

Microplastic ingestion by scleractinian corals

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Abstract We report for the first time the ingestion of microplastics by scleractinian corals, and the presence of microplastics in coral reef waters adjacent to inshore reefs on Australia's Great Barrier Reef (GRE, 18°31'S 146°23'E). Analysis of samples from sub-surface plankton tows conducted in close proximity to inshore reefs on the central GBR revealed microplastics, similar to those used in marine paints and fishing floats, were present in low concentrations at all water sampling locations. Experimental feeding trials revealed that corals mistake microplastics for prey and can consume up to $\sim 50 \mu\text{g plastic cm}^{-2} \text{ h}^{-1}$, rates similar to their consumption of plankton and *Artemia* nauplii in experimental feeding assays. Ingested microplastics were found wrapped in mesenterial tissue within the coral gut cavity, suggesting that ingestion of high concentrations of microplastic debris could potentially impair the health of corals.

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Introduction

Microplastics (i.e. plastic fragments < 5 mm in diameter) are a widespread form of contamination in marine ecosystems around the globe (Moore 2008). Coastal ecosystems, such as inshore coral reefs, are likely to be particularly heavily impacted by microplastics because these contaminants often enter the marine environment through fragmentation of larger plastic items from terrestrial sources (Thompson et al. 2004), including via water treatment plant effluent (Browne et al. 2011; Fendall and Sewell 2009). Additionally, coral reefs are popular sites for short and long-term visits by tourists, as well as trawlers and recreational vessels, which carry many components that are composed of various forms of plastic (Claessens et al. 2011). Routine boating, fishing and other recreational activities can potentially introduce plastic debris into the marine environment through minor damage to boat hulls that releases paint chips into the ocean, and/or inadvertent loss of ropes and rigging lines, fishing floats and marker buoys (Ivar do Sul and Costa 2014).

At present, the impacts of the accumulation of persistent plastic products in the environment remain poorly understood. In some cases, microplastics may be considered a harmful pollutant because they can act as both a sink (Mato et al. 2001) and a source (Laist 1987; Teuten et al. 2009; Zitko and Hanlon 1991) of environmental contamination. That is, plastics adsorb and transport other contaminants in seawater such as heavy metals (Ashton et al. 2010) and persistent organic pollutants (Endo et al. 2005; Mato et al. 2001; Teuten et al. 2007). Neither plastics nor these contaminants easily degrade in the environment, or during digestion by organisms, enabling them to bioaccumulate in the food chain (Gregory 1996; Rios et al. 2007), and ultimately reach higher trophic levels (Carpenter and Smith

1972). For example, the presence of plastics contaminated with organic compounds can lead to a significant increase in the accumulation of such compounds in sediment-dwelling worms (Teuten et al. 2007). Similarly, seabirds that ingest relatively high levels of marine plastics accumulate chemicals from those plastics in their body tissues (Tanaka et al. 2013). As microplastic debris occupies the same size range as sand grains and planktonic organisms (Fendall and Sewell 2009), it is available to a wide range of invertebrates near the base of the food chain (Browne et al. 2008). There is growing evidence that microplastic ingestion can have negative impacts on organisms. For example, copepods had significantly reduced algal feeding rates when microplastics were present within cultures (Cole et al. 2013), and both algal growth and photosynthesis together with plankton body size and reproduction were impeded by plastic presence in a mixed *Scenedesmus-Daphnia* culture (Besseling et al. 2014). Similarly, in addition to blocking the digestive tract and preventing normal feeding, microplastic ingestion can damage the cells and tissues of organisms such as blue mussels (von Moos et al. 2012), fish and crustaceans (Laist 1987). However, in other instances, microplastic ingestion has had negligible impact on organisms, e.g. environmentally relevant concentrations of polyethylene plastics did not affect growth or survival of sea urchin larvae, (Kaposi et al. 2014), and plastic ingestion did not substantially increase exposure to certain plastic additives for marine worms and fish (Koelmans et al. 2014). In general, the effects of microplastics on marine organisms appear to be context and/or species specific, and further research is required to determine whether and how particular species traits enhance vulnerability of organisms to microplastic contamination.

Ingestion of microplastics by amphipods, copepods and zooplankton is a potential concern for coral reef health since these planktonic organisms are the prey of corals (Ferrier-Pagès et al. 2003). Despite previous studies showing that several species of invertebrates are capable of ingesting microplastics, there has been no research to date on microplastic ingestion by corals. Although symbiosis between corals and *Symbiodinium* spp. provides a source of photosynthetic carbon to the coral host, many coral species are active heterotrophs, ingesting organisms ranging from bacteria to mesozooplankton (plankton size classes range from 0.2 to 1,000 μm) that can contribute more than 50 % of daily carbon requirements (Houlbreque and Ferrier-Pagès 2009). Previous studies have demonstrated that coral feeding is generally non-selective in relation to the types of zooplankton captured, but there is a preference for food sources $<400 \mu\text{m}$ (Palardy et al. 2008), with common species of scleractinian corals feeding on fine particles that range in size from 10 to 100 μm (Anthony 1999; Anthony and Fabricius 2000; Mills et al. 2004). An affinity for

smaller-sized food sources such as picoplankton and nanoplankton rather than larger sources like dinoflagellates and diatoms has also been observed among scleractinian (Houlbreque et al. 2006). Since microplastics fall within the size range of particles that corals ingest, corals may be sensitive to this pollutant.

