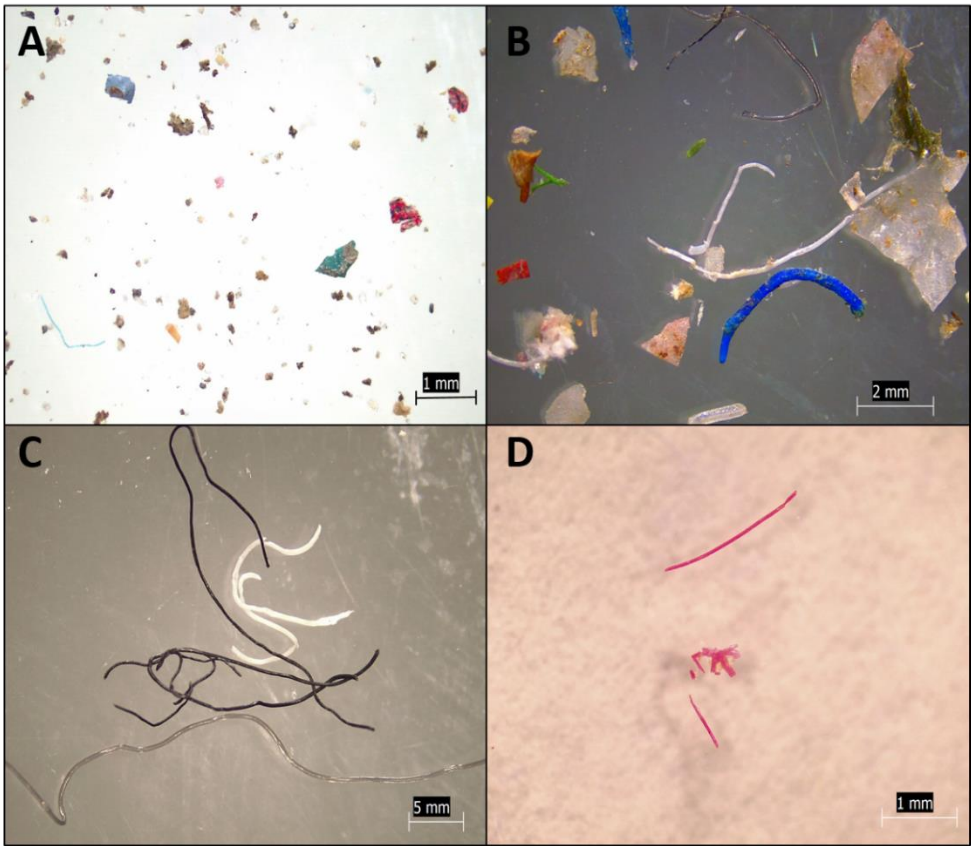

Figure 4.3: *A: Examples of plastic particles in the 2-5mm size range. B: Examples of plastic particles in the 1-2mm size range. C: Fibres taken from boat carpet. Note that white and grey fibres would be counted as boat fibres in photo (B) above. D: Most common fibres found in water samples that were from the net.*

Table 4.1: *Number of particles analysed using Fourier Transform Infrared Spectroscopy for each particle type, sample type, and certainty level. Note that some of the particles that I thought to be not plastic, were actually plastic under my criteria.*

Particle category	Sample type	Particle type	Number of particles	% Plastic
Likely plastic	Water	Fibre	41	17%
		Particle	41	82%
	Sediment	Fibre	33	60%
		Particle	55	76%
Possibly plastic	Water	Fibre	33	18%
		Particle	33	33%
	Sediment	Fibre	35	66%
		Particle	29	48%
Unlikely plastic	Water	Mostly particles	18	22%
	Sediment	All	20	10%
Total			338	

4.2.6 Statistical analysis

All corrected microplastic particle counts from the water samples were standardised per cubic meter of water sampled, which was calculated by using the total tow distance (in meters), multiplied by the area of the net. Data from sediment samples were standardized per 1 kg of sediment to facilitate comparison with other similar studies. All preliminary calculations occurred in Microsoft Excel and all data analysis was conducted in IBM Statistics SPSS vs. 25 and RStudio.

For the water sample data, a two-way ANOVA with a type III sum of squares was used to detect any significant differences in microplastic concentrations between sampling locations (i.e., freshwater, estuary, port channel versus Pallarenda) and seasons (i.e., before versus after wet season). Sampling locations grouped samples from all freshwater sites (n=9 per season, across all storm drains), estuary and river mouth (n=9 per season), Pallarenda beach (n=6 per season), and the port channel (n=9 per season). Data were treated as independent between seasons, rather than repeated measures, because surface waters are dynamic through time due to wind and water flow and tows were conducted at slightly different sites in each season. To meet ANOVA assumptions, the data were log10 plus one transformed prior to analysis. Q-q plots showed residuals were approximately normally distributed for this analysis, and Levene's test showed that variances were homogenous ($F = 1.208$, $p = 0.276$). For the sediment sample data, I hypothesised that microplastic concentrations would be higher close to the storm drains after the wet season, when the input from storm drains is most likely the largest. Therefore to determine whether proximity to the storm drain affected microplastic concentrations within river sediments, and whether this effect depended on sampling season and/or varied among locations, a three-way repeated measures ANOVA was conducted. I used a linear mixed-effects analysis in R, with proximity to storm drain within season and within drain as the random effect to account for the repeated sampling of sediments adjacent to drains. Data were log10 + 1 transformed prior to analysis and inspection of residuals versus fitted values indicated that residuals were approximately normally distributed and with homogenous variances for this analysis.

4.3 Results

4.3.1 Microplastic loads within the river and bay after seasonal rainfall flushes

Across all surveyed sites there was an overall average of 0.17 microplastic particles m^{-3} of water in the pre wet season and 0.29 particles m^{-3}in the post wet season. These particles ranged in size from approximately 0.5 - 5 mm in size. Microplastic concentrations were highly variable within sites, particularly in the estuary where concentrations ranged from 0 to 2.19 particles m^{-3} (Figure 4.4). Microplastic particles were most abundant in the estuary in the post-wet season, with an average of 1.31 particles per m^{-3} compared with 0.01 in the freshwater in the pre-wet (Figure 4.4). However, differences among locations were not statistically significant (Table 4.2). Despite sampling across multiple locations in the river, and between seasons where rainfall differed 19-fold (36.6 mm in the pre-wet season and 687 mm over the duration of the wet season) there was no seasonal difference found in the water samples across the different locations, and the similarity between seasons was consistent among locations (Table 4.2).

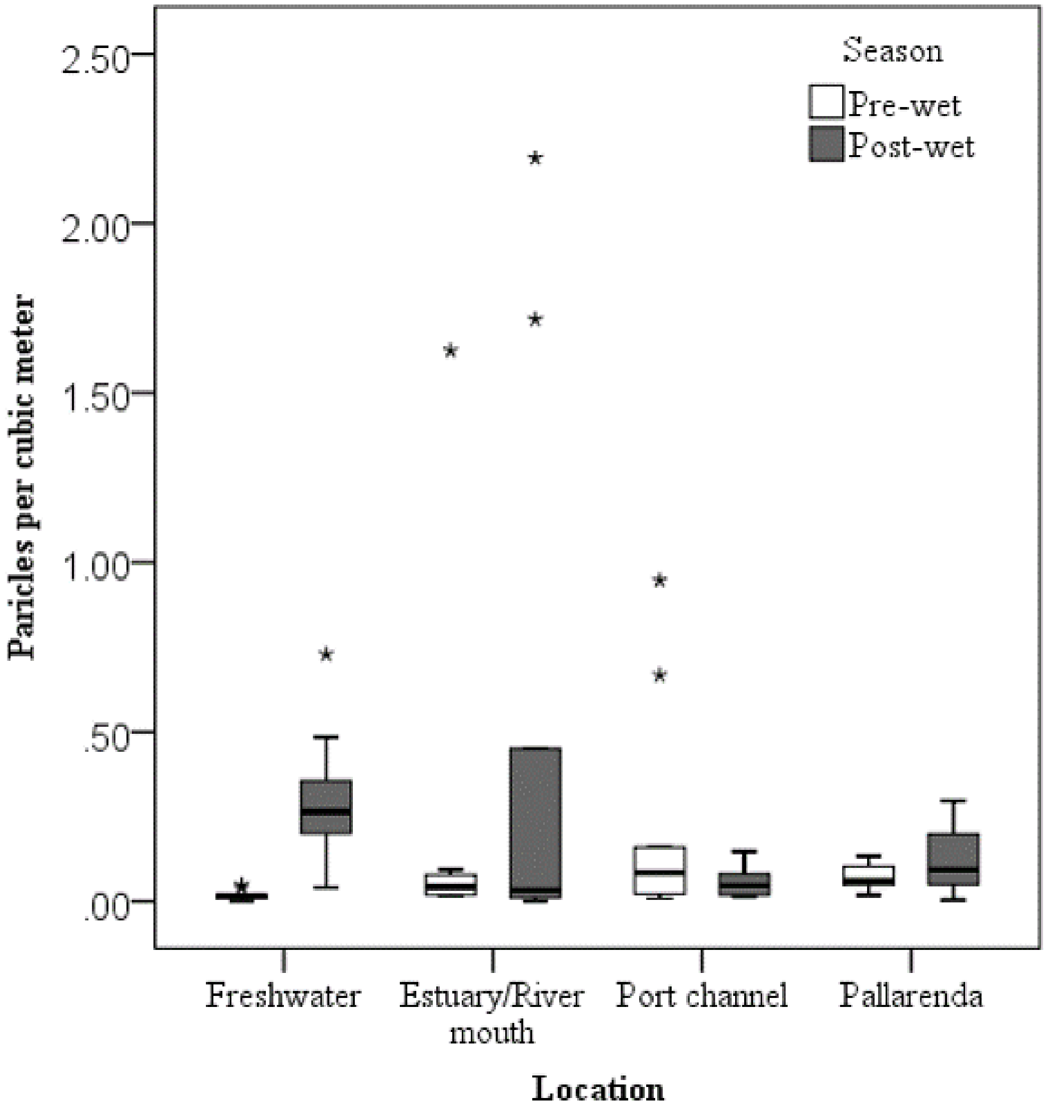

***Figure 4.4**: Total number of particles per cubic meter (FTIR-corrected) for water samples collected at each site. Fibres were excluded. Since there was no significant difference between high and low tides at the river mouth (n=6), these were combined for graphical reasons. Similarly, all water sampling tows at Pallarenda beach (n=6) and the port channel (n=9). Boxes represent the median, with the upper and lower quartiles. Whiskers represent a 95% confidence or maximum value. * indicates outliers (1.5 x Inter Quartile Range).*

Table 4.2: *ANOVA of microplastic concentrations in surface water and sediment samples between pre-wet and post-wet seasons and between river locations (for water samples) and also at different distances from the drain (for sediment samples).*

Sample	Factor	df	F statistic	p-value
Water	Location	3,65	0.60	0.62
	Season	1,65	1.84	0.18
	Location*Season	3,65	1.98	0.13
Sediment	Location	3,3	13.8	<0.05
	Season	1,3	0.63	0.82
	Distance	1,6	0.13	0.73
	Site * Season	3,3	0.44	0.74
	Site * Distance	3,6	1.91	0.23
	Season * Distance	1,6	1.95	0.21
	Site * Season * Distance	3,6	1.22	0.38

4.3.2 Influence of storm drains on microplastic loads in Ross River sediments

Overall, microplastic concentrations in sediments were highly variable among sites, with an average of 141.5 ± 19.6 (SE) microplastics kg^{-1} sediments across all sites (Figure 4.5). Fibres were slightly more abundant than particles, with an average of 78.9 (± 13.4 SE) fibres kg^{-1} of sediment, compared to particles with an average of 61.4 (± 9.3 SE) particles kg^{-1} of sediment. Microplastic counts within the sediments were found to differ between sites, and were recorded the lowest in the estuary, with an average of 6.15 particles kg^{-1} sediment (± 3.19 SE) (Table 4.2, Figure 4.5).

Microplastic particles that were counted ranged from 1-5 mm in size, with fibres sometimes slightly larger (one fibre was 32 mm in size). Other materials within the 1-5 mm size range, such as glass and aluminium, were also found within the sediments. For example, a total of 81 clear glass spheres were observed in pre-wet sediment samples, which doubled to 170 in post-wet samples (not standardised). These clear glass spheres were sometimes encased in bitumen or concrete with yellow paint, and therefore assumed be parts of the reflected paint used on roads as have also been reported by (Horton et al., 2017a).

Proximity to storm drains did not affect microplastic loads within the sediment (Table 4.2). Similar to the pilot study, there was no significant difference found between microplastic loads within the sediments 1 m away from the storm drain compared with 27 m away (Table 4.2), and this effect was consistent between seasons (Table 4.2). In addition, there was no significant interaction between the plastic loads in sediments collected in the pre and post-wet season and the distance from the drain (Table 4.2). In comparison to water samples, where the highest plastic loads were found within the estuary site, plastic loads were the lowest in the sediments in this location (Figure 4.6).

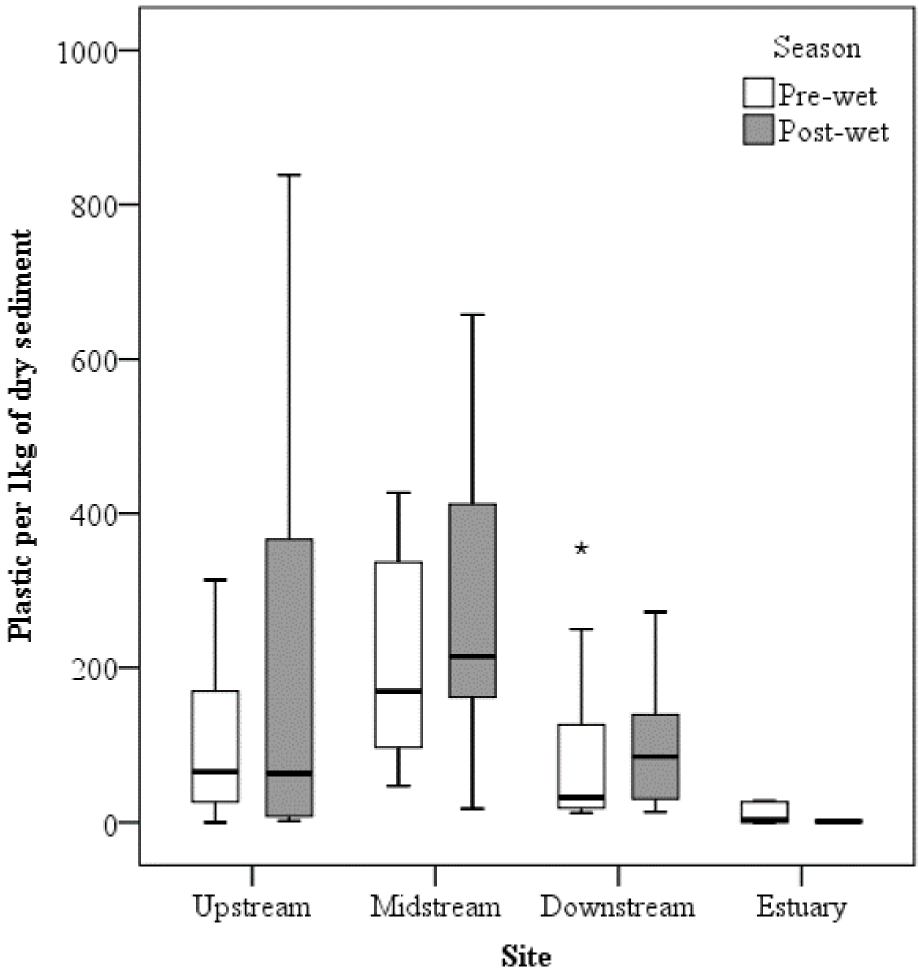

Figure 4.5: *Microplastic abundance within sediments at different locations within the freshwater section of the river, and in the Estuary. Sediments were collected outside storm water effluents, 3 and 27 meters away along three different transect lines. Whiskers represent a 95% confidence. * indicates outliers (1.5 x Inter Quartile Range).*

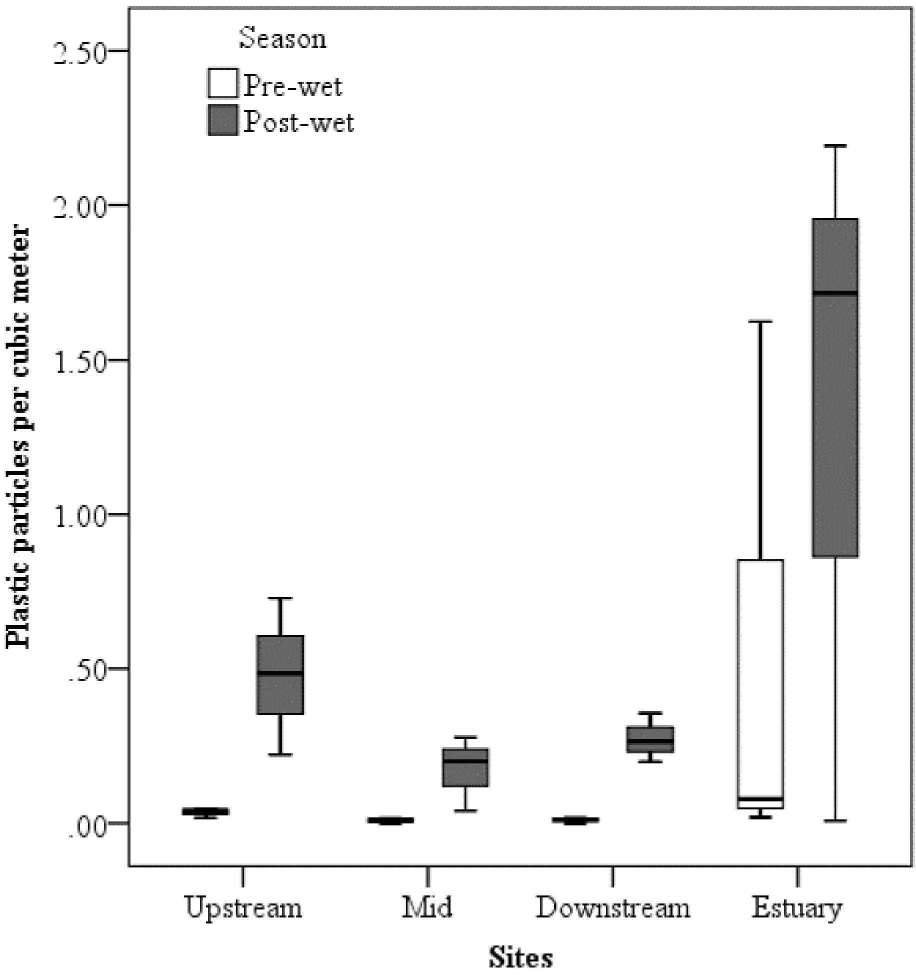

Figure 4.6: *Microplastic abundance compared between the pre and post-wet season within the freshwater and estuary in the water surface samples. Plankton tows were performed outside the same storm drains where sediment samples were collected. For water samples, fibres were excluded. Boxes represent the median, with the upper and lower quartiles. Whiskers represent a 95% confidence. * indicates outliers (1.5 x Inter Quartile Range).*

4.4 Discussion

4.4.1 Microplastic loads within the river and bay after seasonal rainfall flushes

For this chapter, I aimed to quantify the microplastic loads in a Queensland river system by sampling microplastic concentrations close to storm drains and coastal waters elevated after rainfall events. For the first time, this study quantifies microplastic loads within a small urban river system in tropical Queensland, Australia. Results reveal that rainfall (687 mm) during the wet season did not lead to a measurable change in plastic loads within the river or bay. Moreover, there was no seasonal change in microplastic abundance in any other location of the river or bay, and there was no clear gradient of microplastic abundance leading out of the river after the wet season. While these patterns are inconsistent with results from other freshwater systems in Australia (Hitchcock and Mitrovic, 2019) and around the world (Castaneda et al., 2014; Fischer et al., 2016), these findings are consistent with the results in chapter 3, where wet-season rainfall had negligible effect on macro plastic loads in the river. Unlike my study site, much of the current literature investigating microplastics in freshwater systems focusses on large, continuously flowing rivers (e.g. (Castaneda et al., 2014; Morritt et al., 2014; Yonkos et al., 2014). I suggest that the presence of weirs and a dam in Ross River, which constrict water flow for at least half of the year, likely underpins the differences between my results and other studies of freshwater rivers.

As rainfall was below the overall average for Townsville, which is typically approximately 1000 mm per year (Australian Bureau of Meteorology, 2017), it is also possible that seasonal differences in microplastic loads could occur during years with higher rainfall and increased outflow from the river. Indeed, at the time of sampling after the wet season and a heavy rainfall event, all of the weirs were flowing but the dam was not spilling. After several years below average rainfall in the area and little water movement (Townsville BOM), hydrodynamic models suggest that plastic particles will biofoul and sink to the bottom of the river, where they are unlikely to become re-suspended unless there is significantly water movement from rainfall or wind (Kooi et al., 2018). This is consistent with my findings of high microplastic loads within river sediments. The only place that did not have high plastic loads in the sediment was within the estuary, where sediment resuspension due to large tidal flow and water movement (Allen et al. 1980) and would prevent particles from accumulating (as per modelling study (Kooi et al., 2018). In addition, due to slow water flow, the river system has significant aquatic plant life that grows on the surface of the water. During years with limited rainfall, this plant life accumulates along the weirs. While sampling, floating microplastic particles were observed to be trapped in the vegetation. This has been recorded previously in freshwater models and studies (Kooi et al., 2018; Williams and Simmons, 1996), and it means that microplastic counts reported in this study are likely underestimates, as the vegetation prevents release of microplastics into the open river water and sediments and therefore cannot be efficiently sampled using a plankton tow net (Kooi et al., 2018). Regardless, in the event of a cyclone or other large scale storm, much of the plastic accumulating within the river vegetation is likely to be washed out to sea.

4.4.2 Storm drains as a source

In addition to finding no seasonal effect on microplastic abundance within the river, proximity to storm drains did not affect the abundance of microplastics in sediments. A likely explanation for this finding is that microplastics can be wind driven, and after heavy rainfall they can be subject to turbulent mixing (below the surface of the water), and accumulate in “microplastic hotspots” (Besseling et al., 2017; Kooi et al., 2018). Therefore, the nature of water flow out of the storm drain and within the river will determine where microplastics accumulate. Instead of a gradient sampling design for sediment samples, I suggest randomised sediment sampling such as that performed in (Nel et al., 2018; Peng et al., 2018), or sampling patterns associated with sources and provide a more accurate estimate of microplastic concentrations across all locations and sediment types. For water samples, I suggest that alternative sampling methods, such as that conducted by Dris et al. (2018) which instead captured water exiting the storm drains directly, would be useful for quantifying microplastic loads in storm water effluents.

Some items collected in sediment samples such as glass beads used as reflectors in road-marking paint, were found in high abundance in sediment samples and doubled in abundance in the post wet season, suggesting the influence of storm drains to the river environment. The road paint is often made up of thermoplastic composite paints, and were similar in appearance to the glass beads from roads found in the Thames River (Horton et al. 2017a). Although these beads and surrounding paint could not be reliably identified by FTIR in my study, possibly because the paint coating was worn, excluding these beads from my analysis means that plastic particle concentrations could be underestimated in my study. Additional research is needed to determine whether these sediment-associated particles are derived from urban roads in the Ross River catchment.

Overall, microplastics collected in both water and sediments were largely particles and fibres that are likely to be fragments of larger plastic pieces. This suggests that a large number of the microplastics within the Ross River originate from the macro debris items collected in Chapter 3 (Bauer-Civiello et al., 2019). Therefore, macroplastic reduction strategies, such as the reduction of litter in nearby parks and the placement of river booms, will likely be beneficial to reduce microplastic loads within the river on a local scale.

4.4.3 Plastic loads within Ross River and Cleveland Bay compared to other studies

In comparison to other studies on microplastic contamination in freshwater systems and estuary systems around the world, my water samples contained relatively low concentration of microplastic (see review by Li et al., 2018). For example, a recent study in New South Wales, Australia found microplastic concentrations in the surface waters outside three estuaries between 98 to 246 particles m^{-3} within 45-5000 µm in size (Hitchcock and Mitrovic, 2019). While other larger rivers, such as the Yangtze Estuary with population sizes up to 400 million people have been found to have average abundances of 4,414 particles m^{-3}, of which, approximately 33% of this was made up of particles from 1000-5000 µm in size (Zhao et al., 2014). In contrast, my study only found between 0.124-0.308 particles m^{-3} on average in the pre and post-wet season (within the size range of 500-5000 µm), respectively, with a maximum concentration of 2.25 particles m^{-3}. Since previous research, such as that by Hitchcock and Mitrovic 2019, includes particles a magnitude smaller, it is likely that the counts reported in this chapter are underestimated. Nevertheless, previous research indicates that local population size and local industry influences plastic abundance (Jambeck et al., 2015), suggesting that contamination of Ross River waters is low due to the relatively low population density in the catchment.

Conversely, microplastic abundance in sediments were equivalent to those reported from river and lakes systems in urban areas of Europe (Fischer et al., 2016; Horton et al., 2017a; Vaughan et al., 2017). For example, microplastic loads (1-4 mm in size, similar to the present study) in the Thames ranged from 185 particles per kg to 660 particles per kg (Horton et al., 2017a). In comparison, I found an average of 143.43 kg +/-20.16 SE particles in Ross River. While sampling techniques differed between studies, collectively these results indicate that relatively low inputs of microplastics have been accumulating within the sediments of Ross River over the course of successive low-rainfall years. Only with more widespread and continued standardised sampling will we know more about spatial and temporal variation in microplastic loads in freshwater systems, particularly in comparison to other river systems world-wide.

4.4.4 Study limitations and future directions

Fibres are typically one of most abundant particle type found in both freshwater and marine environments from a variety of sampling methods and techniques (Carr, 2017; Gago et al., 2018). In this study, fibres were removed from analyses of plastics in water samples due to evidence of contamination of these samples by fibres from external sources (within tap water, and within the laboratory environment). Based on the contamination of samples I observed, I stress that any future research in this field be more vigorous in contamination control, particularly with regard to net and boat carpet contamination. To the best of my knowledge, no other studies have accounted for net contamination, yet the type of plankton net used for sampling in this study is commonly used for plastic sampling around the world (e.g. Prata et al., 2018).

In addition, there were some difficulties in extracting plastics from very fine river sediments, and from water samples with very high organic matter content (Appendix 3). Other studies use a fluidised sand bath, or density separation to rinse microplastics free from sediments (Claessens et al., 2013; McCormick et al., 2014; Van Cauwenberghe et al., 2015; Van Cauwenberghe et al., 2013). However, these methods could not be used with very fine river sediments that are too small to remain at the base of the sand bath, or remained suspended in high density solutions (Appendix 4). Similarly, in other studies, water samples are usually first sieved to remove organic material, with material extracted from the sieves then placed in a high density solution to separate plastics from organic material (Mani et al., 2015; Masura et al., 2015). Unfortunately, the organic material encountered in Ross River and Cleveland Bay plankton tow samples was too adhesive and dense to allow sieving (Appendix 3). Therefore, I omitted sieving and instead allowed samples to settle with the organic material sinking, with the assumption that plastics floating would remain floating. Although visual inspection showed there were no obvious microplastic particles or fibres on the surface of the organic matter layer, it’s possible that some particles and fibres may have been trapped within this dense and sticky layer. These challenges mean that microplastic concentrations reported here are likely to underestimate true concentrations.

Although contamination was eliminated to the best of my ability, it is possible that samples were contaminated via 'in-situ' rinsing. I was following the protocol of similar studies (Barros et al. 2017), however in retrospect, it is possible that other boat contaminations, such as paint chips could have contaminated rinses and samples (Cole et al. 2011). This contamination may have occurred in the estuary, and open water samples, where a painted boat was used.

Finally, due to the difficulties in extracting plastics from fine river sediments, microplastic particles less than 1 mm in size were not able to be quantified. Particles less than 1 mm in size are difficult to extract and quantify accurately (Nuelle et al., 2014; Quinn et al., 2017). In addition, hydrodynamic and river-flow models suggest particles larger in size (millimetres) are more likely to be retained, whereas particles around the 5 µm size range are more likely to be expelled into the ocean from river systems (Besseling et al., 2017). Therefore, identifying smaller plastic sizes, particularly in the pre-wet season, may have been important to identify plastic loads in Townsville.

Despite the caveats outline above, I have provided a baseline dataset as a foundation for monitoring plastic loads through time. However, further research and monitoring is essential to confirm the sources of microplastics in the Ross River. I recommend future studies within the region should focus on the following:

1. Randomised sampling throughout the river using a water grab may be beneficial to estimate microplastic loads entrapped in areas with high aquatic vegetation (Barrows et al., 2017).
2. Sampling throughout the water column may also provide a more accurate representation of plastic particles, particularly after rainfall events, where turbulent mixing is most likely to occur (Kooi et al., 2018).
3. Randomised sediment sampling, or using grids to randomise sampling locations would also be beneficial to determine plastic accumulation hotspots, and overall plastic loads within the river.
4. Further development of methods for extracting microplastic <1mm from fine sediment types, or use of analytical techniques on sediment samples directly without need for extraction (Such as Dumichen et al. 2015).

4.5 Conclusion

In this study, I show the presence of microplastics within the sediment and surface waters in a river system in Australia, and provide baseline data that can be monitored through time. Monitoring plastic loads from local sources is the first step to reducing plastic in important ecosystems. This not only effects local coastal marine systems, but contributes to plastic in the oceans around the world

Chapter 5:
Assessing prospective indicator species of plastic contamination for nearshore coral reefs

Microplastics are an emerging contaminate of concern in the marine environment, but are difficult to sample. Bioindicators are important tools to monitor contaminants in aquatic environment. I focus on two benthic, filter feeding species, based on criteria suggested by Fossi et al. (2018) including the sponge, *Carteriospongia foliascens*, and the soft coral, *Lobophytum s*p. to understand the impact and interaction of plastics on coral reef ecosystems. I tested if plastic was ingested and retained by these two species, and whether ingestion reflected differences in microplastic concentrations. I found total ingestion of particles was low relative to the concentrations provided, with less than 1% of the particles ingested within the tissues. However, I found adherence of microspheres to the surface of the soft tissue to occur at approximately half the ingestion rate for *C. foliascens*, and approximately double the ingestion rate for *Lobophytum sp*. These results indicate that collecting and quantifying microplastics attached to the surface of marine organisms is possibly a more effective mechanism for monitoring microplastic concentrations in the environment than taking biological samples for measurement of ingestion.

Citation: Bauer-Civiello A, Paley A, Hoogenboom M. Assessing prospective indicator species of plastic contamination for nearshore coral reefs *in prep*

5.1 Introduction

Microplastic particles (<5 mm) are a threat of emerging concern, with models estimating as much as 2.25 trillion tonnes of microplastic particles existing in global oceans (Avio et al., 2017; Eriksen et al., 2014). This increasing contamination poses a hazard to marine life, as numerous field and laboratory studies have shown that plastic ingestion can cause direct harm to individuals by blockage of the gut leading to starvation and internal abrasions (Wright et al., 2013; Zettler et al., 2013). Ingestion of plastic particles can also lead to disease, reduced fecundity, and other harmful impacts (Browne et al., 2015; Cole et al., 2015; Gall and Thompson, 2015; Koelmans, 2015). The risk to organisms likely depends on the quantity of plastics present at a location, and whether or not plastic exposure is acute or prolonged. However, except for a few well-sampled areas such as the Pacific garbage patch (Law et al., 2014), there is only limited data quantifying temporal variation in microplastic concentrations *in situ*.

Quantifying the concentrations of microplastics in rivers and oceans are logistically challenging (Bauer-Civiello, Chapter 4). Microplastic particles in aquatic environments tend to aggregate together, meaning that the spatial distributions of these particles are patchy and highly dependent on waves, wind, and currents (Bauer-Civiello Chapter 4, Critchell and Lambrechts, 2016; Paul-Pont et al., 2018). Depending on the density of the plastics themselves, and how long the particles have been in the environment, microplastics can occur on the water surface, within the water column, or in the sediment (Lusher, 2015; Paul-Pont et al., 2018). Plastic particles can also be ingested by organisms, transported to the ocean floor as faeces or detritus and subsequently be re-suspended by waves, and currents (Paul-Pont et al., 2018). Furthermore, weather events such as heavy rainfall and flooding can contribute to large pulses of microplastics from land based sources (Cheung et al., 2016; Dris et al., 2018). To date, much of the current research has attempted to determine plastic loads on the water surface, and within the sediment (Lusher, 2015), whereas the concentrations of microplastics within the water column are more relevant to the ecology of plankton-feeding and suspension-feeding organisms. Consequently, new approaches are needed to quantify how much microplastic is 'available' for ingestion by marine organisms in their natural environments.

Bioindicators are "processes, species, or communities used to assess the quality of the environment and how it changes over time" (Holt and Miller, 2010) and can be useful tools to determine the abundance of microplastics, and the interactions between these contaminants and local marine life (Bonanno and Orlando-Bonaca, 2018). Research identifying bioindicators for microplastic pollution is still in its infancy, but is a topic of increasing attention in the scientific community (e.g. recent review by Bonanno and Orlando-Bonaca, 2018). According to Fossi et al. (2018), bioindicators for microplastics need to meet the following criteria: i) commonness within multiple habitats; ii) widely distributed across habitats; iii) ease of collection without impact to surrounding habitat; and iv) have been previously identified to ingest plastic. To date, mussels have been identified as ideal bioindicators to monitor microplastic abundances, as they occur in a wide range of coastal environments and can ingest particles at a rate that reflects the concentration of plastics in the environment around them (Li et al., 2019). However, these organisms have only been tested in areas where they are likely to be continuously exposed to microplastics, such as river mouths and estuaries close to urban areas. In habitats with lower microplastic abundances, an additional criterion that must be met by a prospective bioindicator is that the organism must also be capable of retaining ingested particles within their tissue long enough to be identified by sampling efforts. Further research is needed to identify species that meet all of these criteria in different habitats and ecosystems.

To provide an easier, less-invasive way to determine plastic loads interacting with marine organisms, alternative sampling methods should also be considered for bioindicators. There is recent evidence that microplastics may adhere to the surface of sessile organisms rather than being ingested, as has been shown for seagrasses (Goss et al., 2018) and bivalves (Kolandhasamy et al., 2018). However, the adherence of plastics to tissue in addition to microplastics that are directly ingested has only recently been identified, and rarely considered in microplastic research. Therefore, the identification and quantification of plastic adherence to exposed tissue of benthic and sessile fauna may provide additional information about the relative threat of plastic pollution to marine organisms.

There is limited knowledge about the microplastic concentrations in coral reef ecosystems, and the use of bioindicators could be beneficial to determine the relative threat to reef systems worldwide. However, bivalves are difficult to extract without causing damage to neighbouring reef organisms. In contrast, sponges and soft corals can be easily removed from reefs without destruction of nearby habitat and are commonly found in a wide range of environments, including nearshore reefs (Bannister et al., 2012). Sponges are an important part of the reef community, as they serve as a link between benthic and pelagic habitats (Bell, 2008; Diaz and Rützler, 2001; Simister et al., 2012). In addition, some species of sponge have been used to detect gradients of a sewage outflow, demonstrating their utility as indicators of environmental conditions (Perez et al., 2003; Topçu et al., 2010). Soft corals are also an important part of reef communities and obtain energy and nutrients via photosynthesis of their symbionts and by feeding on plankton and particles present in the water column (Lewis, 1982). There is a high diversity of soft corals in nearshore habitats that are likely to be regularly influenced by river plumes (Fabricius et al., 2005), which can be a large source of microplastic pollution in the ocean (Schmidt et al., 2017).

The aim of this study is to assess the possible use of the sponge *Carteriospongia foliascens,* and the soft coral *Lobophytum* sp., as bioindicators of plastic loads in reef ecosystems. Since polyp or pore size can influence the ability to ingest plastics, and size of the plastic can also impact how long ingested particles are retained within the tissue of the organism (Qu et al., 2018); I aimed to answer the following questions: (1) Do *Carteriospongia foliascens* (sponge) and *Lobophytum* sp. (soft coral) ingest plastic particles, and is ingestion dependent on microplastic particle size? (2) How long are microplastic particles retained within tissues? (3) Does the ingestion reflect differences in microplastic concentrations present in the water column? (4) Do microplastics adhere to the tissues of these filter feeding species?

5.2 Methods

5.2.1 Species selection

Two benthic filter feeding taxa, *Carteriospongia foliascens* (sponge), and *Lobophytum sp.* (soft coral), were selected as potential indicator species of plastic contamination based on the criteria suggested by Fossi et al. (2018). Both taxa are prevalent on the Great Barrier Reef, and are easy to locate and identify (Michalek-Wagner and Willis, 2001; Wahab et al., 2014b; Wilkinson, 1983). Both taxa are found at depths ranging from inshore intertidal reef flat to lower slopes of mid-shelf reefs (Michalek-Wagner and Willis, 2001; Wahab et al., 2014a). Comparable species can be found on coral reef habitats around the Indo-Pacific, and the potential for identifying similar indicator species globally is high (Sung et al., 2009; Wahab et al., 2014b). For example, the *Lobophytum* genus is found throughout the Indo-pacific, and the Red Sea (Sung et al., 2009). Lastly, collection of both species involves minimal damage to the surrounding habitat, and they are relatively easily maintained in aquaria.

5.2.2 Sample collection

Specimens of each species (54 per species, 108 specimens in total) were collected on the reef flat and crest around Orpheus Island, a coastal island within the Palm Island group in the central Great Barrier Reef (18.6161° S, 146.4972° E) in May 2018. Specimens were collected from three bays, approximately 2 km apart, to ensure the collection of different genotypes. Each specimen had a maximum diameter of 10 cm. Specimens were typically located within the intertidal zone, from 0.5 to 3 m in depth (depending on the tide), and were collected using hammer and chisel via snorkel. Solitary specimens were targeted to minimise harm to surrounding fauna, or injury to the experimental specimens. For example, *C. foliascens* specimens were often located on small pieces of rubble, making their extraction from the reef habitat unobtrusive. To keep the specimens upright, a small piece of rock was placed at the base of the organism if necessary. Specimens were temporarily stored in large buckets of seawater covered with a shade cloth, before being transferred to the aquaria facilities within 5 hours of collection.

5.2.3 Experimental set up and preparation

The experiment occurred in the outdoor aquaria facilities of Orpheus Island Research Station under a 50% ultraviolet shad canopy. Specimens were divided evenly between 60 experimental feeding chambers (11.5 cm wide x 12 cm deep x 41 cm long, 5.6 1 L in volume), with 1 to 2 specimens per chamber (Figure 5.1). Each chamber was filled with natural seawater at ambient temperature (~24 – 25 °C), filtered to 5 µm and allowed to flow-through the system. Each feeding chamber had flow rate of approximately 1 L per 90 seconds. This was the maximum flow rate possible to prevent microplastic particles from overflowing the 5 µm filter bags that were used on the system effluent to prevent contaminating the local environment. Specimens were placed upright or laying on its side (for *C. foliascens*), or propped up by rock or tile when needed. Specimens were allowed a minimum of 3 days to acclimate to aquaria conditions prior to the start of the experiment.

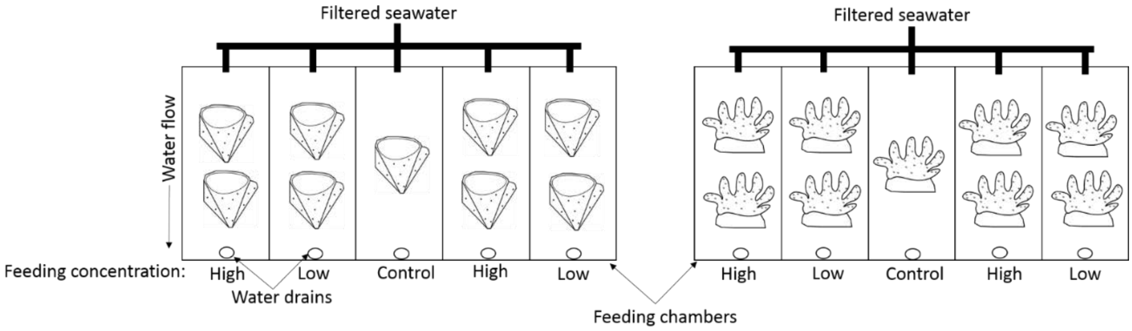

Figure 5.1: *Schematic of experimental feeding chambers structure and specimen distribution across chambers for Carteriospongia foliascens (left), and Lobophytum sp. (right). The same species, undergoing the same feeding concentration shared the same feeding chamber.*

A mixture of supplemental coral food (Aquasonic SeaFood) and fluorescent coloured polyethylene (PE) microspheres (Cospheric LLC) was prepared prior to the experiment. Polyethylene is likely to be one of the most common plastic materials in the marine environment, and can be neutrally buoyant (Andrady, 2011; Cole et al., 2011). Plastic microspheres used in this mixture consisted of two different size ranges and colours: orange (45-52 µm) and green (27-32 µm). This is consistent with the size range of food items such as diatoms and plankton (Ribes et al., 1999) and the size range used in other coral feeding experiments (Hall et al., 2015).

To ensure neutral buoyancy of microspheres, the larger orange microspheres were coated in the surfactant Tween80 by Sigma-Aldrich (composed of Polyethylene glycol sorbitan monooleate, Polyoxyethylenesorbitan monooleate, or Polysorbate 80) following the manufacturer’s protocol. Briefly, 50 µl of Tween80 was added to 500 ml of Milli-Q water heated to 80 ºC, and allowed to cool. Once at room temperature, 1 g of orange microspheres (45-52 µm) were placed in the solution, and soaked for a minimum of 19 hours. Plastic microspheres were subsequently rinsed twice in a 39 µm sieve with Milli-Q water to remove any excess surfactant. The smaller green spheres were neutrally buoyant in seawater, so no further action was needed. The coated orange microspheres were combined with 0.131 g green microspheres to ensure that the concentration of particles were exactly the same, and added to a 3:1 ratio of filtered seawater and the supernatant of Aquasonic SeaFood to replicate biofouling (Paul-Pont et al., 2018). The solution was kept at -20 ºC between feeding days.

5.2.4 Feeding trials

Once acclimated, specimens were exposed to a three day feeding trial based on the results of a pilot study that demonstrated measurable microsphere ingestion within this time frame (Appendix 4). Specimens were fed the plastic-food mixture approximately 2 hours after dusk (~ 8 pm) during normal active feeding times for corals in the field (Lewis and Price, 1975), with the assumption that sponges do not have active feeding periods, rather feed continosly. During feeding, the water flow was turned off for one to two hours to ensure that plastic microspheres would interact with the experimental specimens.

On each feeding day, the prepared plastic food mixture was placed on a John Morris Scientific, MIXcontrol 20 magnetic stirrer plate to ensure a homogenous suspension of microbeads. A 3 ml aliquot of the plastic food mixture was extracted from the middle of the mixture using a 3 ml syringe. To assess whether ingestion is concentration-dependent, specimens were exposed to either high or low concentrations of plastic food mixture. High concentrations (3 ml of food mixture) resulted in 24,900 orange microspheres and 24,876 green microspheres, equating to a total of 49,776 microspheres, or 8,888 spheres L^{-1} fed to each specimen per night. Low concentrations (1.5 ml of food mixture) were exactly half of the high concentration (4,444 spheres L^{-1}). The high and low concentrations were fed to 24 individuals of each species per treatment (12 chamber per species per concentration; Figure 5.1). The food mixture was expelled directly over the top of each specimen, such that each sample was potentially exposed to a maximum of ~75,000 (low concentration) or ~145,000 (high concentration) microspheres. Such high concentrations of plastics are unlikely to occur *in-situ*, however, these concentrations were selected to enable detection of concentration-dependent microplastic ingestion and adherence. The remaining 54 specimens were placed into six control feeding chambers interspersed throughout the experimental chambers and fed 1 to 2 ml of Aquasonic SeaFood in place of the plastic-food mixture. These control samples were included to ensure that any accidental cross contamination could be accounted for.

On the third day of feeding (subsequently referred to as day 0 after the plastic exposure period), six high, six low of each species were sampled at random (using a random-number generator) approximately one hour after feeding, placed in individual specimen bags, and immediately frozen at -80 ºC. This sampling was repeated on days 2, 7, and 14, after the plastic exposure period (Figure 5.2). Since fluorescent spheres were used, it was deemed that control samples were not needed throughout the entire experiment. Therefore a total of 6 specimens were used as controls were spread out throughout the experiment, with 3 specimens extracted from day zero and three extracted from day 7. To ensure adequate food supply for survival of the organisms after the plastic exposure period, any remaining specimens were fed between 1 to 1.5 ml of Aquasonic SeaFood every other day at the same time of the feeding trials until the experiment was over. Also, to ensure that the specimens were not continuously exposed to plastic particles after the three day feeding trial, each experimental feeding chamber was gently siphoned and wiped down with a cloth. Care was taken not to touch the specimens when cleaning the chamber, however, any mucus strands were removed from the organism as these would typically be swept away with the currents in the natural habitat. Throughout the experiment, there was only one mortality of *Lobophytum sp.,* which was most likely due to stress of transportation/aquaria setting, rather than plastic ingestion. This individual was added to day 2 collections, resulting in one fewer individual sampled on day 7.