The overall objective of this study was to determine whether corals can capture and ingest microplastics from the water column, using the mound-shaped stony coral *Dipsastrea* (i.e. the Indo-Pacific genus previously classified as *Favia*, see Budd et al. 2012) as a study organism. Secondly, this study aimed to assess whether or not microplastics are present in Great Barrier Reef (GBR) waters by analysing subsurface plankton samples for plastic presence. These data increase knowledge of microplastic presence in GBR waters, which is currently limited to a single study reporting data from only 15 samples in the region (Reisser et al. 2013). Clearly, additional data with a larger spatial and temporal coverage are required to assess the level of plastic contamination in these waters. Corals are the foundation species of reefs, and create much of the structural complexity of reefs that, in turn, provides habitat for thousands of invertebrate and vertebrate species (Sano et al. 1987; Stella et al. 2011). Hence, this study provides a critical first step towards understanding the potential impacts of microplastic contamination on reef ecosystems.

Materials and methods

Coral collection and experimental setup

Fragments of *Dipsastrea pallida* (previously classified as *Favia pallida*, see Budd et al. 2012) were collected from various sites around Orpheus Island in the central region of the GBR (18°31'S 146°23'E) during April and May 2013 from an average depth of ~5 m relative to tidal datum. Fragments were transported back to aquarium facilities at James Cook University and allowed to acclimate to laboratory conditions for >4 weeks. Subsequently, we conducted two experiments to determine whether corals do ingest microplastics and to quantify the rates of plastic ingestion (see Table 1 for an overview).

Microplastic ingestion trials

Fragments of *D. pallida* ($n = 6$, size 21–84 cm^2) were exposed to shavings of blue polypropylene plastic (size 10 μm –2 mm, 0.395 g L^{-1}) for 48 h in feeding chambers (2.5 L) equipped with small pumps to generate water flow (see Table 1). Polypropylene was used as it is among the most abundant of plastics commonly found in the marine environment (Reisser et al. 2013). In the absence of prior information that quantifies how

Table 1 Overview of methodology of various experiments

| Experiment type | Coral replicates | Chamber type | Plastic concentration (\pm SD) | Duration (h) | Response variable |
|-----------------|------------------|----------------|---|--------------|---|
| Ingestion | 6 | Open chamber | 2.5 L, 0.395 g L ⁻¹ | 48 | Presence of microplastic particles in mouth and/or gut cavity |
| Feeding rates | 3 | Open chamber | 2.5 L, 0.197 g L ⁻¹ (\pm 0.2) | 12 | Rate of plastic ingestion |
| | 6 | Closed chamber | 2.1 L, 0.24 g L ⁻¹ (\pm 0.13) | 3 | |

coral microplastic ingestion depends on plastic concentration in the water column, we used a high concentration of microplastics (0.395 g L⁻¹) in these trials because our aim was to determine whether corals do, in fact, ingest plastic particles. We note that plastic particles are highly buoyant resulting in a realised concentration of plastic in suspension within the feeding chambers that was substantially lower than the initial concentration. Based on visual observation of the plastic particles circulating within the chambers, we estimate that the concentration of circulating suspended plastics was ~10–30 % of the initial concentration (i.e. 0.1–0.3 g L⁻¹). An incubation period of 48 h was used to enable corals to feed on plastics during two successive nights. After the incubation period, corals were preserved in 10 % formalin in seawater before being decalcified in 3 % formic acid over a period of 72 h. Subsequently, the decalcified tissues were dissected using a dissecting microscope to separate individual polyps from each other, and polyps were then sectioned longitudinally. Microplastic ingestion was determined by the presence of microplastics in the mouth and among the mesenteries of the polyps.