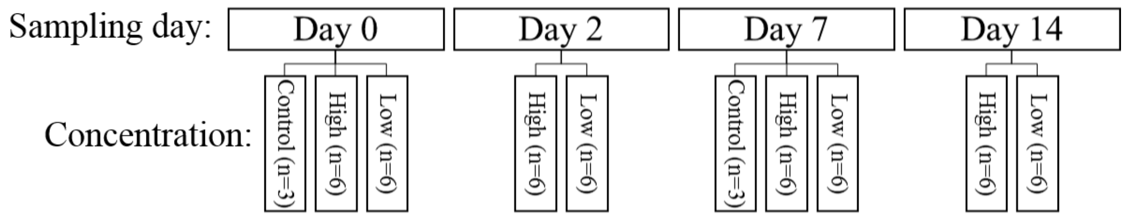

Figure 5.2: *Experimental sampling design for Carteriospongia foliascens and Lobophytum sp. after the three day feeding trial. 'Day zero' specimens were sampled on the third day of feeding.*

5.2.5 Laboratory analysis

All specimens were frozen and transferred on ice to the laboratory facilities at James Cook University in Townville, Australia and stored at -80 ºC until further analysis. In preparation for tissue digestion, samples were rinsed and thawed in a hyper-saturated saline solution (800 g of NaCl in 1.2 L of DI water) to remove any plastic particles adhered to the external tissue of the organism (as protocol by Thompson et al. 2004). The resulting salt solution was used to determine adherence concentrations by vacuum filtering microspheres onto glass filter papers (Macro Science MS GA, porosity 1.6 µm). The fluorescent plastic microspheres were then counted using a dissecting microscope (Olympus SZ40) under illumination by a deep-violet VI Light (Northwest Marine Technology, Washington, USA) to assist visual detection (following modified protocol by Cole et al. 2013). To ease quantification, a 1 cm clear grid was placed on top of the filter paper.

After rinsing, tissue samples were transferred onto an aluminium weigh boat and dried in an oven at 60 ºC for 48 to 72 hours until dry. After drying, samples were cooled to room temperature and weighed using a Sartorius Entris balance with accuracy 0.00 g. To assess whether plastic ingestion was evenly distributed, specimens extracted on experimental day 0 were subsampled at three different parts of the body. Subsamples of *C. foliascens* were randomly selected from the left, middle, and right side of the body were subsampled and digested separately. For *Lobophytum sp.,* a branch tip, mid branch, and the connecting tissue were subsampled and digested separately.

Samples were digested using a sodium hydroxide (NaOH) solution, with a concentration of 0.5 M for *Lobophytum sp*., and 1 M for *C. foliascens*. Before experimental digestions took place, pilot tests were performed to test if NaOH was appropriate, and how long digestions would take with extracted species taken before experiment commenced. It was noted that *C. foliascens* took longer to digest using 0.5M concentrations, so to shorten the digestion length, concentrations for this species was increased to 1M. Visual inspections of plastic particles exposed to 1 M NaOH for 6 hours in a pilot tests demonstrated that this digestion process did not affect the fluorescence of the microspheres. During digestion, samples were placed in individual 100 ml Erlenmeyer flasks with enough NaOH solution to cover the sample entirely (between 50 – 70 ml). The flasks were then heated to 80 ºC on a Ratek dry block heater (solid state control) and samples were left until the tissue was completely digested into a liquid state. *Lobophytum sp.* tissue was fully digested after 1 hour, whereas *C. foliascens* tissue was fully digested in 0.5 M NaOH after 18 hours (or after 6 hours in 1 M NaOH). Each sample was then diluted into 800 ml of DI water, and vacuum filtered onto 5 to 6 glass filter papers (Macro Science MS GA, porosity 1.6 µm). The filter papers were allowed to dry under a fume hood and temporarily stored in an aluminium envelope before microspheres were counted as described above.

5.2.6 Statistical analysis

Microspheres counted within the digested tissue were standardised per gram of tissue to account for variation in the size of the sampled corals and sponges. All analyses were conducted using IBM SPSS Statistics v 23, and R studio 3.5. Since control samples were simply used to ensure no natural particles were counted as the fluorescent particles and account for any accidental cross contamination irrespective of time, data from control samples collected at day zero and day 7 of the post-plastic exposure period were combined for greater statistical power. Comparison of the tissue subsamples from different parts of the specimens showed consistency in feeding rates within samples (*C. foliascens* (Table 5.1, Figure 5.3) so data were averaged across the subsamples for each of the different time points for subsequent analyses. To compare the total ingestion rates to the overall abundance of microspheres adhered to the surface of the organism, the ingestion rate per sub sample/g was multiplied to the total weight of the organisms.

To test differences in overall preference for particle size, mean ingestion rates were compared. Several transformations were attempted to normalize data, however the Shapiro-Wilk test showed that data still violated normality assumptions. Therefore, a non-parametric Kruskal-Wallis test was used to compare the ingestion of orange particles (45-52 µm) and green particles (27-32 µm) within species.

A two way ANOVA with a Tukey's post hoc test was used to test for variation in retention of microspheres across time and concentration. For this analysis, both sizes of microspheres were combined to assess overall ingestion. Counts of microspheres from control samples revealed presence of low concentrations of microspheres in some controls, averaging 1.94 ± 0.95 microspheres g^{-1} for *Lobophytum sp*., and 0.97 ± 0.50 microspheres g^{-1} for *C. foliascens*. Therefore, the total average of ingested microspheres across control samples was subtracted from the total counts of the treated samples. To meet ANOVA assumptions, microsphere counts for *Lobophytum sp*. were square root transformed, and data for *C. foliascens* were log10 plus one transformed. *C. foliascens* rejected the null hypothesis for the Shapiro-Wilk test of normality for both time, and consumption, however *Lobophytum* sp. showed normal distribution for all but one time point and one concentration (Shapiro-Wilk time point 2, $p=0.004$, and low concentrations $p = 0.000$). However, since there is no non-parametric test to test interaction effect, I used this test cautiously.

A two-way ANOVA was used to detect whether total microplastic that adhered to the surface of the organism varied over time and between microsphere concentrations for each species. Again, to account for any potential contamination of samples with microspheres adhered to the surfaces, the average number of adhered microspheres g^{-1} from control samples was subtracted from total ingested particles for both species. To test for normality, a Shapiro-Wilk test was conducted using square root transformed data for *C. foliascens*, and log10 plus 1 transformed data for *Lobophytum sp.* showing that the data was normally distributed throughout time, and across concentrations.

5.3 Results

Both species were found to ingest plastic microspheres of both size ranges (Figure 5.3). On day zero, *C. foliascens* individuals ingested an average of 142.8 ± 31 particles g^{-1} (SE) when fed the high concentration, and 48.2 ± 10 particles g^{-1} when fed the low concentration. This is between 1 to 1.3% of the total plastics fed across the three days of microsphere exposure assuming that each sample was potentially exposed to the maximum of ~75,000 (low concentration) or ~145,000 (high concentration) microspheres at each feeding time. In comparison, *Lobophytum sp.* individuals ingested on average 18.1 ± 5 particles g^{-1} when fed the high concentrations, and 18.8 ± 3 particles g^{-1} when fed the low concentrations, suggesting that individuals consumed 0.1 to 0.3% of the total amount of plastic introduced across all three days. On day zero, initial ingestion values were on average (± SE) 142.8 ± 0.19 particles g^{-1} for feeding rates of *C. foliascens* were 2.5 to 7 times higher than *Lobophytum sp*.

Microspheres were detected within the tissue of both species throughout the 14 day experiment, however average plastic loads within the tissue decreased substantially for *C. foliascens,* (up to an average of 95% egestion by day 14). For *Lobophytum* sp. the majority of microspheres remained within the tissue, only decreasing by an average of 52% of the initial ingestion for *Lobophytum sp*. by day 14 (Figure 5.5). However, high variation among samples meant that this decline over time was not statistically significant (Table 5.1). Of the ingested particles, orange microspheres (54 microns) were consumed in approximately 2-fold higher numbers than green (37 microns) for *Lobophytum sp*. (Table 5.1). However, there was no significant difference between particle sizes detected for *C. foliascens* (Table 5.1). When the two microsphere sizes were combined, ingestion and retention by both species did not reflect differences in microplastic exposure concentrations. Moreover, there was a significant difference between time treatments, with up to 96% of the particle expelled from the tissue by day 14, and this decrease consistent regardless of initial concentration (Table 5.1).

Table 5.1: *Statistical analysis and test results for the ingestion, retention and adherence of microspheres to Lobophytum sp. and Carteriospongia foliascens.*

Species	Dependent variable	Factor/s	Df	Test statistic	p
Lobophytum sp.	Ingestion	Within-colony variation	2,44	K-S = 3.59	0.17
	Ingestion	Microsphere size	1,47	χ^2= 12.00	<0.05
	Retention	Time Concentration Time * Concentration	3,47 1,47 3,47	F = 2.2 F = 0.41 F = 0.26	0.1 0.53 0.86
	Adherence	Time Concentration Time * Concentration	3,47 1,47 3,47	F = 24.2 F = 23.8 F = 1.4	<0.01 0.01 0.26
C. foliascens	Ingestion	Within-colony variation	2,44	F= 0.91	0.41
	Ingestion	Microsphere size	1,47	χ^2= 0.78	0.38
	Retention	Time Concentration Time * Concentration	3,47 1,47 3,47	F = 19.7 F = 3.8 F = 1.3	<0.01 0.06 0.30
	Adherence	Time Concentration Time * Concentration	3,47 1,47 3,47	F = 12.3 F = 6.8 F = 1.5	<0.01 0.01 0.23

Microspheres were 2 times more likely to be ingested by *C. foliascens*, than adhered to the surface (at day zero), but adherence was more variable (Figure 5.5). While there was a significant difference for adhered particles between time and concentration, there was no overall significant interaction between concentration and time (Table 5.1). Instead, the average number of microsphere g^{-1} that adhered to the surface of the organism decreased by approximately 85% for high and 74% for low concentrations by day 14 (Figure 5.5, Table 5.1).

Unlike *C. foliascens*, adhered microspheres for *Lobophytum sp.* were equal or double the amount of the ingested microspheres. Moreover, unlike ingestion rates, particle loads decreased over time, showing a significant difference of approximately 3 fold between high and low concentrations on day 2 (Table 5.1, Figure 5.4). 33-25% of the original microspheres remained on the surface up to seven days, and by day 14, only 5-11% of the initially adhered particles remained on the surface.

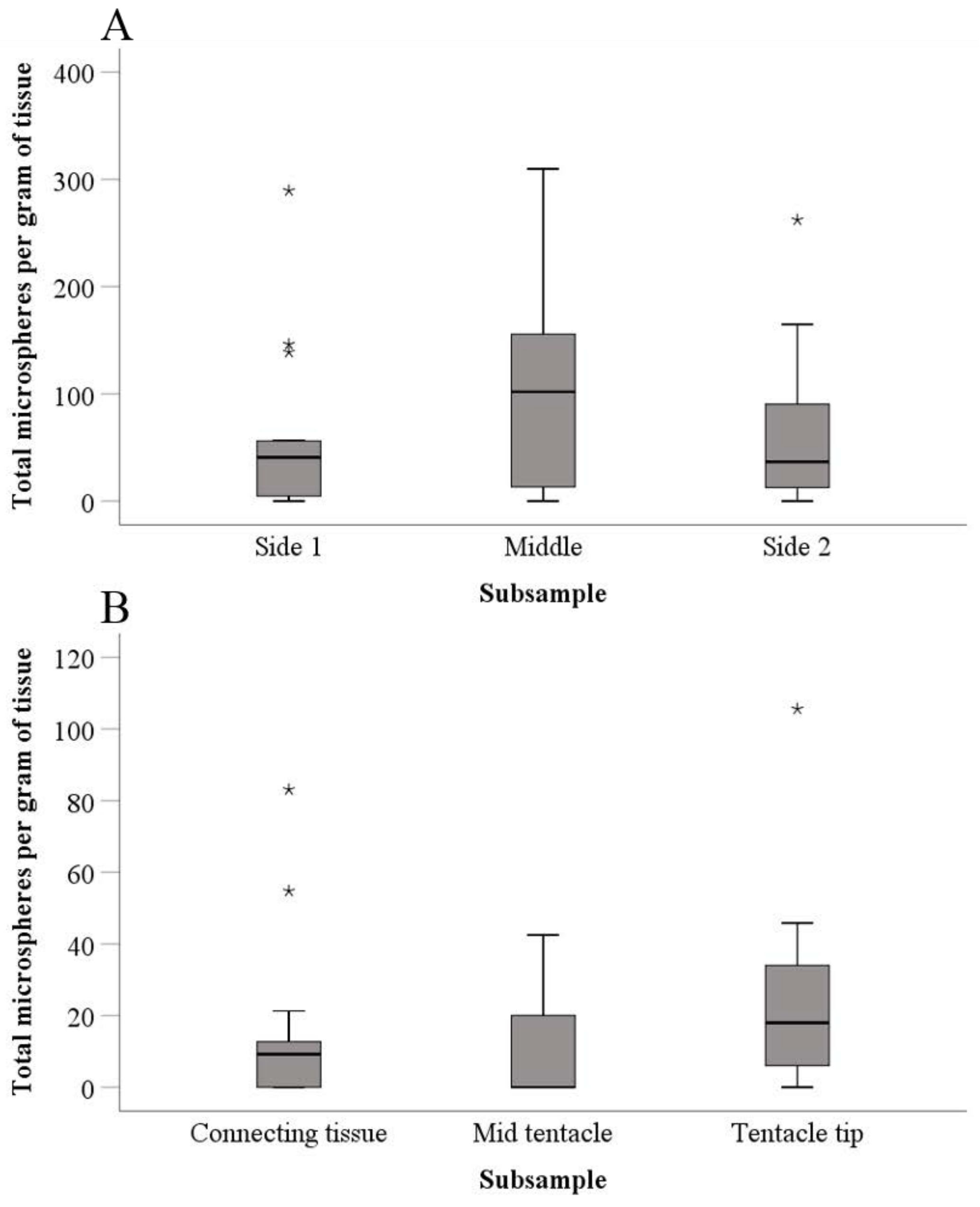

***Figure 5.3**: Subsamples taken from different parts of the organism to ensure that particle ingestion was equal for (A) Carteriospongia foliascens and (B) Lobophytum sp. Box plots represent median and interquartile (25^{th} and 75^{th}). Whiskers represent highest and lowest values, apart from *, which indicate outliers.*

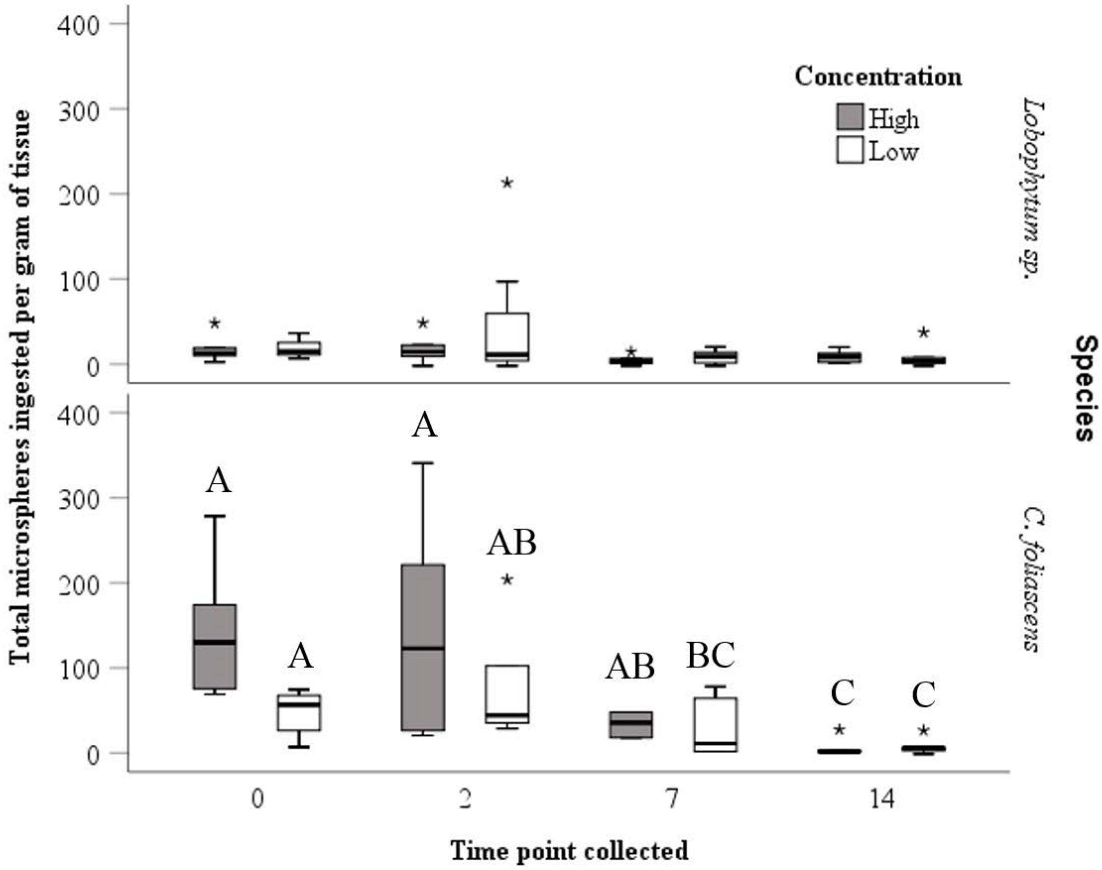

Figure 5.4: *Comparison of the total microspheres (minus the average number collected from controls) ingested by Lobophytum sp. versus Carteriospongia foliascens after three days of feeding plastic microspheres at two different concentration (high and low). Box plots represent median and interquartile (25^{th} and 75^{th}). Whiskers represent highest and lowest values, apart from *, which indicate outliers. Letters indicate significant differences between concentrations within the same time point.*

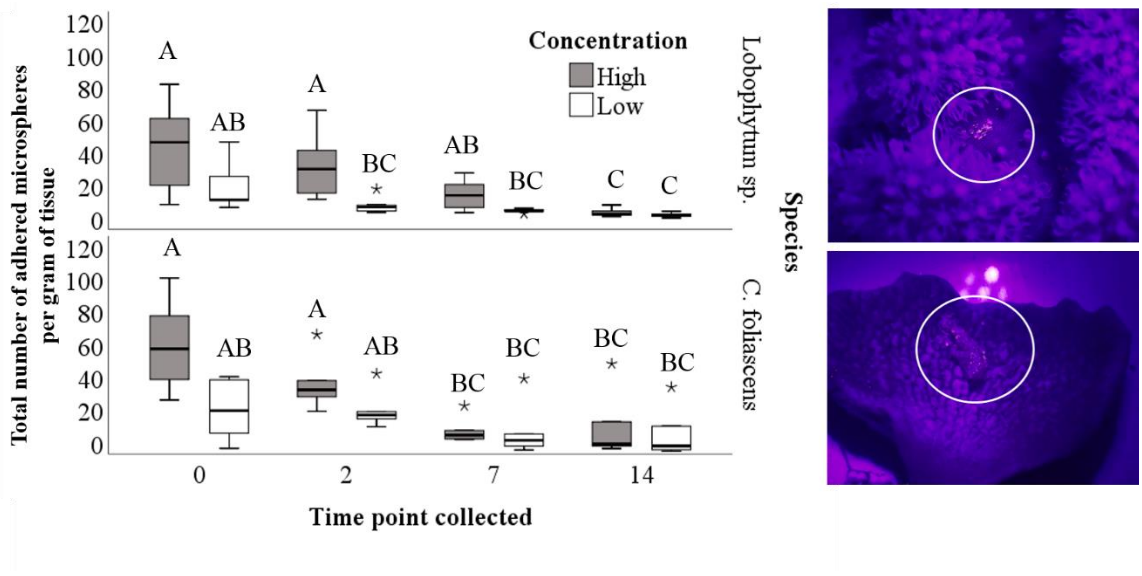

*__Figure 5.5:__ Total number of plastic microspheres per gram of tissue (minus the average number collected from controls) that adhered to the surface of the organism for Lobophytum sp. and Carteriospongia foliascens tissues under two different concentrations (high and low). Box plots represent median and interquartile (25^{th} and 75^{th}). Whiskers represent highest and lowest values, apart from *, which indicate outliers. Letters indicate significant differences between concentrations within the same time point. Photos show orange microspheres visible by the eye (45-54 μm) that adhered to the surface of each species, and shed by mucus.*

5.4 Discussion

This chapter aimed to identify if two benthic reef species, *Carteriospongia foliascens* (sponge) and *Lobophytum* sp. (soft coral) could be used as indicator species for microplastics on subtidal reefs. This research shows, for the first time, that the sponge, *C. foliascens* and soft coral, *Lobophtyum sp*. are capable of ingesting and retaining plastic microspheres. However, total ingestion did not depend on microsphere concentrations in experimental tanks, and was low (~1%) relative to the concentrations of microspheres to which both species were exposed. There was considerable variation between species: *C. foliascens* ingested 3-8 times more microspheres than *Lobophytum* but expelled 83-95% of the plastics by 7 days post-exposure whereas *Lobophytum sp.* retained microspheres throughout the entire 14 day experiment. However, since the ingestion by this species was so low, it may not be detectable in *in-situ* samples. In addition, microspheres were also found to adhere to the external tissue surface in both species, but this was also low (<1%) relative to the concentration of microspheres exposed to both species. Based on these findings, I do not recommend these species as bioindicators for microplastic pollution.

The initial ingestion of *C. foliascens* and *Lobophytum sp.* is considerably lower compared to observations of other sessile fauna. For instance, the concentration of microspheres accumulated in the tissue of bivalves was similar to that in the surrounding waters (Kolandhasamy et al., 2018; Qu et al., 2018). Whereas for *C. foliascens* and *Lobophytum sp.* the concentration in the water column was between 75 to 494 times higher than what was ingested (Figure 5.4). Also, greater plastic abundances were found within the tissues of other coral and sea anemones species under experimental settings, although it is difficult to compare concentration loads between studies because of methodological differences (Hall et al., 2015; Okubo et al., 2018). The low ingestion of microspheres by *Lobophytum sp.* might have been due to environmental conditions within the experimental tanks, particularly water flow (i.e., relatively slow flow and absence of waves). Soft corals thrive in areas with high water flow to filter feed (Hoegh-Guldberg, 2008), which could not be replicated in my experimental setup. During the experiment, it was noted that only 43 - 60% of the corals exhibited polyp activity/expansion on the three days of exposure to the microsphere-food mix, and this may have influenced the low ingestion. However, additional research is required to determine how microsphere ingestion would change under natural field conditions. Nonetheless, this study showed that despite low initial ingestion, *Lobophytum sp.* retain microspheres in their tissues for at least 14 days, and the sponge *C. foliascens* can retain microspheres up to seven days. Further research on the ingestion and retention of microbeads for a range of filter feeding species is required to identify other potential bioindicators.

Recent research has identified that the accumulation and retention of microplastics varies depending on the particle types, sizes, and shape (Qkubo et al., 2018; Qu et al., 2018). In this study, *C. foliascens* did not show a preference for particular particle sizes but *Lobophytum sp*. was more likely to ingest the larger microspheres (54 µm in size). Previous research has observed the opposite in bivalves, where smaller microspheres were more easily taken up and incorporated in tissues, whereas larger particles were quickly expelled (Okubo et al., 2018). Therefore, the size and shape of microspheres used in the experiment might have influenced the rates or patterns of ingestion of microspheres which I observed in the present study. In an effort to improve precision of counts of ingested microspheres, commercially produced florescent microspheres were used to determine microplastic ingestion and retention. However, other studies suggest that degraded particles and microfibers were more likely to be retained by indicator species than the microspheres, possibly due to their jagged and irregular edges that make it easier to be trapped within the gut tissue (Qu et al., 2018). While this has only been documented in bivalves, it is possible that other active filter feeders, such as sponges and corals, also are more likely to retain certain particles types over the microspheres used in the present study. Future research on bioindicators species should introduce greater variation in particle types and sizes to account for the potential differences in particle preferences. Microsphere adherence to the surface of the organism occurred for both species. For *C. foliascens*, microspheres were more likely to be ingested than to adhere to the surface, with adherence concentrations approximately half the value of the ingested particle concentrations (Figure 5.5). This was similar to the adherence concentrations recorded for mussels which were about 50% of the ingested particles, the only other species where microplastics have been observed on the surface (Kolandhasamy et al., 2018). Conversely, adherence levels for *Lobophytum sp*. were up to 2-fold higher than values for ingested microspheres during the first week post-exposure. However, by day 14, 4 times more particles remained within tissues (ingested) than remained adhered to external tissue surfaces, indicating that most particles were shed off by the mucus layer after two weeks. Moreover, the adherence of particles on *Lobophytum* varied depending on the concentration of microspheres during the exposure period, indicating that it may be possible to determine the microplastic concentration in the environment based on adherence. It is important to note that both species showed relatively high variability in adherence concentrations, likely due to differences in morphology of the sampled corals. Therefore, future studies replicating this experiment on a larger scale, using species and colonies with different morphologies, would be useful.

Mucus production is a sediment-removal mechanism used by many benthic marine species, including corals and sponges (McGrath et al., 2017). These mucus ‘ropes’ are used to trap sediment and organic matter suspended within the water column, and can be collected in a non-invasive manner directly off fauna (e.g.

Broadbent and Jones 2004;Wild et al., 2004). Therefore, *in-situ* mucus deposits may allow for detection and possibly quantification of microplastic loads in the marine environment. This could particularly be important after an acute contamination event, such as flood plumes from extreme weather events which can transport terrigenous materials up to 50 km offshore (Bainbridge et al., 2012; Devlin and Brodie, 2005; Devlin and Schaffelke, 2009). Further research is needed to test the utility of sampling mucus ropes from benthic species under natural field conditions, particularly in areas of high and low microplastic concentrations, such as nearshore and offshore reefs.

5.4.1 Caveats and future research

Previous experiments on microplastic ingestion by filter feeding species found that aged plastics were more preferred than pristine ones (Vroom et al., 2017). Therefore, the 'clean' microspheres provided to the organisms in the present study may have influenced the ingestion of the two species, as microplastic particles occurring *in-situ* within the water column are likely to have biofouling (Fazey and Ryan, 2016). Although the particles in the present experiment were placed in a food-particle mixture, this may have influenced the 'willingness' of corals and sponges to ingest the microspheres. Therefore, the influence of biofouling needs to be further investigated to determine if this influences plastic ingestion.

Lastly, microplastic particles are known to have positive charges in seawater, which possibly makes them more likely to adhere to plastic walls of experimental tanks (Keller et al., 2010; Paul-Pont et al., 2018). Indeed, during my feeding trials, a significant amount of microspheres was observed attached to the sides of the feeding chambers (made out of Polyvinyl chloride). While the concentrations of plastic particles in this study were high enough to detect ingestion and retention of microsphere particles, the adherence to the tank wall may have lessened the interaction rate of the microspheres with the organism. For future research, I therefore suggest to include an internal pump within each tank that ensures continuous circulation of the water column to prevent adherence of particles to the tank wall and maximize availability to the organism, while the water flow is turned off.

5.5 Conclusion

The research presented in this study shows for the first time that *C. foliascens* is capable of retaining microplastics up to 7 days, and *Lobophytum sp.* can retain particles for at least 14 days. Moreover, microplastics were found to also adhere to the surface of both species, with greater concentrations found on the outside of *Lobophytum sp.* than ingested. *C. foliascens* also had high concentrations adhered to the surface, but greater proportions of microspheres were found to be ingested. Based on the ingestion results, neither *Lobophytum sp*. nor *C. foliascens* are suitable candidates to use as indicator species for microplastic presence on reef systems because concentrations ingested did not reflect outside concentrations. While *Lobophytum sp.* were able to retain the microspheres for the entire 14 day experiment, microspheres were ingested in such small quantities, they are unlikely to be detected in *in-situ* samples. Further research is needed to identify species that meet all of these criteria in different habitats and ecosystems. In addition, further research needs to be done to identify species that could be helpful for monitoring plastic loads in the marine environment. However, I provided insights in to testing microplastic pollution on reefs and propose that further investigation on mucus extraction may be possible to detect plastic loads interacting with plankton-feeding and suspension-feeding organisms.

Chapter 6
Understanding Public Perception and Awareness of Marine Plastic Pollution in Relation to Littering: A case study in the Great Barrier Reef, Australia

Reducing litter in urban environments is an important way to mitigate plastic waste and stop it from reaching the ocean. To do this, we first must understand underlying factors that influence human behaviour, such as littering, and determine if there is a connection between the act of littering to the consequence of marine debris. To fill this knowledge gap, a questionnaire was developed and distributed in Townsville, Queensland Australia. This questionnaire examined resident responses on overall knowledge and awareness of marine debris, stewardship/care of place, level of concern about the marine environment, and social norms that are believed to influence their decisions. A total of 566 respondents participated in the survey. Survey results indicated that Townsville residents had a well-defined working knowledge of what constitutes marine plastic pollution and that littering in Townsville was a contributing factor. Furthermore, there was a strong sense of connection and responsibility of people towards the Great Barrier Reef. As a result, targeted messaging focusing on individual responsibility, plus pride, and identity may resonate strongly for Townsville residents to take actions in regard to marine debris. Furthermore, future management and education tools can move away from educating the public to not litter, but rather, support individuals, and work on campaign where people can easily participate to reduce litter and plastic use.

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6.1 Introduction

Marine plastic pollution is a pervasive and complex global issue, with an estimated 8-13 million tons of plastic existing in the oceans today (Rochman et al., 2015). Due to their longevity and durability, plastic materials are capable of remaining in the environment for years, impacting marine fauna, such as turtles, fish, and whales, in addition to habitat-building organisms, such as corals (Lamb et al., 2018; Worm et al., 2017). As plastic production and use continues to increase, models predict that plastic within the marine environment will increase 25% by 2025 (Jambeck et al., 2015), suggesting that immediate action on plastic production, use and pathways is required to reduce the impacts on marine ecosystems.

Some studies have suggested that up to 80% of marine plastic pollution in the world's oceans originates from land-based sources (Andrady, 2011; Oosterhuis et al., 2014). Mismanaged waste such as littered items in parks, streets, sidewalks, and beaches, overflowing bins and dumps, sewage waste, and industrial spills from urban, inland and coastal communities can be washed directly into the ocean, or into waterways that connect to the ocean (Bauer-Civiello et al., 2019; Jambeck et al., 2015; Lebreton et al., 2017). For example, it is estimated that approximately 1.15-2.41 million tonnes of plastic from inland sources are transported to the ocean from rivers around the world per year alone (Lebreton et al., 2017). In addition, I found that even in the relatively low population of Townsville, Queensland, large amounts of litter was entering and accumulating in local waterways (Chapter 3 and 4). Therefore, reducing mismanaged waste from both inland and coastal communities is a vital component in the reduction of global marine plastic pollution.

Targeted management strategies have been used to reduce mismanaged waste and litter in the environment before it arrives in the ocean world-wide. This can include a variety of policy based strategies that intervene with plastic waste management on an international, national and state based, scales. On an international scale, this can include setting global waste management goals, such as providing adequate, safe and affordable waste collection services to all countries (United Nations Environment Programme 2015. Other top down policy measures, such as plastic bag bans and container deposit schemes, encouraging the production of alternative materials, and implementing infrastructure such as bins and recycling centres are some components in which targeted management can be applied for overall source reduction (Clapp and Swanston, 2009;

Critchell et al., 2019; Xanthos and Walker, 2017). These are structured to help eliminate waste production, and therefore, reduce the chance of waste in the environment.

Effective top down management incentives also require community support, knowledge, and awareness regarding the connection between litter in the environment, and marine pollution (Vince and Hardesty, 2017). Yet, understanding the community perception of marine debris to design or implement effective management strategies is rarely acknowledged in the marine debris literature, and there is limited research that attempts to identify whether people are aware that their actions can contribute to marine debris, and whether they are able to connect littering that occurs inland, with the consequence of marine plastic pollution (Campbell et al., 2016; Hartley et al., 2018; Slavin et al., 2012). Understanding the connection, or lack of connection, between littering in the urban environment and marine pollution is important for applying targeted management aimed at changing behaviours to reduce littering, and/or to encourage preventative and curative interventions, such as picking up litter, reducing the use of plastic products or supporting policy measures aimed at mitigation (Veiga et al., 2016).

6.1.1 Study context and theoretical background

Littering behaviours are complex, and the choice to litter or not can be influenced by a wide range of motivational drivers (Kollmuss and Agyeman, 2002). These drivers can include the level of concern for the environment and the relative knowledge of environmental impacts (Gifford, 2014). Littering behaviours can also be influenced by overall values and morals, or a person's attachment toward the environment. For example, recent research has shown that a strong relationship with the ocean or their home city can improve behaviours linked to the environment (Pahl et al., 2017). This can include specific connections to charismatic marine fauna, or culturally important ecosystems, such as World Heritage Areas and national parks (Jefferson et al., 2014; Goldberg et al., 2018). Therefore, focusing on the connection between the actions of littering to the impacts on the marine environment is important to understand underlying factors that drive littering behaviour, and as a result, mitigate marine debris (Madhani et al., 2009).

The first steps to understand the community engagement of marine debris and its sources, is to understand the overall perception, whether or not the community perceives it as a threat, and if people recognise whether or not their actions contribute to marine debris (Slavin et. al. 2012). Previous research regarding this connection between litter and marine debris have used a combination of different social theories to describe environmental behaviours that drive littering behaviours, such as the theory of planned behaviour, the theory of pro-environmental behaviour, norm-activation-theory, value-belief-norm theory, value-action gap, and social marketing (Eagle et al., 2016; Hartley et al., 2018; Slavin et al., 2012). All of which use the four overarching researched themes described above: knowledge and awareness of environmental issues (via education and experience), stewardship and care of place, level of concern about the marine environment including environmental values and attitudes, and the societal norms that influence their decisions. These drivers of action and perception of environmental issues can vary greatly depending on location and individual communities, and therefore it is important to understand these on a local scale to provide a robust basis for allocation of effective resources towards marine debris management (Hartley et al., 2018). Therefore, I aim to investigate the community understanding of marine debris and its sources at a local scale (Townsville) to provide meaningful data on ways to engage and empower the community regarding littering and marine debris.

6.1.2 Research Questions

In order to determine the perception and awareness of marine plastic pollution sources on a local scale, the city of Townsville, Australia was used as a case study. Townsville is the largest city in the state of North Queensland (population of 229,000), and neighbours the Great Barrier Reef World Heritage Area (GBRWHA, or GBR for short). The GBR is an iconic ecosystem that holds cultural importance, both on a national and global scale (Goldberg et al., 2016). People view the GBR as a natural wonder and are willing to travel from all over the world to visit the largest coral reef ecosystem in the world. Importantly, recent research found that Australians rate the GBR as one of the most inspiring Australian icons, and the majority of Australians feel that the GBR is part of their Australian identity (Goldberg et al., 2016). Recently, plastic pollution has been identified as a threat of emerging concern to GBR ecosystems, and even more so, the GBR's neighbouring state, Queensland, is regarded as the most littered state in Australia, with 1.4 times the litter than the national average (GBRMPA Outlook Report 2014; Boomerang Alliance 2015). Sources of long-term monitoring suggest that over half (56%) of litter found on the beaches of the Queensland coast originates from land-based sources, suggesting that littering in urban environments, such as Townsville, could contribute to a portion of marine debris (Australian Marine Debris Database).

To understand the overall knowledge and perception of marine debris and its sources in Townsville, I used a social survey that focuses on the underlying factors of pro-environmental behaviour and marine stewardship in relation to littering and marine debris. Specifically, I aim to answer the following questions: (1) What is the current state of knowledge and awareness of marine debris and its sources? (2) What are the attitudes and values regarding littering and marine debris? (3) What does the community level of knowledge or responsibility to care for the local marine environment predict the level of concern for marine plastic pollution? And lastly, (4) how can this information be used to engage the local community in Townsville and shape local policy measures and future research to reduce plastic? These questions have a direct relevance to reducing plastic pollution in the oceans.

6.2 Methods

6.2.1 Survey design

Residents of Townsville were surveyed to determine community awareness of marine debris and its sources within the local region. Participants were first asked a small selection of demographic questions, such as age, gender, highest degree or qualifications, how long they have lived in Townsville, and whether they had previously attended a beach clean-up. The remainder of the survey was structured using a mixed method approach, with a combination of Likert scale questions (1-10, strongly disagree to strongly agree), ranking questions, multiple choice, and qualitative-open ended questions (full survey located in Appendix 5). All multiple choice or ranking questions were automatically randomised into different orders for each individual survey to reduce any biases toward numerical order. These questions were constructed using similarly structured questions described with previous litter perception studies, such as

Hartley et al., (2018), Pearson et al., (2014), and Slavin et al., (2012). Lastly, in attempt to understand the connection and responsibility with the Great Barrier Reef specifically, three statements were taken from a recent broader survey developed by Marshall et al. (2016).

6.2.2 Knowledge and awareness of marine debris, littering, and local sources

At the beginning of the survey, participants were first asked to define the term 'marine debris' in order to obtain a general understanding of what participants were likely to say in regard to this specific terminology, without being prompted by the rest of the survey. The term 'marine debris' was chosen because it is a popular colloquialism for 'any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the coastal environment' and is a term used by many non-profit organisations and government agencies (Australian Department of the Environment and Energy, 2019). However, since over 90% of marine debris is made up of plastic (Auta et al., 2017), I later defined marine debris to specifically mean 'plastic pollution in the marine environment' after the question was answered. Participants were asked to keep this in mind throughout the survey.

To determine the relative awareness of litter in the area and knowledge of marine debris sources, participants were asked to identify the top three items they thought were the most littered in Townsville. Nine categories were presented, including: straws and/or plastic utensils, plastic drink bottles, soft drink cups (take away cups- e.g. McDonalds), other types of plastic food packaging such as candy wrappers and chips bags, plastic shopping bags, cigarette butts, fishing line/net or other gear, disposable coffee cups, items of clothing. Similarly, participants were asked to choose the top three locations where they saw the most litter, such as local beaches, parks, and carparks. These questions were followed by a series of statements, (n=6) where participants were asked to rate their opinions on scale of 1-10 (strongly disagree to strongly agree) to determine if litter was a problem within Townsville, Queensland, and Australia.

To understand Townsville residents' knowledge of sources of marine debris, survey respondents were first asked to rate the top three most likely sources of marine debris in Townsville. They were provided eight possible options, including: overflowing bins, storm water discharge from roads and sidewalks, illegal dumping on land, waste reaching Australia from other countries by ocean currents, deliberate or accidental littering in parks and suburbs, illegal dumping or accidental loss from boats at sea (such as commercial cargo ships), deliberate or accidental loss of items from recreational use of beaches, accidental loss of fishing gear from fishing boats. This question was supported by Likert scale statements (n=7), in which participants were asked to agree or disagree on a scale of 1-10 with statements relating litter in the environment to marine debris. This included statements such as ‘Litter left near our waterways, such as Townsville’s Ross River, is likely to become marine debris,’ and ‘Litter left near our beaches is likely to become marine debris’ were used.

6.2.3 Responsibility, care and norms regarding the Great Barrier Reef

Since the level of responsibility toward the local environment is a key factor that influences littering behaviour (Spehr and Curnow, 2015), participants were asked to rate how strongly they felt responsible for the Great Barrier Reef and the marine environment from a scale to 1-10 (strongly disagree to strongly agree). This included three statements by Marshall et al. (2016): ‘It is not my responsibility to protect the GBR’, ‘Coastal residents should take steps to reduce their impacts on the GBR’ and ‘It is the responsibility of all Australians to protect the GBR.’ Participants were also given a multiple choice question, asking them who they thought had the most responsibility for reducing marine debris, in which answers included the following options (participants could only choose one): Individuals, Council (local government), Queensland state government, Australian federal government, Plastic manufacturers, and Retailers of plastic products (e.g. supermarkets). Finally, to determine individual responsibility and sense of empowerment, they were given an open-ended question: What can individuals do to reduce marine debris?

To understand overall norms surrounding marine debris, participants were asked to rate two questions on a scale of 1-10 (strongly disagree to strongly agree) to determine the norms surrounding littering and concern about marine debris. This included ‘My family and friends think it is bad to litter’ and ‘My family and friends worry about marine debris.’ At the very end of the survey, participants were given the opportunity to add any additional comments on the topic.

Since pro-environmental behaviour is influenced by experience, concern, knowledge and education, values, attitudes, responsibility, and norms, and place attachment, among other life experiences (Gifford, 2014), I used these factors to determine the predicting values toward littering behaviour, using a stepwise linear regression. For this analysis, I used the statements 'If I litter, I feel I'm impacting important marine habitats, such as the GBR' as the dependent variable. I used four overarching variables including: demographics (age, gender, education level, and how long they lived in Townsville), the level of interaction/experience with marine debris, i.e. whether they attended a beach clean-up, and themed questions including: knowledge and awareness of litter: 'Littering in Townsville contributes to pollution in the oceans', responsibility: 'I feel responsible for local marine environment and wildlife', social norms: 'My family and friends think it is bad to litter' and concern: 'I am concerned about the impacts of marine debris.'

6.2.4 Concern about the threats of marine debris

To determine level of concern about marine debris, participants were asked to agree or disagree with the following three statements on a scale of 1-10 (strongly disagree to strongly agree), including: 'I am concerned about the impacts of marine debris,' 'Plastic litter should be a primary concern for management of the Great Barrier Reef,' and 'There are more pressing threats to the Great Barrier Reef than plastic pollution.'

To understand the factors that influence concern about marine debris, I used a stepwise linear regression with the dependent variable of 'I am concerned about the impacts of marine debris.' Similar to the previous regression to the factors influencing littering behaviours in the previous section, level of concern was tested against the four overarching variables including: demographics (age, gender, education level, and how long they lived in Townsville), the level of interaction/experience with marine debris, i.e. whether they attended a beach clean-up, and themed questions including: knowledge and awareness of litter: 'Littering in Townsville contributes to pollution in the oceans', responsibility: 'I feel responsible for local marine environment and wildlife' and social norms: 'My family and friends think it is bad to litter.'

6.2.5 Community views on policy

At the end of the survey, participants were provided an opportunity to provide, in their own words, any additional comments they would like to make in regard to marine debris and littering in Townsville. This information was used to gather more details about overall approval of current policies, and opinions on how to improve waste management in Townsville.

6.2.6 Questionnaire distribution

Surveys were conducted both online and in-person over the course of 5 weeks during dry season, in the months of June and July of 2018. This was chosen based on the likelihood of better weather conditions, where residents are likely to be outdoors. Participants were residents of Townsville who had lived in the region for at least three months and were 18 years of age or older. Online surveys were distributed through social media and posted on city council pages, university pages, and Facebook groups. In addition to the online surveys, in-person surveys were conducted at five different sites around Townsville, including two river-side parks, a beach park, a boating launch ramp, and a shopping mall. These sites are all busy sites, where residents are known to attend regularly. The range of sites were chosen in effort to target a wide range of potential respondents. To diversify access to any potential respondents, each site was visited four days of the week (three week days and one weekend day) for 4 hours per day. Sampling days and time periods were not chosen using any structured method, rather chosen simply based on availability and time. Sampling periods differed depending on site to ensure as many surveys were achieved as possible. Most often, surveys were performed for 2 hours in the morning and 2 hours in the afternoon. Survey location for each week was randomised, with the exception of one outdoor site week, which was switched with an indoor one due to poor weather conditions. To differentiate where the survey was taken, the respondents were asked to indicate whether they completed the survey online or in person.

All surveys were conducted by the same three surveyors, including myself. Surveyors participating in face-to-face interviews were briefed on survey methods to ensure that surveys were conducted in the same manner. To obtain as many surveys as possible on survey days, every person present was approached and asked to participate in the survey when possible. In the outdoor park locations, such as the Strand, only who were people sitting in the area (as opposed to those passing by, walking or jogging) were approached to improve the likelihood of a completed survey. Surveyors accessed the surveys online via Survey Monkey on an IPad. When approached, participants were asked if they wanted to participate on a survey conducted by a JCU student about marine debris.

6.2.7 Analysis

Before any analysis, the dataset was processed and cleansed to remove data from respondents who lived outside the Townsville region. Any incomplete surveys were retained in the analysis, except when conducting factor analysis and stepwise hierarchical regressions analysis for direct comparisons. I also acknowledge that there may be fundamental differences between the people who are likely to take the survey online, versus those who were randomly asked to take the survey in-person. Therefore, I selected key representative Likert-scale statements under each major theme (Knowledge, awareness, responsibility, and norms), and tested the overall mean between online and in-person responses using a student's t test. This included questions such as that had more definitive statements, including: Littering in Townsville contributes to pollution in the ocean; I feel responsible for the local marine environment; and my family and friends think it's bad to litter. Although there were significant differences in respondent demographics (including gender, education and age) between online and in-person samples (Table 6.1), there were no major differences in overall views on plastic pollution and littering (Table 6.2). Therefore, all analyses shown below combine in-person and online responses.

Table 6.1: *A comparison of demographic analyses of respondents that took the survey online, or in-person. Age brackets were chosen based on Australian census categories.*

Demographic	Online % n = 240	In-Person % n = 326	F/X^2	P-value
Male	27%	50%		
Female	72%	50%		
Total responses			31.346	p = 0.000
High school (or lower)	11%	33%		
Bachelor degree/graduate diploma	45%	35%		
Masters or PhD	31%	10%		
Other	0%	1%		
TAFE/Vocational	11%	21%		
Total responses			76.122	p = 0.000
18-24	12%	8%		
25-34	29%	24%		
35-44	18%	30%		
45-54	18%	13%		
55-64	13%	10%		
65 and higher	11%	13%		
Total responses			16.193	p = 0.006
Previously attended a clean-up before (Yes)	46%	30%		
			23.463	p = 0.000

Table 6.2: *A comparison of representative Likert-scale survey questions from online responses, versus in-person responses. Responses were averaged across survey methods. Note that two questions, show slight skewed responses, ending in a significant difference between the two means. However, for these two questions, I note that response means only vary by one point.*

Survey Question	**Survey method**	**N**	**Likert scale mean**	**F**	**Levene's Test**	**T-test P-value**
I feel responsible for local marine environment and wildlife'	Online	218	8.5			
	In-person	318	7.5	16.043	0.000*	0.000*
If I litter, I feel that I'm impacting important marine habitats, such as the Great Barrier Reef.'	Online	214	8.9			
	In-person	315	8.7	0.227	0.634	0.192
Littering in TSV contributes to pollution in the oceans	Online	218	8.9			
	In-person	316	8.8	0.007	0.934	0.402
The further away the litter is from the ocean (for example in the western suburbs), it is not likely to become marine debris	Online	218	8.8			
	In-person	316	9.0	0.541	0.462	0.572
My family and friends think it is bad to litter	Online	218	9.1			
	In-person	312	9.0	0.038	0.846	0.539
I am concerned about the impacts of marine debris	Online	218	3.5			
	In-person	316	4.0	12.175	0.001*	0.045*

There was a total of 566 respondents participated in the survey (0.4% of the Townsville adult population- confidence interval of 4.11), with 240 completed online, and 326 in person. An additional 237 people were approached to do the survey in-person, but declined to partake in the survey.

All quantitative analysis and collection of descriptive and Pearsons chi-square analysis was performed in IBM SPSS Statistics 23. Likert scale questions are reported with medians and their interquartile range to show variation in responses. A factor analysis with direct oblimin rotation was conducted to determine patterns and groupings of themes (as above), however, these did not produce any identifiable themed results. Instead, a Cronbach's alpha was used to test for internal consistency amongst chosen themes. Furthermore, to determine relative accuracy of awareness of litter in the area, survey data was compared to data within the Ross River and Townsville provided by Chapter 3 of this thesis and the Australian Marine Debris Database.

All qualitative coding of open ended questions were performed in NVIVO 12, and coded into common responses using a qualitative phenomenological approach. Coding was conducted by myself and overlooked by supervisor, Dr. Claudia Benham. The final question, in which respondents were allowed to provide any additional comments, was coded using policy tools categories, including: economic and market based instruments (such as container deposit schemes); improved regulations and performance standards (such as providing incentives), info-based instruments (such as education tools), and improving technology innovation and infrastructure (such as creating environmentally friendly packaging materials).

6.3 Results

Of those who participated in the survey 337 were female, 227 were male, and 2 people choose not to identify their gender. 52% of the participants were between the ages 25-44. Approximately 10% of respondents were aged between 18 and 24, and the rest (39%) were above the age of 45. This is consistent with the population of Townsville, where the median age is 36 years old (Townsville Bureau of Statistics). On average, participants lived within Townsville 18 years (+/- 16.42 SD). Education levels varied, with 39% of participants possessing a bachelor's degree (or equivalent), 24% with a high school degree (or lower), and 17% and 19% with a trade or graduate level certificate, respectively. Respondents who performed the survey online were more likely to have participated in a beach clean-up before, with almost half (46%) responding to with 'yes' χ^2 (df= 1, n=557) = 15.447, p<0.000). In comparison, 30% of respondents on those surveyed in-person had previously attended a beach clean-up.

In their own words, participants gave a wide range of definitions for the term 'marine debris,' however, a total of 338 of the 566 responses defined marine debris to be either litter, rubbish, plastic and waste in the marine environment (Figure 6.1). Alternative responses included 'anything that should not be there' or natural based debris, such as timber, coral, and other dead-biological material. A total of 25 people responded with 'not sure', and eight additional responded with 'guessing' answers, such as 'something to do with the marine environment', 'fish', 'marine scientists' etc.

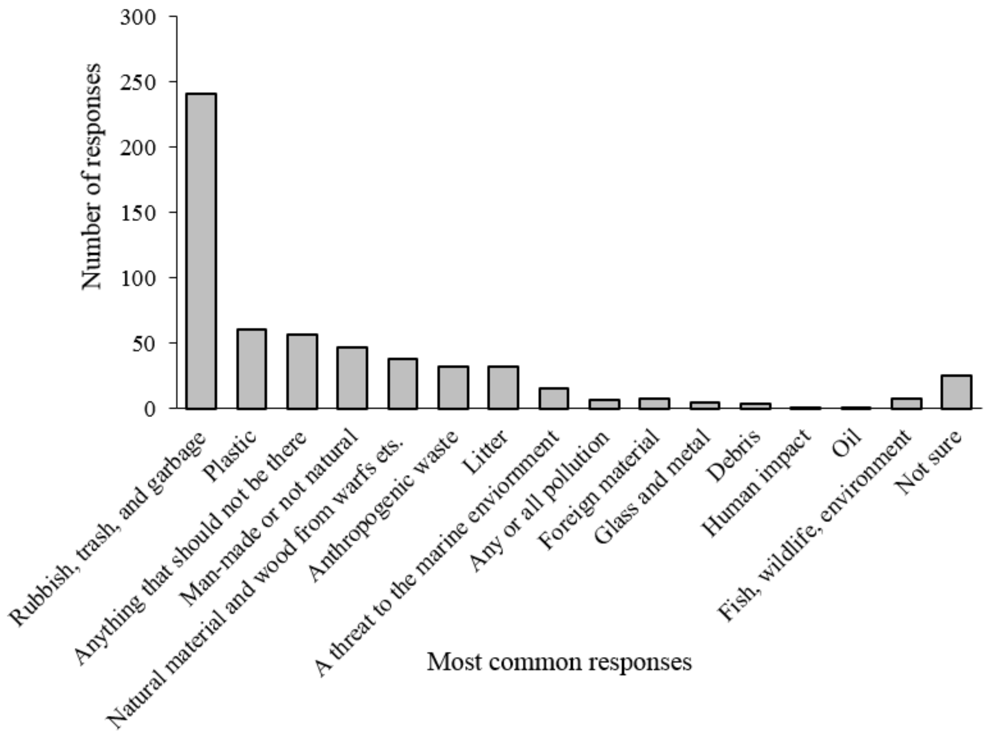

Figure 6.1: *Most common responses for the open-ended question: "What does marine debris mean to you?"*

6.3.1 Knowledge and awareness of marine debris, littering and local sources

When asked to choose the top three sources of marine debris in Townsville, over half of the participants chose 'littering in parks and suburbs' and storm 'water discharge' (67% and 61% respectively) as their top choices (Table 6.3). Marine based sources were less preferred, with 'fishing gear from fishing boats' and 'litter from boats at sea' among the lowest selected as the primary sources of marine debris. The majority of respondents (average response 8.0 +/- 0.409 variance) agreed that littering was a problem in Townsville, Queensland, and Australia (α=0.773), and that litter on streets and inland suburbs and beaches can contribute to marine debris (α= 0.714) (Figure 6.2). The majority (79%) of respondents disagreed with the statement "It is less important to pick up litter on streets as it is to pick up litter on beaches;" and 76% disagreed with the statement "The further away litter is from the ocean, it is not likely to become marine debris."

Table 6.3: *Percent of respondents choosing the top three sources of marine debris in Townsville.*

	% Selected as one of top 3
Sources of marine debris	**ALL n=565**
Littering in parks and suburbs	67.3%
Storm water discharge	61.1%
Littering on beaches	39.1%
Dumping on land	30.6%
Overflowing bins	28.0%
Fishing gear from fishing boats	16.3%
Dumping from boats at sea	26.4%
Waste from other countries	10.6%

When asked to identify the top three most littered items in Townsville, 61.5% of participants chose plastic drink bottles, 47.3% chose cigarette butts, and 46.8% chose plastic shopping bags. Plastic food packaging was identified as the fourth highest littered item, with 41.9% of participants choosing it as a top item. Furthermore, car-parks were identified as the most littered locations in Townsville, with 52.4% of people choosing it within their top three littered locations. Parklands and suburban streets followed with 39%, and 36% of respondents, respectively.

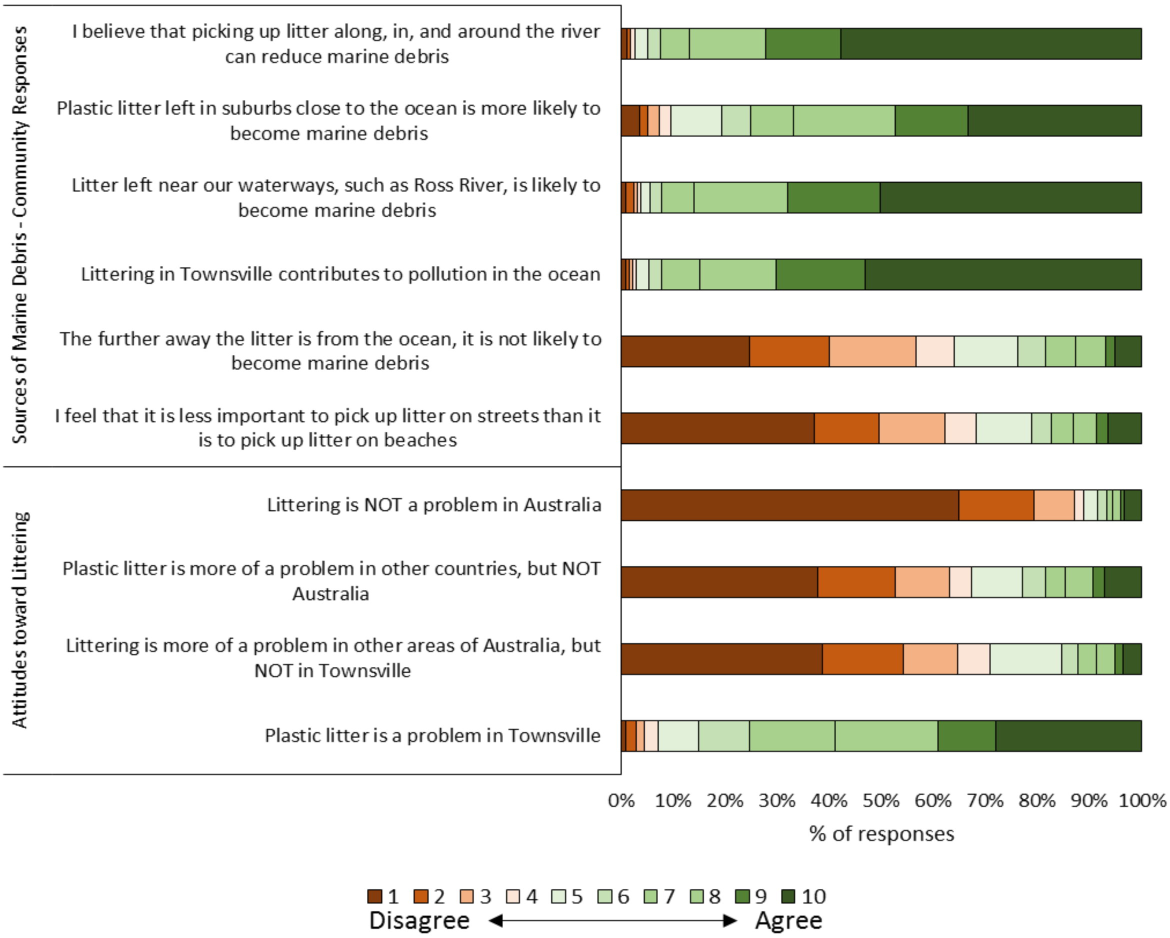

Figure 6.2: *Number of responses from Likert scale questions. 1= strongly disagree to 10= strongly agree. A reliability analysis show consistency within the grouped questions within sources (α=0.714), and attitudes toward littering in local areas (α=0.733).*

6.3.2 Responsibility, care, and social norms regarding the Great Barrier Reef

Responsibility and care for the Great Barrier Reef and local marine environment/wildlife was consistently strong (α=0.696), with an average of 8.8 (out of 1-10 scale) (Table 6.4). Overall, participant's feelings of responsibility toward protecting the GBR and concern about marine debris were strongly related. Approximately 90% of the respondents strongly agreed (answered with 8 or higher on 1-10 scale) that it is the responsibility of all Australians to protect the Great Barrier Reef. Furthermore, 88% of the respondents strongly agreed (answered with 8 or higher) that their family and friends thought it was bad to litter. Conversely, only 58% strongly agreed (answered 8 or higher) that their family and friends were worried about marine debris.

The stepwise comparison determining predictive variables of littering behaviours in regard to the Great Barrier Reef showed no significant difference between the first three models (demographics, where the survey was conducted, and the level of interaction with marine debris) (see Table 6.5). The fourth variable was significant, suggesting that values, such as responsibility, social norms, and understanding of sources predict values of concern for marine debris, with knowledge as the strongest predictor of concern.

When provided an opportunity to expand in their own words, an overwhelmingly number of participants (67%) thought that individuals had most responsibility for reducing marine debris, over government, manufacturers, and retailers. When asked the open ended question: 'what can individuals do to reduce marine debris?' participants (n=523) responded with a mixture of preventative and mitigation techniques, such as reducing plastic use and consumption, reuse and recycle, and dispose of litter correctly (Figure 6.3). Fewer people suggested to participate in curative events, such as picking up litter, or participating in organised clean-ups. Only one person responded with 'Individuals can do nothing.'

6.3.3 Concern about marine debris

The concern about marine debris and plastic was high, with 97% of respondents stating that they were concerned about the impacts of marine debris. Moreover, 79% strongly agreed (responses scaled 8-10) that plastic litter should be a primary concern for management of the Great Barrier Reef. Conversely, participants were not sure how to respond when asked if there were more pressing threats to the Great Barrier Reef than plastic pollution. There was a wide range of responses from 1 to 10 (strongly disagree to strongly agree) with the highest number of respondents (115 of 535 (21%)) choosing a 5 (mildly disagree/unsure).

The stepwise comparison determining predicting variables of concern for marine debris again showed no significant difference between the first three models (demographics, where the survey was conducted, and the level of interaction with marine debris) (see Table 6.6). Only the fourth variable was significant, suggesting that values, such as responsibility, social norms, and understanding of sources predict values of concern for marine debris, with knowledge as the strongest predictor of concern.

Table 6.4: *Respondent agreement on their level of concern for the local marine wildlife and environment, and their impact on the marine environment (1=disagree to 10 agree). (α=0.859 took the average of these questions for further analysis).*

Responsibility & care for the local marine environment/GBR	**n**	**Median score**	**Interquartile range**	**Variance**
'I care about local marine wildlife'	534	10	9-10	2.5
'I believe that my actions influence the marine environment'	536	10	8-10	4.6
'If I litter, I feel that I'm impacting important marine habitats, such as the Great Barrier Reef'	529	10	8-10	4.0
'Coastal residents should take the steps to reduce their impacts on the Great Barrier Reef'	533	10	8-10	4.0
'I feel responsible for local marine environment and wildlife'	536	9	7-10	5.8
'It is not my responsibility to protect the GBR'	534	1	1-2	4.9

Table 6.5 *Hierarchical regression analysis for variables predicting littering behaviour (n=525).*

	Model 1			Model 2			Model 3			Model 4			Model 5			Model 6		
Variable	B	SEB	t	B	SEB	t	B	SEB	t	B	SEB	t	B	SEB	t	B	SEB	t
Demographics:																		
Age	0.103	0.078	1.503	0.108	0.082	1.578	-0.007	-0.005	-0.128	-0.023	-0.017	-0.408	-0.047	-0.035	-0.860	-0.048	-0.037	-0.927
Gender	-0.298	-0.075	-1.698	-0.305	-0.076	-1.742	0.117	-0.029	-0.814	-0.115	0.029	-0.813	-0.196	-0.049	-1.419	-0.218	-0.055	-1.646
Qualification	0.017	0.012	0.268	0.017	0.011	0.261	0.033	0.022	0.612	0.023	0.016	0.448	0.027	0.018	0.528	0.018	0.012	0.377
How long they lived in Townsville	-0.094	-0.083	-1.593	-0.105	-0.092	-1.755	-0.020	-0.018	-0.413	0.012	0.010	0.238	0.014	0.012	0.298	0.000	0.000	-0.008
Experience:																		
Previously attended a beach clean up				-0.226	-0.055	-1.241	-0.1.62	-0.039	-1.086	-0.073	-0.018	-0.494	-0.068	-0.016	-0.470	-0.022	-0.005	-0.160
Psychological variables:																		
(Knowledge & Awareness) Littering in Townsville contributes to pollution in the oceans.							0.672	0.578	15.935*	0.582	0.502	12.604*	0.469	0.404	9.506*	0.318	0.274	6.073*
(Responsibility) I feel responsible for the local marine environment and wildlife.										0.144	0.175	4.342*	0.122	0.147	3.734*	0.052	0.063	1.589
(Social Norms) My family and friends think it is bad to litter.													0.238	0.224	5.580*	0.160	0.150	3.765*
(Concern) I am concerned about marine debris.																0.371	0.320	6.763*
R^2	0.012			0.015			0.341			0.365			0.401			0.450		
F for change in R^2	1.595			1.539			253.934			18.851			31.135			45.733		
Model F	0.174			0.215			0.000			0.000			0.000			0.000		

*p<0.05

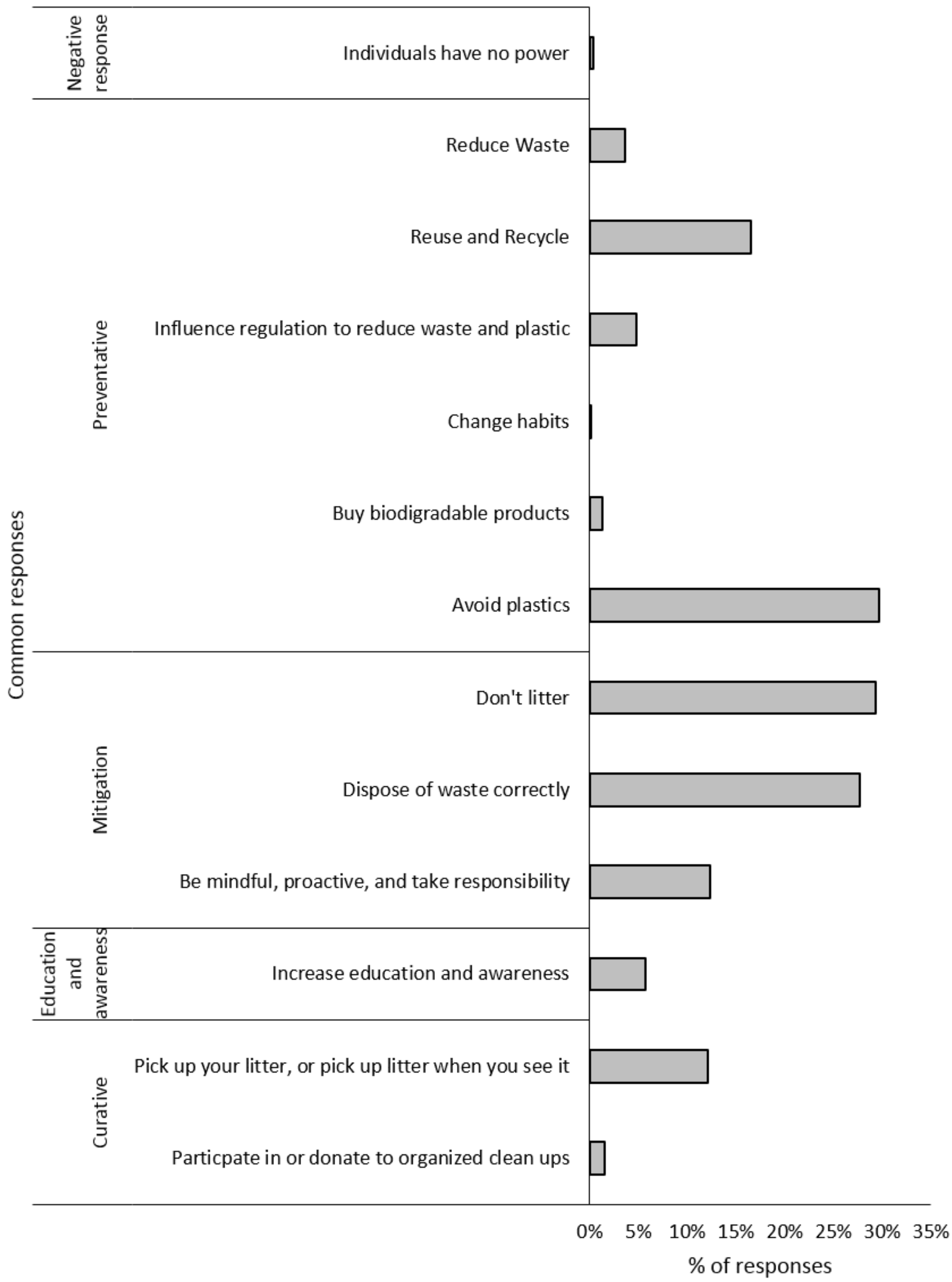

Figure 6.3: *Percent of most common responses to open-ended question: "What can individuals do to reduce marine debris." n=523. Coded in NVIVO.*

Table 6.6*: Hierarchical regression analysis for variables predicting concern for marine debris (n=525).*

	Model 1			Model 2			Model 3			Model 4			Model 5		
Variable	B	SEB	t	B	SEB	t	B	SEB	t	B	SEB	t	B	SEB	t
Demographics:															
Age	0.148	0.132	2.549*	0.156	0.138	2.684*	0.056	0.050	1.225	0.036	0.032	0.840	-0.028	-0.25	-0.679
Gender	-0.024	-0.007	-0.161	-0.035	-0.010	-0.234	0.142	0.042	1.220	0.148	0.043	1.343	0.113	0.033	1.085
Qualification	0.018	0.014	0.319	0.017	0.013	0.308	0.029	0.023	0.670	0.014	0.011	0.338	0.024	0.019	0.617
How long they lived in Townsville	-0.072	-0.074	-1.419	-0.087	-0.089	-1.704	-0.007	-0.007	-0.175	0.040	0.041	1.048	0.037	0.038	1.017
Experience:															
Previously attended a beach clean up				-0.318	-0.090	-2.057	-0.234	-0.066	-1.937	-0.115	-0.033	-1.000	-0.086	-0.024	-0.787
Psychological variables:															
(Knowledge & Awareness) Littering in Townsville contributes to pollution in the oceans.							0.626	0.629	18.373*	0.502	0.504	14.012*	0.442	0.444	12.725*
(Responsibility) I feel responsible for the local marine environment and wildlife.										0.203	0.289	7.914*	0.165	0.235	6.669*
(Social Norms) My family and friends think it is bad to litter.													0.182	0.264	7.837*
R^2	0.013			0.021			0.407			0.471			0.527		
F for change in R^2	1.710			4.467			335.111			61.695			47.647		
Model F	0.146			0.042			0.000			0.000			0.000		

*$p<0.05$

6.3.4 Community views on policy

The respondents that chose to participate in the option to further comment on littering and marine debris at the end of the survey, encouraged a wide range of governmental policy instruments to reduce marine debris. However, the need for more education and awareness campaigns were among the most common suggestions to reduce marine debris, particularly from the impacts of littering (Table 6.7).

Approximately 20% of participants that chose to provide further statements, supported improvements on regulations and performance standards, such as bans on plastic bags, and harsher punishments for those that litter. Additionally, 16 of the 215 responses asked for more bins and for all bins to be more regularly maintained, particularly around parklands, pathways, and popular recreational fishing spots.

Table 6.7: *Economic policy measures commonly mentioned in open-ended questions: "Do you have any other comments about littering that you would like to add?" Note- This question was posed as optional. Participants were not required to pose a response.*

Theme	Category	Example of suggestions/comments (quotes)	Responses n=217
Economic and regulatory based instruments	Support the container deposit scheme	"… the introduction of 'no single use plastic bags' at retailers and the take- back scheme for bottles and cans, we may see a reduction on the litter often found in our local environments."	1
Improve regulations and performance standards	Collaborative actions on all levels are needed	"Individuals, industry and the government need to be actively concerned about cleaning up the environment as well as leading in waste reduction."	5
	Harsher punishments, provide incentives, and increase taxes	"We need harsher punishments (or any punishment) for people that litter, especially out of their car." "Higher fines for those caught littering."	8
	Support plastic bans locally and world-wide	"We need a worldwide ban on all kinds of single-use plastics" "More steps need to be taken toward banning other types of plastics. E.g. coffee cups, straws, takeaway containers, etc."	18
	Improve regulations and transparency of recycling practices in Townsville	"I am originally from Italy and recycling is compulsory everywhere now in every single shire or city. I found it very distressing QLD doesn't have such a thing." "There needs to be more transparency on how recycling operates in Townsville. I believe people actually think everything they recycle is being recycled, which isn't true. If people realize their plastic waste is just going to landfill, hopefully they would be less inclined to use plastic in the first place."	6
	Improve regulations for boats at sea	"Long line fishing, poachers, large cargo ships are getting rid of their rubbish." "….ban lead sinkers"	4

Theme	Category	Example of suggestions/comments (quotes)	Responses n=217
	Improve performance standards of local government	"…I feel existing rubbish is now Council responsibility." "Local council could do more to keep our beaches litter free."	6
	Put 'pressure' on corporations to hold them accountable	"Pressure on retailers/producers is needed." "Big companies are the biggest polluters. Plastic bottles are ridiculous."	6
Individual behaviour changes	It's everyone's responsibility	"Pick up rubbish when you see it and try to help out." "It is everyone's responsibility to clean our planet."	12
	Reduce plastic use & Recycle	"Reduce plastic packaging across the board and reduce the use of fast food plastics." "I hope the current movement towards reducing and recycling plastic and other waste gains momentum and continues to grow."	8
	Report littering	"More people need to report to either local or state government when they witness someone littering or illegal dumping. Anyone can report it and fines apply.	1
	Dispose of waste correctly	"Don't be a pig." "People are becoming complacent with their litter."	8
Education	Education and awareness campaigns & organized community clean-ups	"There should be a more concerted effort to create community involvement activities that focus on clean ups and conservation education." "I think people need more information about litter that comes from Australia and litter that comes from other countries, like Indonesia." "Adding recycling and reducing waste as a national school curriculum."	51
Technology innovation and improvement of infrastructure	Use/improve mitigation techniques	[Implement] "filters on washing machines to prevent polymer particles entry into the environment." "The litter traps in storm water drains the council use need to be well maintained and cleaned out regularly." "Bins along the foreshore and other public spaces need to be emptied more often as often overflowing in Townsville."	2
	Create or use more environmentally friendly products, and make packaging design clearer to dispose	"Industry should be working on new packaging materials that biodegrade." "We need more degradable products…" I think it would help to recycle their waste if all packaging was clearly labelled with instructions on how to deal with it. Either recycle or place in the garbage bin."	12
	Increase available infrastructure	"No bins in the park, so rubbish builds up." "Have more recycling places around. Container deposit scheme is great." "Not enough bins at parklands and walking paths, not emptied enough. More dump sites along highways." "Not enough bins on river way park." "There needs to be more places for people to dispose of cigarette butts in Townsville."	16

6.4 Discussion

This research shows that Townsville residents have a well-defined working knowledge of what marine plastic pollution was and how it arrives in the environment. Over half of the participants were able to define the term marine debris and primarily associated it with litter, rubbish, waste or specifically plastic pollution in the marine environment. Furthermore, over half (67% of participants) believed that land-based pollution is the primary source of the debris in Townsville and repeatedly identified that litter originating away from beaches and coastal areas (such as inland suburbs, streets, and carparks) could also contribute to marine plastic pollution. This suggests for the first time in primary literature that urban residents in Australia are able to connect the action of littering in inland sources with marine debris.

Moreover, participants in this study generally held a strong connection to the Great Barrier Reef, further supporting previous research that Australians consider the Great Barrier Reef as part of the Australian identity (Goldberg et al., 2016; Marshall et al., 2016). Similar to the findings in Goldberg et al. (2018), the present study found that over 90% of respondents strongly believed that it was the responsibility of all Australians to protect the Great Barrier Reef, which was linked to overall concern about marine debris. This sentiment has been linked toward marine protected areas both Australia and globally, with research showing that people are in favour of supporting policies to protect biodiversity and reduce hazards to the marine environment (Trenouth et al. 2012; Trenouth and Campbell 2013; Tonin and Lucaroni 2017). In this study, this view among the community did not vary among demographic groups, and respondents' previous experience with marine debris, supporting an overall connection to the world heritage area. Instead, the strongest drivers for the concern of marine debris and littering behaviours were the psychological variables surrounding sense of responsibility, social norms, and most importantly, the knowledge that litter in Townsville contributes to marine debris (Tables 6.3 and 6.4.). As such, this research suggests that the majority of respondents were concerned about the Great Barrier Reef, and felt that plastic litter should be a primary concern for management. These findings are supported by the broader research in the area (Kollmuss and Agyeman, 2002), suggesting that the overall awareness and sense of responsibility regarding littering can influence pro-environmental behaviour.

In addition to being well informed and aware of local marine debris sources, Townsville residents seemed reasonably aware of commonly littered items and places around the region. When provided possible top pollutants, participants indicated that the top littered items consisted of plastic drink bottles, cigarette butts, and plastic bags. While these items are in fact abundant within the Townsville environment, regular reports from long term monitoring sources such as the Australian Marine Debris database, and Bauer-Civiello et al. (2019), found plastic food packaging was among the highest observed and recorded items, over plastic bags and drink bottles, however this was not ranked as highly from participants. It should be noted that the perceptions of the most common debris items may be influenced by media, where participant's top ranked items such as plastic bags are commonly shown in marine debris media (Eagle et al., 2016), and recent source reduction policies, such as the recently introduced plastic bag ban and the container deposit scheme, which had received significant media attention. In addition to the awareness of litter, participants were also reasonably aware of litter issues within the region, and reported that litter was most commonly observed in car parks, suburban streets, and parklands. High awareness of environmental problems, such as littering and marine debris, suggests that there is a high level of congruence between what residents think, and what science tells us for highly visible pollutants (Benham, 2017).

Apart from the overall positive results of this study, it can be argued from my data that further education, engagement, and campaign tools are still needed for the small portion of respondents that that were less knowledgeable, or less motivated regarding marine debris. Studies have shown that education and engagement campaigns can improve behavioural change regarding littering and marine debris (e.g. Uneputty et al. 1998; Storrier and McGlashan 2006; Taylor et al. 2007). However, unlike previous research in this space, in my dataset there was not a particular demographic (age, gender, qualification) that dominated participants that were relatively unaware, or unconcerned about littering or marine debris (Arafat et al., 2007; Bator et al., 2010; Campbell et al., 2014; Slavin et al., 2012). Rather, my data indicates that there may be other factors influencing knowledge and awareness of marine debris in relation to littering cut across all demographics or were characteristics of demographics that were not examined in this study, such as political beliefs, income, occupation status, or other social-economic factors that can influence litter in the environment (Campbell et al., 2014; Santos et al., 2005; Torgler et al., 2012). While this makes it difficult to create targeted litter campaigns, it indicates that more work needs to be done to go beyond standard demographic categorisation when targeting litter reduction initiatives.

6.4.1 Policy and influence community engagement

The results of this study suggest that there is a fundamental contradiction in which people love and identify with the Great Barrier Reef, but are not motivated enough or are unaware of the actions they can take to induce change (Goldberg et al., 2018). Moreover, there is a gap between knowledge and awareness, and the presence of litter indicates a contradiction in the value-action gap, where the majority of participants were aware and informed, but litter remains a problem. This suggests that the current campaigns surrounding increasing knowledge and awareness of marine debris and its sources may not be as beneficial for behavioural change. Rather, messaging surrounding what individuals can do, and how they can participate in solutions, may be more impactful for source and litter reduction, such as participating in organised clean ups, and popular media campaigns like the #trashtag or the 2 minute-beach clean. Yet, when asked what individuals can do about marine debris, only about 20% of participants identified that individuals can pick up litter when they see it, or participate in or donate to organised clean-up events. This suggests a high proportion of participants (80%) may not be aware that they have the option to participate in these events, or not willing to act. Participating in clean-up events, or individuals simply picking up items on their own, not only provide curative actions, but also allows community members to participate in citizen science, which is an important tool to raise the perception of risk of plastic pollution, stakeholder involvement and provide better communication between scientists and the community (Storrier and McGlashan, 2006; Syberg et al., 2018).

Barriers to action, such as convenience, cost, lack of alternatives, and other priorities that are likely factors to influence litter in the environment (Critchell et al., 2019; Harland et al., 2007). Given that participants were found to care for the reef and believed that littering was a main source of marine debris suggests that residents may be influenced by some of these barriers. In these cases, encouraging pro-environmental behaviours to stop intended littering is not enough, because there appears to be a systemic structural problem around plastic consumerism, lack of infrastructure, or policy that would prevent accidental littering to occur. Instead, a mixed method approach around adapting policies, increasing infrastructure, and raising awareness may be more appropriate (Critchell et al., 2019). For example, as suggested in Campbell et al. (2014), people are more likely to litter, and probably less likely to pick up litter, if a bin is not around (Finnie, 1973). This is supported by the fact that approximately 7% (n=15) of the participants that chose to provide further comments at the end of the survey indicated that there were not enough bins in high use recreational parks, or the bins are not emptied enough. Therefore, increasing available infrastructure may be important for litter reduction.

The results of this chapter indicate that approximately 56% of participants participate in preventative techniques such as plastic and waste reduction, suggesting that the other half of participants remain unware or unable to participate in source reduction opportunities (Figure 6.2).Research shows that due to the excessive use and reliance of disposable plastic items alone, at least a portion of this is attributed to accidental release (rather than intentional) (Sibley and Liu, 2003). For example, some research has shown that accidental roadside littering is likely to make up about 45% of the available litter in the United States (Forbes, 2009). Therefore, providing information regarding the circular economy, and ways individuals can reduce plastic waste generated at a household level could also be helpful to avoid accidental loss as mentioned above, particularly for the individuals that are already motivated and engaged, but remain unsure of what individuals can do. This would help provide the information needed to ensure that these individuals to make the right choice in regard of waste reduction, to eliminate the chance of plastic arriving in the environment.

6.4.2 Limitations and recommendations for future research

The survey I conducted was structured to identify physiological constructs around environmental issues, including knowledge, awareness, and norms and concern, but in hindsight, it would have been beneficial to ask specific questions targeting specific littering behaviours, and the likelihood of individuals picking up litter (other than participating in beach clean-ups). Knowing this could provide further information on this gap, and allow me to provide a more quantitative analysis on the value-action gap, but the interpretation of these types of data would depend on knowing the degree to which the participants told the truth. Future research not only needs to concentrate on this gap, but also needs to focus on how and why accidental littering occurs, and the structures that allow that to happen. Regardless, this study can be used as a step to further understand behavioural change regarding plastic use and disposal, and incorporate community perception and views to influence local management (Benham, 2017).

One aspect of littering in the urban environment that was not addressed in this research, was litter from the tourism industry. Instead, the research conducted focused on the knowledge, awareness, and concern about marine debris in relation to littering from residents only. As a tourism town, Townsville receives an average of over 5 million tourists per year (Tourism Research Australia, 2019), and previous research shows, due to the lack of connection to the environment, tourists are capable of contributing to litter in the environment (Brown et al., 2010). Therefore, this may be an important aspect to include in future research.

In addition to the factors outlined above, the expansion of this survey across other cities and more rural communities in Queensland and including more age groups (i.e. younger than 18) would also be beneficial to determine if views and perceptions differ. Previous research in Europe has noted that views can differ depending on location, and therefore is an important factor to explore (Hartley et al., 2018). In addition, some studies have described in previous literature that individuals younger than 18 are more likely to litter (Reich and Robertson, 1979; Robinson, 1976). In my survey I was unable to include anyone younger than 18 years of age due to ethical constraints of my permits. Information from people under 18 would provide additional details needed regarding litter and marine debris management, particularly if communities need individual attention, or if a wider approach of education and management can apply across the state.

6.5 Conclusion

The findings from this research contribute to a growing knowledge base surrounding the perceptions and knowledge of littering in relation to marine debris, and fill a gap relating littering behaviour in Australia. Critically, Townsville residents felt that they were a contributing factor toward marine debris, and that individuals held the most responsibility to reduce plastic in our oceans. In a culturally valued ecosystem, such as the Great Barrier Reef, I found that residents have a strong connection to the environment, high awareness about the connections of littering and marine debris, yet littering still occurs. As a result, targeted messaging focusing on individual responsibility, pride, and identity may resonate strongly for Townsville residents to take actions. Furthermore, future management and education tools can move away from educating the public about why littering is bad, and instead, support individuals, and work on campaigns where people can more easily participate to reduce litter and plastic use.

Chapter 7
General Discussion

Marine debris, which is made up to 95% plastic, is a complex environmental pollution issue and a hazard to the marine environment (Ryan, 2015). Marine debris can originate from a wide range of sources, and can be comprised of different materials and of different sizes. Once in the ocean, marine debris becomes a pervasive issue to marine habitats and wildlife (Wilcox et al., 2016; Wilcox et al., 2018; Wilcox et al., 2015). While the degree to which plastic can impact the marine environment on a species or ecosystem level remains unknown (Galloway et al., 2017), it is clear that individuals of many species are affected. Furthermore, the growing use and reliance on plastic in society is leading to continued input into the ocean, which is likely to increase exposure to marine wildlife (Jambeck et al., 2015). Therefore, minimising current and future impacts will require immediate responses and source reduction solutions are needed to reduce plastics world-wide.

It is becoming increasingly clear that management of marine debris requires a wide range of infrastructure development, policies, and incentives, all targeted at specific sources, until overall plastic production and use is reduced. However, there is not a one-size fits all solution to reduce waste, even in local jurisdictions. The issues of waste minimisation, waste processing and waste management alone are socially complex, and require both national and international attention to reduce overall plastic inputs (Critchell et al., 2019). To improve our understanding plastic inputs and sources, further research is needed to identify pathways, monitor sources, and identify common items so that infrastructure and policies can be used effectively.

Interdisciplinary research is one mechanism that can be applied to improve the understanding of complex environmental issues. For example, eliminating light pollution for sea turtles nesting sites (Kamrowski et al., 2014), reducing illegal fishing (Riskas et al., 2018) and the input and placement of marine protected areas (Carr, 2000) all require an understanding on human behaviour, policy, environmental research, and an understanding of ecological impacts to provide successful management strategies. Therefore, for this thesis, I use this interdisciplinary research to comprehensively understand the relative threat of plastic pollution and provide an empirical knowledge baseline for interventions aimed at "turning off the tap of plastic" (Pahl and Wyles, 2017). This research includes understanding the abundances of various types of debris, the common types of material, the distribution and dispersal pathways of debris, coupled with improving the knowledge of the social drivers that influence plastic use and disposal (Rochman, 2016; Rochman et al., 2016). Furthermore, this research furthers the understanding of the potential impacts and interactions on marine fauna. This is not only an important aspect to monitoring debris loads, but can also can be used as a tool to engage the community and policy makers to implement change. For example, media images showing the impact of single-use plastics on turtles was found to be influential in many plastic bag bans around the world (Eagle et al., 2016). Overall, interdisciplinary knowledge can be a powerful tool to reduce plastic both locally and world-wide.

The overarching aim of my thesis was to use interdisciplinary approaches to understand local sources of marine debris and plastic pollution in Queensland and how it can be effectively mitigated before arriving in the ocean. More specifically, my thesis aimed to inform knowledge gaps required for management using four overarching themes:

- Theme 1: Understanding distribution patterns to narrow down potential sources of debris (Chapter 2)
- Theme 2: Identify pathways of plastic entering the aquatic environments and why they occur (Chapter 3 & 4)
- Theme 3: Identify approaches to monitor macro and microplastic loads to identify impacts, create baselines, and monitor change. (Chapter 4 & 5)
- Theme 4: Understand community awareness and concern about marine debris to reduce land based sources, such as from littering. (Chapter 6)

My thesis makes a novel contribution to the larger body of scientific work produced globally and provides additional key, locally specific information on the pathways, loads, and monitoring techniques that can be used in other local jurisdictions of Australia and around the world.

7.1 Understanding distribution patterns and quantifying plastic loads in aquatic environments

My thesis provides new insights into the abundance of debris and plastic loads within an Australian tropical river systems and the pathways through which litter and plastic waste can enter aquatic environments. In Chapter 2, I identified a relatively low but consistent load of debris on reefs throughout Queensland, ranging anywhere from an average of less than 1 item per survey to 27 items per survey. Items recorded on the reef surveys mostly consisted of fishing and boating related debris, with the most items recorded on higher-used and accessible reefs closer to larger cities. Since limited macro items were found on Queensland reefs, particularly those on the Great Barrier Reef systems, it implies that current loads of debris on Queensland coastal habitats (apart from fishing and boating related debris, including: fishing line, rope, net etc.) is 1) mostly pelagic and 2) easily dispersed, 3) buoyant, and collectively more difficult to detect on subtidal reefs. As such, common items found on Queensland beaches (such as straws, plastic bottles, and plastic packaging) are less likely to be found on the reefs themselves, but may still effect pelagic reef dwelling creatures. Overall, these data suggests that subtidal debris on Queensland reefs are currently low, however continuous monitoring is needed to identify any potential and future issues.

In chapter 3, I identified that over the course of three years, greater than 27,000 items (primarily plastic) had entered small sections of Ross River in Townsville, Queensland Australia. Throughout a single wet season, an average of 23 to 32 items entered the monitored section of the river system per day (depending on the site). In addition to macro debris, in chapter 4, I found that microplastic loads within the freshwater section of the river are capable of increasing by 16% after the wet season and when the weirs are overflowing. As only a small portion of the river was sampled, these results suggests that a relatively small urban area is capable of creating and contributing the large amount of litter in the local aquatic environment. The sampled locations provide examples of what can be occurring in other parts of the river, creek, and even marine system, where storm water systems or parklands can attribute to litter in the environment directly.

Ross River itself is unlikely to have an impact on plastic abundances on nearshore reefs and coastal environments in years with low rainfall. Instead, my results indicate that Ross River is likely to retain large quantities of debris and plastic (including microplastics) due to limited water flow over the artificial dam and weirs. However, higher retention of plastic items within the river causes the microplastic abundance in the sediments of Ross River to be relatively high for a city the size of Townsville. For example, in comparison to other studies, average microplastic loads in the sediment of Ross River were approximately half the reported loads found in the Thames, a larger river system flowing through industrial cities of England (Figure 7.1).

It is possible that a larger weather event, such as a cyclone or flooding event, could potentially flush the retained particles from the water column, benthic sediment, and banks, creating a pulse event of debris entering the marine and coastal habitats, rather than continuous exposure to Cleveland Bay, and by extension, the Great Barrier Reef. However, further research and modelling of the discharge and water movement, specifically for Ross River, is needed to identify potential plastic inputs into Cleveland Bay (Besseling et al., 2017; Kooi et al., 2018).

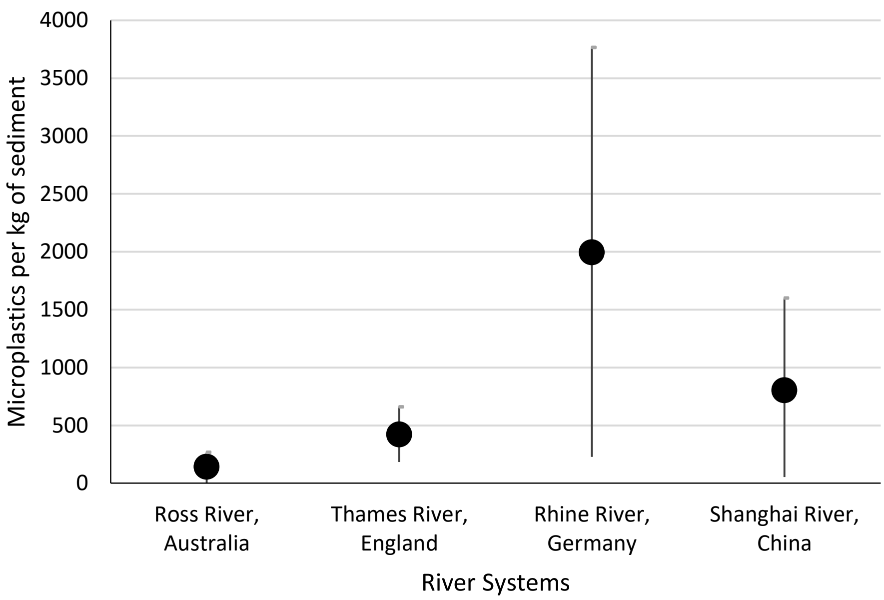

Figure 7.1: *Comparison of plastic loads in Ross River to other river systems. Dot represents average number of microplastics per kg of sediment, and lines represent the minimum and maximum value provided in the studies. Although these studies collect sediment samples using different methods, this figure provides rough estimates of overall plastic loads across major river systems in Europe and Asia, to a small, relatively rural system in Australia. Data used from: (Horton et al., 2017; Mani et al., 2015; Peng et al., 2018)*

7.2 Sources and pathways of anthropogenic debris and microplastics in Townsville

Although my results suggest that Ross River has limited contribution of plastic to the marine environment, I produced novel information on where infrastructure and other intervention techniques could be used to reduce plastic input into the local freshwater system. For instance, in Chapter 3, a large portion of anthropogenic debris entering the river system could be attributed to wind and direct littering along river banks and adjacent parklands, in addition to rainfall washing debris through street gutters and storm water systems. I was also able to confirm that microplastics in Ross River are likely to be from larger littered items, degrading nearby (such as on streets or in gutters) or in the river itself via exposure to UV light as opposed to primary microplastic particles. Much of the microplastic items collected in Chapter 4 consisted of broken fragments and fibres, in contrast to microspheres or manufactured pellets which are commonly referred to as primary microplastics. This suggests that the elimination of littering in the catchment areas of storm drains by means described in Figure 7.2, could reduce the long-term accumulation of microplastics within Ross River.

7.3 Creating baselines and monitoring change

As described in Chapter 3.4.1, all debris loads recorded over the sampling period were uploaded into the Australian Marine Debris database, which is a database used to monitor debris loads in urban and coastal environments across Australia. The database was established to bridge the gap between informal clean ups, long term monitoring programs, and scientific data collection, and to gather as much information as possible for source reduction management both locally and nationally. Traditionally, the database focused on beach clean-up events, however, it has gradually been expanded to include data from other types of debris monitoring, including rivers and catchments. The continued monitoring of debris types and loads within creeks and rivers are important for improved and targeted policy and infrastructure.. For example, my data collected in Ross River can now be used to monitor changes in plastic loads after the recent ban on the use of plastic shopping bags in Queensland and the container deposit scheme. It can also be used more broadly to monitor any changes due to community engagement and less formal source reduction initiatives, such as the reduction of straw use, and infrastructure programs used to mitigate debris loads.

Apart from monitoring plastic and debris loads within the environment, it is also important to monitor changes of plastic abundance within the biota to understand the level of interaction and the potential impacts of plastics in the environment (Fossi et al., 2018). This is particularly important for microplastics, as they are patchy in abundance, and difficult to accurately detect and sample in the marine environment (Critchell and Lambrechts, 2016; Paul-Pont et al., 2018). Therefore, in Chapter 5, I investigated two commonly found benthic marine filter feeders in the Great Barrier Reef to examine their potential use as an indicator species to quantify microplastic loads on subtidal reefs. I identified that both species ingested less than 1% of the concentrations provided. The sponge, *Carteriospongia foliascens,* retained 83-95% of the ingested microspheres up to 7 days, while the soft coral species, *Lobophytum sp.* retained microspheres for the full 14 day experiment. These results indicating that the use of microplastic ingestion of for these two species were not suitable options to use as indicator species. Yet during the experiment, I found microplastic particles were found to adhere to the surface of both organisms and were shed via mucus production. *C. foliascens* ingested twice the amount of plastic particles as the amount adhered to its surface. However, for *Lobophytum sp.* the amount of particles adhered to the surface were equal to or double the ingested microspheres for the first week. Furthermore, adhered particles for *Lobophytum sp.* showed a detectable difference in concentration loads for day 2, suggesting that it is possible to detect differences in concentration loads between reefs by looking at the adhered particles. While my results did not recommend the use of these two species as indicators, I recommend further research to look into the ingestion of plastic particles on sessile benthic species, as well as the possibility of extracting mucus from these organisms. Mucus extraction could be a reliable, non-invasive way to monitor plastic loads as it is relatively easily collected and extracted not just by scientists, but potentially by citizen scientists and management agencies. This could have broad implications for monitoring plastic loads on reef systems world-wide by maximising the amount of data collected, potentially providing more information for education, community engagement, and support in regard to plastic pollution.

7.4 Understanding community awareness and concern about marine debris to reduce land based sources, such as that from littering

Understanding the community awareness and concern about marine debris is one of the most important steps to "turning off the tap" and eliminating plastics at its original source, humans (Veiga et al., 2016). Therefore, in chapter 6, I used social surveys to identify the overall awareness of marine debris from Townsville residents, and if they were aware that plastic occurring inland can attribute to plastic in the marine environment. I found that Townsville residents were aware that inland littering is a contributing factor toward marine debris and that individuals in Townsville felt they held the most responsibility to reduce plastic in our oceans. Furthermore, I found that Townsville residents showed a strong connection to the Great Barrier Reef and felt responsible for its protection. Based on these results, I suggest that targeted messages focusing on individual responsibility, pride, and identity is likely to be beneficial to reduce litter before it arrives in the waterways. Moreover, combined with the results from chapter 2, these messages can be site specific, which provides a more cost-effective and targeted solution to the people using this part of the river. For example, one survey site found more snack sized food packaging, likely from the school children that use the parks and pathways to make their way to school. Alternatively, additional messaging focusing on care for Great Barrier Reef toward recreational fishing and boating can also be used to limit that litter directly entering onto the reef itself, such as that found in Chapter 2.

It is also important to note that survey respondents in this study were not able to identify the extent that marine debris poses a threat as compared to other environmental issues. This does not go unwarranted, as the relative threat of plastic pollution is still under considerable debate with some scientists (Stafford and Jones, 2019). This suggests that future educational material should provide accurate statements on the threat of plastic pollution, in addition to other environmental hazards.

7.5 Management outcomes achieved by my thesis research

These data collected in this thesis is useful to local managing organisations as it provides more targeted, effective solutions based on limited council budgets. In addition, it provides further information for management and policy makers, as it provides direct evidence of plastic pollution in the river and indicates the benefits of reducing or eliminating litter within the river as a hazard in local aquatic environments. Recent research about the effectiveness of waste abatement campaigns and government policies found that local councils that applied up to 8% of their budget toward waste management have lower marine debris loads on beaches and coastlines (Willis et al., 2018). Furthermore, Willis et al. (2018) provides broad abatement interventions along the waste stream, but based on the data collected in this thesis, I suggest an updated version (Figure 7.2), where infrastructure could be more effectively placed in certain areas, such sites along major roads, but other methods, such as implementing additional bins with lids, clean ups, and targeted messaging, would be more beneficial around recreational areas. For example, given that litter within the river was likely to be from nearby sources (Chapter 3) and a common complaint from Townsville residents were a lack of bins or bins not emptied enough near parklands (Chapter 6), a good first step for waste management in Townsville would to be improve this infrastructure and place gross pollutant traps, either in the river, or on the drains. This would both limit waste from entering the river, and as a result, reduce microplastic accumulation.

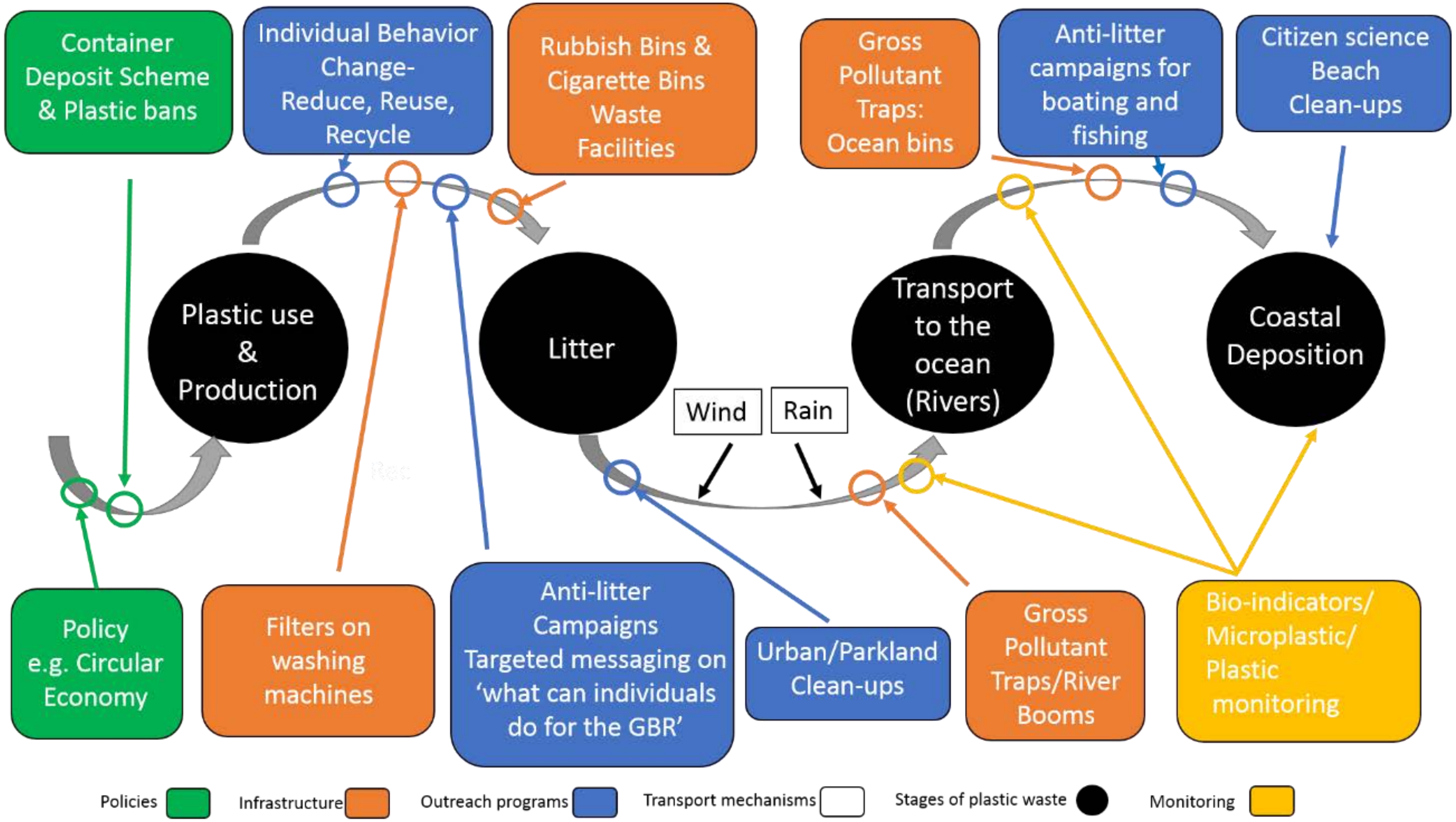

Figure 7.2: *A summary of pathways, infrastructure, and mitigation techniques needed to manage marine debris, modified and updated from Willis et al. (2018).*

The conclusions I draw in my thesis are directly relevant to management and they are currently being used to inform and manage marine debris and litter in local areas in Townsville. Throughout my PhD research, I have had conversations with local management agencies and businesses such as Townsville City Council and the Clean-up Water Group to implement infrastructure and create opportunities for further monitoring. Moreover, the Great Barrier Reef Marine Protection Authority have established Local Marine Advisory Committees (LMAC) to enable local communities to provide strategic input towards marine park management. I was invited by the Townsville LMAC to present my thesis outputs and have been active in promoting the issue of marine plastic pollution on the GBR. In addition, I recently aided in the coordination of a project within the LMAC to receive a grant to continue monitoring marine debris loads and to use the new knowledge gathered from Chapter 6 as a basis for community awareness and engagement campaigns by the Townsville City Council. Furthermore, the microplastic load data collected in my thesis will be used in a regional report card created by the Dry Tropics Partnership for Healthy Waterways for future monitoring of plastic loads and relative health of coastal systems in Townsville.

Lastly, I create new and novel insights into alternative methods to monitor microplastic loads on the reef (Chapter 5) and provide further research on potential indicator species for coral reef ecosystems. As the most recent GBR Strategic Assessment Report and the Reef 2050 Plan reports, key knowledge gaps include types, quantities, and the fate of microplastics within regions most likely to be affected by coastal cities. Therefore, the use of an indicator species can guide management actions and responses at local scales and shed light on the cumulative threat of microplastics on benthic invertebrates in the Great Barrier Reef.

7.6 Thesis limitations and directions for future research

My thesis provided data and insights about plastic pollution of a relatively small city, and how this contributes to the more global problem of plastic pollution. Although my data has been collected on a small sections of the Ross River, these collection sites were chosen because they were representative for other sections of the river, especially those adjacent to suburbs. Nonetheless, I cannot exclude that my data underestimates the overall debris loads entering the river and care must be taken when extrapolating my results to other river systems. In addition, it was outside the scope of my thesis to collect samples or plastics from connecting creeks, lakes, or storm drain effluents that expel directly into the marina or onto the beaches. Therefore, additional empirical data is needed to make more robust estimations about the amount of debris items that enter the marine environment. In addition, future research would greatly benefit from freshwater models to determine the likelihood of plastic discharge from the river at various rainfall or water flow levels. This information would be important for managing organisations to understand the potential impact of large scale events, such as the recent flooding event that occurred in February of 2019, where the dam exceeded its capacity and consequently flooded large areas of Townsville's riverside suburbs.

As shown in this thesis, littering on land is connected by many complex pathways before it ends up in aquatic systems. Therefore, it is important to continue research that investigates these connections and pathways. For example, Chapter 3 explored the connection between litter in parklands and debris collected in the adjacent river. To further investigate how litter arrives into the river system, additional surveys should be conducted along the conduits of the storm drains to identify the types of debris and quantify the accumulation of debris along the pathways. Such information can provide insights that could assist source reduction strategies. Future research should also continue quantifying the plastic loads into river and coastal systems year round, to have a better understanding of the seasonal effects and the impact of large weather events, such as cyclones and flooding, on plastic pollution in aquatic systems.

To reduce the input of plastic into the environment, further research into environmentally friendly use, reduction, and disposal of plastics is essential. This can involve experiments in which different infrastructures are tested in litter hotspots (e.g. cigarette bins near bus stops), or through social surveys to investigate the economic and social constraints around reducing overall plastic use. Furthermore, as mentioned in Chapter 6.4, additional information on the perceptions of marine debris and littering in younger age groups, such as teenagers and young adults could also provide information on an age group that is rarely surveyed in peer reviewed literature.

This thesis provided the first steps into testing possible indicator species to monitor plastic loads on the reef. To determine if my species or others can be used to detect plastic loads on the reef, further research is essential. This includes experimental research focussed on testing different species exposed to various plastic sizes, shapes, and types in addition to field-based research. More specifically, field based research should include organisms collected from the reef, where the plastic loads found within the organism is compared with that found in the sediment and surface waters, similar to experiments performed in Bonanno and Orlando-Bonaca (2018). Identifying indicator species could greatly advance our ability to detect and estimate microplastic abundance in the environment, which would provide the evidence needed to understand the relative impact on the Great Barrier Reef. Hopefully this information could lead to more efficient and targeted waste management strategies.

To improve future monitoring of microplastics in the environment and biota world-wide, refining the standardisation of the characterisation of plastic size classes, plastic type, and FTIR analysis in future research would help with reporting and comparing microplastic loads within the environment. Therefore, data could be more readily compared to studies that were unable to extract a wide range of microplastic sizes. In addition, there was very little research that provides information on how many particles are needed to scan, and how the data was corrected. Due to this lack of information, it was difficult to determine the appropriate methods to use and if they can be accurately estimated against other research papers. I suggest that future research should include this information to provide results that can be more readily comparable.

Lastly, the overall implications of my thesis suggests that plastic management can vary greatly on a small, local scale, and is heavily influenced by local urban infrastructure, community attitudes, and local environmental factors. Therefore, the expansion of the research conducted in this thesis to other river systems could greatly contribute to the improvement of our understanding of the sources of microplastic pollution nation-wide. For example, it is likely that other river systems in Australia may have other factors that influence plastic abundances, such as sewage effluents, or occur in industrial areas that use or manufacture pellets. Therefore, further research on these areas could identify sources, and encourage policy and infrastructure, such as the improvement on the filtration systems on household washing machines, or more vigorous regulations on the transportation and production of resin pellets. The expansion of this research could improve our overall understanding on plastic inputs into aquatic and coastal systems.

7.7 Concluding remarks

Marine debris is a global issue, and people from every country contribute to the problem. Local, national, and global incentives and initiatives are needed to reduce marine debris. Interdisciplinary research, such as mine, is essential to understand and reduce plastic sources and solutions on a local scale. As a relatively new field in marine conservation science, my research lays a platform for management, further research and monitoring regarding plastic pollution in aquatic environments, especially in Townsville. I also identified important aspects about waste management that require improvement and provided the baseline on how the community perceives marine debris and its sources.

The research I conducted in this thesis does not attempt to undermine overarching environment issues affecting the marine environment (e.g. climate change), and acknowledges that Australia, as a relatively small populated country does not contribute to the debris in the oceans on the same scale as some other countries. Instead, I used data from Townsville to understand the distribution of debris loads at a management relevant scale, and look at a small piece of the puzzle by identifying the contribution of local sources and ways to empower and encourage local residents to induce change. By conducting this research, I hope I created a catalyst for further research and change in management strategies to reduce plastic in our oceans.

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Appendix 1

A1.1 Table: *List of reefs and sites used for data collection. Notes region of sites Great Barrier Reef (GBR) or Southeast Queensland (SEQ), whether sites are near (N) or offshore (O), fishing restrictions (take or no-take), total number of surveys, and average debris abundance per survey.*

Reef Name	**Site Name**	**Region**	**N/O**	**Take or no-take**	**# of surveys**	**Avg. debris/ survey ($400m^2$)**
Agincourt Reef	Agincourt 3D (Pontoon)	GBR	O	No-Take	18	0.44
	Phil's Reef	GBR	O	No-Take	5	0.00
	The Point	GBR	O	No-Take	4	0.00
Davies Reef	The Lost World	GBR	O	Limited take	6	0.50
Hardy Reef	Hardy Reef	GBR	O	No-Take	16	0.06
Hastings Reef	North Hastings B	GBR	O	No-Take	13	0.08
Hayman Island Reefs	Blue Pearl Bay	GBR	O	No-Take	15	0.83
Heron Reef	Canyons	GBR	O	No-Take	4	0.00
	Cappuccino Express	GBR	O	No-Take	4	0.00
	Coral Cascade	GBR	O	No-Take	3	2.33
	Coral Garden	GBR	O	No-Take	5	0.40
	Coral Grotto	GBR	O	No-Take	5	0.00
	Half Way (Doug's Place)	GBR	O	No-Take	3	0.00
	Harry's Bommie	GBR	O	No-Take	5	0.20
	Heron Bommie	GBR	O	No-Take	4	0.00
	Jetty Flat	GBR	O	No-Take	6	0.17
	Last Resort	GBR	O	No-Take	4	0.00
	Libby's Lair	GBR	O	No-Take	6	0.00
	Research Zone	GBR	O	No-Take	5	0.60
	Shark Bay	GBR	O	No-Take	6	0.00

Reef Name	**Site Name**	**Region**	**N/O**	**Take or no-take**	**# of surveys**	**Avg. debris/ survey ($400m^2$)**
	White Wedding	GBR	O	No-Take	3	0.00
John Brewer Reef	John Brewer	GBR	O	Limited take	5	0.20
Keeper Reef	Keeper Reef	GBR	O	Take	3	0.00
Knuckle Reef	Knuckle Reef	GBR	O	Take	8	0.38
Low Isles Reef	Low Isles	GBR	N	No-Take	14	0.79
Magnetic Island Reefs	Alma Bay	GBR	N	No-Take	12	0.50
	Florence Bay	GBR	N	No-Take	6	0.67
	Geoffrey Bay	GBR	N	No-Take	13	0.38
	Middle Reef	GBR	N	Take	15	0.40
	Nelly Bay	GBR	N	Take	16	0.25
	Picnic Reef	GBR	N	Take	12	2.33
Michaelmas Reef	Breaking Patches	GBR	O	No-Take	3	0.00
Moore Reef	Reef Magic Pontoon	GBR	O	No-Take	12	0.17
Norman Reef	Norman Reef Middle Mooring	GBR	O	No-Take	3	0.00
	Norman Reef North	GBR	O	No-Take	3	0.00
Opal Reef	Bashful Bommie	GBR	O	No-Take	22	0.09
	SNO (South North Opal)	GBR	O	No-Take	7	0.00
	Split Bommie	GBR	O	No-Take	8	0.00
	The Wedge	GBR	O	No-Take	9	0.11
	Two Tone	GBR	O	No-Take	7	0.71
Osprey Reef	Admiralty Anchor	GBR	O	Take	7	0.29
	North Horn	GBR	O	Take	10	0.50
Palm Island Reefs	Cattle Bay (Orpheus Island)	GBR	N	No-Take	7	1.43
	Curacoa Island	GBR	N	No-Take	12	2.50
	Fantome Island	GBR	N	Take	12	1.25
	Juno Bay (Fantome Island)	GBR	N	Take	9	0.22

Reef Name	Site Name	Region	N/O	Take or no-take	# of surveys	Avg. debris/ survey (400m²)
	Orpheus	GBR	N	No-Take	6	1.67
	Pelorus	GBR	N	Take	10	2.60
Ribbon Reef 10	Challenger Bay	GBR	O	Take	8	0.50
	Pixie Gardens	GBR	O	No-Take	5	0.00
Ribbon Reef 3	Clam Beds	GBR	O	No-Take	6	0.50
	Tracey's Wonderland (Joanies Joy)	GBR	O	No-Take	4	0.75
Saxon Reef	Saxon Reef	GBR	O	No-Take	12	0.25
Wheeler Reef	The Mooring	GBR	O	No-Take	8	0.00
Barolin Rocks Reef	Barolin Rocks (Woongarra Marine Park)	SEQ	N	No-Take	4	2.25
Big Woody Island	Big Woody Conservation Park Zone	SEQ	N	No-Take	3	5.33
Burkitts Reef	Burkitts Reef	SEQ	N	No-Take	3	0.00
Currimundi Reef	Currimundi Reef	SEQ	N	Take	14	0.36
ESA Park	ESA Park	SEQ	N	Limited Take	3	0.00
Flat Rock Island	Shark Gulley	SEQ	N	No-Take	8	0.50
Flat Rock Island	The Nursery	SEQ	N	No-Take	10	0.80
Flinders Reef	Alden's Cave	SEQ	N	No-Take	8	0.38
	Nursery	SEQ	N	No-Take	16	0.50
Gatackers Reef	Gatackers Reef West	SEQ	N	Limited Take	3	1.67
Goat Island	Goat Island	SEQ	N	Limited Take	8	3.00
	Goat Island West	SEQ	N	Limited Take	3	2.00
Gold Coast Seaway Reefs	South-West Wall	SEQ	N	Take	9	27.11

Reef Name	Site Name	Region	N/O	Take or no-take	# of surveys	Avg. debris/ survey ($400m^2$)
Inner Gneerings	The Caves	SEQ	N	Take	13	2.38
Jew Shoal	The Pinnacles (The Pin)	SEQ	N	Take	6	4.83
Kings Beach	Kings Beach Reef	SEQ	N	Take	6	1.67
Mudjimba (Old Woman) Island	NorthWest Reef	SEQ	N	Take	3	3.33
	The Ledge (Mudjimba Island)	SEQ	N	Take	13	4.23
Myora Reef	Myora Reef	SEQ	N	No-Take	11	3.82
Palm Beach Reef	Palm Beach Reef	SEQ	N	Take	8	0.50
Peel Island	Peel Island East	SEQ	N	Limited Take	7	7.00
	Peel Island North	SEQ	N	Limited Take	7	4.71
Shag Rock Island	Shag Rock East	SEQ	N	Take	10	2.80
	Shag Rock West	SEQ	N	Take	9	2.89

Appendix 2

A2.1 Table: *Date of each clean up conducted through 2014-2017.*

Date of clean up	Season	Site
November 2014	Pre	Site 1
November 2014	Pre	Site 2
January 2015	Post	Site 1
January 2015	Post	Site 2
27 November, 2015	Pre	Site 1
28 November, 2015	Pre	Site 2
29 January, 2016	Post	Site 1
30, January-22 March, 2016	Post	Site 2
16 September, 2016	During	Site 1
25 October, 2016	During	½ of Site 2
4 November, 2016	During	Site 1
4 November, 2016	During	½ of Site 2
16 November, 2016	During	Site 1
16 November, 2016	During	Site 2
18 December, 2016	During	Site 1
18 December, 2016	During	Site 2
9 January, 2017	During	Site 1
7 March, 2017	During	Site 1
8 March, 2017	During	Site 2
WEIR OVERFLOW AND CYCLONE		
31 March, 2017	During	Site 2
1 April, 2017	During	Site 1
5 May, 2017	During	Site 1
5 May, 2017	During	Site 2
LARGE RAIN EVENT, WEIRS OVERFLOW		
8 June, 2017	During	Site 1

Date of clean up	Season	Site
8 June, 2017	During	Site 2
November, 2017	Pre	Site 1

***A2.2 Table:** List of items collected per effort (one person hour) between 2014 and 2017. ** indicates that items were separated into its own group in the 2016-2017 clean-ups.*

Items	**Categories**	**Number of items collected per effort 2014-2017**	**Total items (Unstand -ardised)**
Plastic packaging & consumer items			
Plastic bags	Plastic	153.64	938
Plastic cups	Plastic	227.45	1498
Plastic cutlery etc.	Plastic	12.63	78
Plastic drink bottles	Plastic	539.75	2737
Plastic film and small plastic pieces	Plastic	255.65	1783
Plastic packaging food	Plastic	886.88	5201
Plastic packing non-food	Plastic	50.79	309
Ziplocs**	Plastic	34.63	229
Hard plastic containers (including Tupperware)	Plastic	17.69	110
Hard plastic pieces	Plastic	229.47	1388
Milk jug	Plastic	0.60	6
Canola Oil bottle**	Plastic	0.11	1
Straws plastic	Plastic	398.79	2648
Confectionary plastics	Plastic	65.81	454
Sushi fish	Plastic	12.23	82
"100% biodegradable" bags	Unknown	0.36	2
Plastic lids			

Items	Categories	Number of items collected per effort 2014-2017	Total items (Unstand -ardised)
Plastic cup/waxed cup lid**	Plastic	17.38	99
Plastic bottle tops	Plastic	372.36	2276
Other lids-including pen lids	Plastic	31.40	205
Other food containers			
Waxed cups (Fast food take-away)**	Plastic	57.82	305
Drink cartons including poppers	Plastic	52.89	286
Paper or card packaging	Paper	15.46	131
Foam items			
Foam food trays etc.	Plastic	56.21	
Foam seat padding	Plastic	0.13	375
Foamed plastic - Other	Plastic	231.79	1289
Toys/Balloons etc.			
Balloon bottom (plastic)**	Plastic	0.19	2
Balloons etc.	Plastic	14.48	91
Pens, markers etc.	Plastic	40.11	207
Toys and similar	Plastic	30.95	182
Bike reflector**	Plastic	0.60	4
Pacifier /teething rings etc.**	Plastic	1.03	5
Plastic balls (including tennis balls)	Plastic	75.10	484
Metal items			
Metal caps or lids	Metal	2.84	12
Metal Cans	Metal	183.27	990
Foil wrappers etc.	Metal	6.39	49
Cigarette items			

Items	Categories	Number of items collected per effort 2014-2017	Total items (Unstand -ardised)
Cigarette Butts & filters**	Plastic	286.44	1657
Cigarette Lighters	Plastic	30.63	189
Personal items			
Entire purse (with personal contents)**	Cloth/ footwear	0.13	1
Aerosol cans	Metal	34.77	242
Personal Effects	Unknown	10.22	60
Sanitary Items	Unknown	2.02	15
Clothes and footwear			
Cloth	Cloth/ footwear	7.07	44
Footwear	Cloth/ footwear	41.37	236
Household/outdoor items			
Plastic garden pot**	Plastic	0.13	1
Plastic gloves**	Plastic	1.33	10
Plastic mesh**	Plastic	0.17	1
Ceramics	Glass	0.18	1
Light bulb**	Glass	0.18	1
Glass (including bottles)	Glass	19.13	111
Newspaper etc.	Paper	8.75	42
Brooms brushes	Plastic	0.60	4
Car air freshener (plastic)**	Plastic	0.11	1
Easy Off oven cleaner**	Metal	0.13	1
Metal broom handle**	Metal	0.09	1
Insect spray/killer	Metal	0.11	1

Items	Categories	Number of items collected per effort 2014-2017	Total items (Unstand -ardised)
Christmas ornament (plastic)**	Plastic	0.09	1
Clothes pin (plastic)**	Plastic	0.22	2
Flashlight**	Plastic	0.13	1
Fly swatter**	Plastic	0.11	1
Plastic bow (for presents)**	Plastic	0.11	1
Plastic car door hanger**	Plastic	0.16	1
School related material (plastic slot for binders)**	Plastic	0.33	3
Plastic watering can**	Plastic	0.13	1
Reusable water bottle**	Metal	0.35	1
Measuring cup (plastic)**	Plastic	0.28	1
Soap pump dispenser**	Plastic	0.12	1
Tupperware spatula**	Plastic	0.13	1
Fishing related items			
Bait & Tackle packaging	Plastic	1.33	12
Fishing line	Plastic	3.78	17
Recreational fishing items	Plastic/metal	2.67	16
Rope &/or net scraps	Plastic	1.88	11
Glow stick	Plastic	0.99	7
Other			
Processed wood	Wood	2.50	12
Wine cork**	Wood	0.11	1
Rubber remnants	Plastic	2.02	8
Strapping band scraps	Plastic	4.30	30
Industry items**			

Items	Categories	Number of items collected per effort 2014-2017	Total items (Unstand -ardised)
Caution fibre below tape-entire roll	Plastic	0.24	2
Hose attachment	Plastic	0.09	2
Learners plate	Plastic	0.09	1
Marine safety distress sheet	Plastic	0.12	1
O-ring	Plastic	0.09	1
Sticker (commercial)	Plastic	0.29	1
Tape	Plastic	0.74	3
Plastic pipe (unknown)	Plastic	1.57	14
Plastic tent stake	Plastic	0.11	1
Tarp piece	Plastic	0.23	2
Wire/electrical	Plastic	0.16	1
Spray paint can	Metal	0.24	2
Pharmaceutical/Drug			
Sharp bottle	Plastic	0.60	5
Plastic bottles/containers made into drug paraphernalia	Plastic	0.40	4
Pharmaceutical packaging	Plastic	4.21	25
Uncommon items**			
Medical face mask	Cloth/ footwear	0.61	1
Metal reusable water bottle	Metal	0.16	1
Roll bar and Chassis spray bottle	Metal	0.11	1
Car log book	Paper	0.14	1
Boat oars	Plastic	0.36	2
Runners bib	Plastic	0.09	1

Appendix 3

A3.1 Table: *Challenges and solutions for microplastic extraction and identification from fine sediments and water with high levels of organic material.*

Sample type	**Stage of processing**	**Challenges**	**Solutions**
Plankton tows	Filtering	Organic within sample was dense and adhesive, and therefore difficult to extract out of sieves available in the laboratory. If there was any plastics within this material, much was lost in the first few samples because of this.	Since samples were immediately processed, we could allow the organic material to sit at the bottom of the jar. Due to the difficulties in removing organic material in sieves, the remaining samples were not sieved. Instead, liquid on top was filtered, and the organic material was placed into plastic bags to be analysed at later time.
Plankton tows	Sieving	Of the few samples that that were sieved, as much material as possible was rinsed from sieve, and placed into aluminium containers. Organic material was placed in a normal refrigerator until analysed. Much of the organic material dried, basically encrusting the bottom of the container. This allowed us to see any plastic in the bottom. Few plastics were observed except for 2 samples had large white fibres.	Since there was such difficulties removing the organic material from the sieves, I did not continue the process. However, this it was noted that because of this, some plastics may be missed from counting procedures.
Sediments	Drying fine, clay-like samples	Based on previous trails, ovens at a low temperature were not effective at drying samples, because it would cause fine grains to solidify and become hard. Sieving of wet sediments were trailed, however, I could not provide accurate or consistent weights of samples to standardise plastic abundance.	The use of the fume hood was gentler, and caused fewer samples to solidify.
Sediments	Use of high density solution only	Fine sediment had high organic material. Recovery trials were attempted using both wet and dry sediments. Both trials showed difficulties in high density solution with much of the sediment clumping and floating to the top which was difficult to separate.	Recovery rates were poor, resulting in <10% of plastics extracted. Instead, a fluidized sand bath was used to test recovery rates between three different plastic types and shapes.

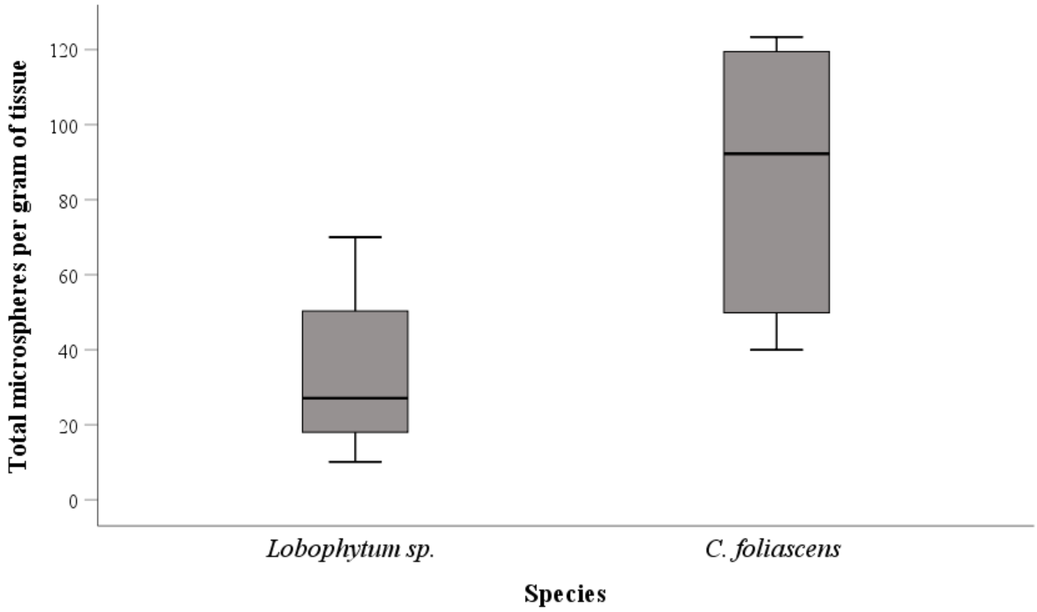
Sample type	Stage of processing	Challenges	Solutions
Sediments	Fluidized sand bath, fine river sediment	Fine sediment did not stay at the bottom of the sand bath like beach sand or other heavier sediment would do. Instead, sediment mixed with the salt water, which resulted in excess sediment expelling from the top of the sand bath. This regularly clogged the mesh sieve catching the outflow.	Flow rate was turned down as low as possible. Often, the sand bath needed to be turned off to unclog the sediment from the filter before continuing trail. Due to the low flow rates, less than 5% of each of the plastic types were recovered.
FTIR analysis		Particles take a long time to get accurate reads. This is particularly hard if the particle is heavily degraded, and/or too small.	Sampled larger particle sizes only, removed fibres from analysis.

Appendix 4

Appendix 4: Pilot study methods:

To determine if two species*, Lobophytum sp.* and *Carteriospongia foliascens* ingested microplastics, a pilot study was first conducted. Six individuals for each species was collected from Orpheus Island. Specimens were allowed a minimum of 3 days to acclimate to aquaria conditions prior to the start of the pilot experiment. Specimens were divided evenly between 12 experimental feeding chambers (11.5 cm wide x 12 cm deep x 41 cm long, 5.6 1 L in volume), with 1 specimen per chamber. Each chamber was filled with 5 µm filtered seawater at ambient temperature (~24 – 25 °C) and allowed to flow-through the system. A mixture of supplemental coral food (Aquasonic SeaFood) and fluorescent coloured polyethylene (PE) microspheres (Cospheric LLC) consisting of two different size ranges and colours: orange (45-52 µm) and green (27-32 µm), was prepared prior to the experiment. Specimens were fed 3 ml of the plastic-food mixture approximately 2 hours after dusk (~ 8 pm) during normal active feeding times for corals in the field (Lewis and Price, 1975). During feeding, the water flow was turned off for one to two hours to ensure that plastic microspheres would interact with the experimental specimens. The above box plots represent median and interquartile (25^{th} and 75^{th}) of the ingested particles per gram of tissue. Whiskers represent highest and lowest values for *Lobophytum sp.* and C*. foliascens*.

A4.1 Figure: *Total number of plastic microspheres per gram of tissue ingested by Lobophytum sp. and Carteriospongia foliascens in a pilot study. Box plots represent median and interquartile (25^{th} and 75^{th}). Whiskers represent highest and lowest values.*



Appendix 5

***Appendix 5*:** Copy of information sheet and final social survey questionnaire used on Survey Monkey.

You are invited to take part in a research project about marine debris and litter in Townsville.

Taking part in this study is voluntary and you can stop taking part in the study at any time without explanation or prejudice by simply closing the browser. Completing the survey you imply consent to participate. Your responses will be strictly anonymous and no identifying information will be collected. This survey will take approximately 10 minutes to complete.

This survey is intended for residents of Townsville Queensland, Australia ONLY. Please do not participate unless you have been a resident of Townsville for greater than three months.

The study is being led by Mrs. Anne Bauer-Civiello, Dr. Claudia Benham and Dr. Mark Hamann, and will contribute to marine debris research at James Cook University. The goal of this project is to understand how people think and feel about marine debris and littering behaviour.
By taking this survey, you agree to allow the researchers to use the data you provide in research publications and reports, such as peer-reviewed international journals.

Section 1: About you.

1. How did you find out about this survey?

- ○ GBRMPA newsletter or other related
- ○ Received a flyer
- ○ Townsville City council newsletter or other media
- ○ Other internet/social media
- ○ Radio
- ○ Took survey in person with a researcher (please specify site location)

2. What is your age?

3. What is your gender?

4. What is your highest degree or qualification?

- ◯ High School Certificate or equivalent
- ◯ TAFE qualification
- ◯ Bachelors degree
- ◯ Masters or PhD
- ◯ Other (Please specify)

5. How long have you lived in Townsville (in years)?

6. What is your postcode?

7. What does the term **marine debris** mean to you?

Marine debris can have a range of different meanings. For the purpose of this survey, we define marine debris to mean plastic pollution in the ocean.

The following questions are about marine debris in Townsville (including Northern Beaches to Alligator Creek, and Magnetic Island). Please answer the questions based on your experiences and knowledge.

8. Have you ever attended a community event, such as a beach clean up, to help clean up litter in Townsville?

◯ Yes

◯ No

* 9. What do you think are the most littered items in Townsville? Please choose the**TOP THREE ITEMS** you think are the most littered.

☐ Straws and/or plastic utensils

☐ Plastic drink bottles

☐ Soft drink cups (take away cups - e.g. McDonalds)

☐ Other types of plastic food packaging such as candy wrappers and chip bags.

☐ Plastic shopping bags

☐ Cigarette butts

☐ Fishing line/net or other gear

☐ Coffee cups (take away)

☐ Items of clothing (thongs, hats towels etc.)

* 10. Where do you see the most plastic litter? Please choose**UP TO THREE PLACES.**

☐ The Strand

☐ Pallarenda park and beaches

☐ Parklands/bike paths near Ross River

☐ Skate parks

☐ Carparks

☐ Boat ramps

☐ Streets in CBD

☐ Suburban streets

☐ I don't see litter in Townsville

☐ Other (please provide details)

The following questions are about marine debris in Townsville. Please answer the following based on your experiences and your knowledge.

* 11. What do you think are the **MOST LIKELY sources** of marine debris in **Townsville**? **Please pick the TOP THREE items.**

- [ ] Overflowing bins
- [ ] Storm water discharge from roads and sidewalks
- [ ] Illegal dumping on land
- [ ] Waste reaching Australia from other countries by ocean currents
- [ ] Deliberate or accidental littering in parks and suburbs
- [ ] Illegal dumping or accidental loss from boats at sea (such as commercial cargo ships)
- [ ] Deliberate or accidental loss of items from recreational use of beaches
- [ ] Accidental loss of fishing gear from fishing boats

Section 3: Your values about marine debris

12. How strongly do you agree or disagree with the following statements (1 strongly disagree to 10 strongly agree):

		1	2	3	4	5	6	7	8	9	10
1	Plastic litter is a problem in Townsville.	○	○	○	○	○	○	○	○	○	○
2	I feel responsible for local marine environment and wildlife	○	○	○	○	○	○	○	○	○	○
3	Reducing plastic litter should be a primary concern for management of the Great Barrier Reef.	○	○	○	○	○	○	○	○	○	○
4	I care about the local marine wildlife	○	○	○	○	○	○	○	○	○	○
5	I believe my actions influence the marine environment	○	○	○	○	○	○	○	○	○	○
6	I believe that picking up litter along, in, and around the river can reduce marine debris	○	○	○	○	○	○	○	○	○	○
7	I feel that it less important to pick up litter on streets than it is to pick up litter on beaches	○	○	○	○	○	○	○	○	○	○

8	Plastic litter is more of a problem in other countries, but <u>not</u> in Australia.	○	○	○	○	○	○	○	○	○	○
9	There are more pressing threats to the Great Barrier Reef than plastic litter.	○	○	○	○	○	○	○	○	○	○
10	If I litter, I feel that I'm impacting important marine habitats, such as the Great Barrier Reef.	○	○	○	○	○	○	○	○	○	○
11	Littering is more of a problem in other areas of Australia, but <u>not</u> in Townsville.	○	○	○	○	○	○	○	○	○	○

		1	2	3	4	5	6	7	8	9	10
12	Plastic litter left in suburbs close to the ocean is more likely to become marine debris.	○	○	○	○	○	○	○	○	○	○
13	Littering in Townsville contributes to the pollution in oceans.	○	○	○	○	○	○	○	○	○	○
14	The further away the litter is from the ocean (for example, in westerns suburbs), it is not likely to become marine debris	○	○	○	○	○	○	○	○	○	○
15	Litter left near our waterways, such as Ross River, is likely to become marine debris.	○	○	○	○	○	○	○	○	○	○
16	Littering is <u>not</u> a problem in Australia.	○	○	○	○	○	○	○	○	○	○
17	Litter left near our beaches is likely to become marine debris	○	○	○	○	○	○	○	○	○	○
18	I feel social pressure not to litter	○	○	○	○	○	○	○	○	○	○
18	My family and friends think it is bad to litter	○	○	○	○	○	○	○	○	○	○
20	My family and friends worry about marine debris	○	○	○	○	○	○	○	○	○	○
21	It is <u>not</u> my responsibility to protect the GBR	○	○	○	○	○	○	○	○	○	○
22	Coastal residents should take the steps to reduce their impacts on the GBR	○	○	○	○	○	○	○	○	○	○
23	It is the responsibility of all Australians to protect the GBR	○	○	○	○	○	○	○	○	○	○
24	I am concerned about the impacts of marine debris	○	○	○	○	○	○	○	○	○	○

13. Below, we have listed some specific impacts of marine debris. How concerned are you of these impacts?

	Very concerned	Quite concerned	Somewhat concerned	Not very concerned	Not concerned at all	Unsure
Marine wildlife (such as turtles and birds) eating plastic						
Marine wildlife becoming entangled in marine debris						
Small plastic pieces (microplastics) on the Great Barrier Reef						
Plastics in the fish we eat						
Larger debris items damaging personal boats or motors						
Beaches ending up covered in marine debris						
Swimming areas covered in marine debris						

Section 4: Reducing marine debris

The following questions are about how we can reduce the marine debris problem. Please answer the following to the best of your ability.

14. Who has the most responsibility for reducing marine debris

- Individuals
- Council (local government)
- Queensland state government
- Australian federal government
- Plastic manufacturers
- Retailers of plastic products (e.g. supermarkets)

15. What can individuals do to reduce marine debris?

16. Do you have any other comments about marine debris or littering that you would like to add?

17. Thank you for your participation! Would you like to hear about the results of this study? If so, please provide your email address below. Your email address and any other identifying information will be stored separately from your questionnaire responses.