Feeding rate trials

Once plastic ingestion was confirmed (see above), rates of plastic uptake by corals were quantified using replicate incubations of coral fragments in re-circulating feeding chambers. Feeding incubations were conducted overnight because this is when most corals extend their tentacles and feed heterotrophically (Lewis and Price 1975). Due to the buoyancy of the plastics, and their tendency to float and aggregate near the corners of the feeding chambers, we used both open to the air (2.5 L volume chamber, no lid, 12 h incubation) and closed (2.1 L volume chamber, fully enclosed, 3 h incubation) chambers with different initial plastic concentrations to ensure that measured feeding rates were not an artefact of the type of measuring chamber used, or the initial plastic concentration. Corals were placed into chambers ~30 min before the feeding trial began and allowed to acclimate and expand their polyps. Subsequently, a known initial concentration of polypropylene shavings was added to the chambers (0.197 g L⁻¹ \pm SD 0.2 in the open chambers, 0.24 g L⁻¹ \pm SD 0.13 in the closed chambers). Weights of plastic within each feeding chamber

were determined by sub-sampling 50 ml of the incubation microplastic/seawater medium, vacuum filtering these samples onto pre-weighed filters (Whatman GF/A, 0.7 pore size 1.6 μ m) to separate the plastics, oven drying the filters at 40 °C for 24 h, and weighing on Mettler Toledo, MS105 Semi-Micro Balance (accuracy 0.0001). For the open chambers, an initial (0 h into the incubation) and final (12 h) plastic concentration was measured, whereas initial (0.5 h), final (3 h) and interim (1 and 2 h) samples were taken for the closed chambers. Change in plastic concentration was also measured in control chambers (i.e. without a coral present) using exactly the same approach as for the coral feeding chambers, in order to account for loss of plastics (e.g. due to them sticking to the walls of the chambers or other non-feeding-related loss) during the feeding trial. For measurements conducted in the open chambers, plastic ingestion by corals was then determined from the difference in initial and final plastic concentrations within chambers minus the change in plastic concentration measured in the control chambers. For measurements made in the closed chambers, feeding rate was determined from the slope of a linear regression of plastic weight versus incubation time minus the change in plastic concentration measured in the control chambers. Feeding rates were standardised per hour to account for differences in the duration of these incubations. Finally, to account for small differences in fragment size, the rate of plastic consumption by corals was normalised to the surface area of each coral as calculated using the aluminum foil wrapping method (Marsh 1970).

Presence of microplastics in GBR waters

Sub-surface plankton tows were conducted in the waters adjacent to Orpheus and Pelorus Islands (offshore Lucinda, Lat: 18°31'S Long: 146°23'E), using a plankton net (with a cod-end mesh size of 200 μ m, radius of net opening 15 cm and a net mesh size of 50 μ m). Four replicate tows of 5 min were conducted at each of three sites (in the channel between Orpheus and Pelorus Islands, in the channel between Pelorus and Fantome Islands and immediately in front of Orpheus Island Research Station). Each tow covered a distance of ~150 m and sampled ~11,000 L of seawater. Plastics were separated from organic matter in the

plankton samples using a hypersaturated saline solution (Hidalgo-Ruz et al. 2012; Thompson et al. 2004), which was vacuum filtered (Whatman GF/A, 0.7 pore size 1.6 μm) and oven dried (40 $^{\circ}\text{C}$ for 24 h). To identify individual plastic particles, attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectra were acquired using a Nicolet Nexus 870 FT-IR spectrometer equipped with a Smart Orbit diamond ATR accessory (Thermo Scientific, Madison, WI, USA). Spectral data were accumulated for 64 scans at 4 cm^{-1} resolution with a wavenumber range of 4,000–400 cm^{-1} . This is a standard technique for identification of microplastics in marine environments (Hidalgo-Ruz et al. 2012) and achieves an unambiguous polymer identification in most cases (Thompson et al. 2004). To isolate individual microplastics, particles were visually identified using a dissecting microscope and removed from the filters. Particles were then pressed directly onto the diamond of the ATR probe without further sample preparation. Absorbance spectra of the particles were matched against reference samples available within our laboratory and against the Hummel polymer library of IR spectra and identified based on the presence of diagnostic peaks.

Results and discussion

Approximately 21 % of polyps analysed ($n = 114$ polyps from six colonies) had ingested at least one microplastic particle, with one polyp ingesting three polypropylene fragments. Ingested plastic fragments varied in shape and size, ranging from approximately 100 μm –2 mm. Clearly, these results reveal that reef-building corals do capture and ingest microplastics from the water column (Fig. 1). When ingested, microplastics were predominately localised deep within the polyp and were wrapped by mesenterial tissue such that it was difficult to remove them from the polyp. This observation raises the potential for plastic ingestion to impede coral digestion of natural food sources because the mesenterial tissues are the primary tissues responsible for digestion (Goldberg 2002; Murdock 1978; Titlyanov et al. 1996). Prior to being ingested, microplastics tended to aggregate and form a film covering the surface of the coral, appearing to adhere to the mucus layer covering coral tissue. Observations of microplastics accumulating on released mucus threads demonstrated corals were able to trap particles circulating in the water column or floating on the surface. However, the possibility that corals produce more mucus in the presence of plastics warrants further investigation, as this might represent an additional energy expense associated with microplastic contamination.

Results of feeding trials show that corals consume plastics at rates between 1.2 and 55 $\mu\text{g cm}^{-2} \text{h}^{-1}$ (Fig. 2, equivalent to ~ 14 –660 $\mu\text{g cm}^{-2} \text{day}^{-1}$ based on a 12 h

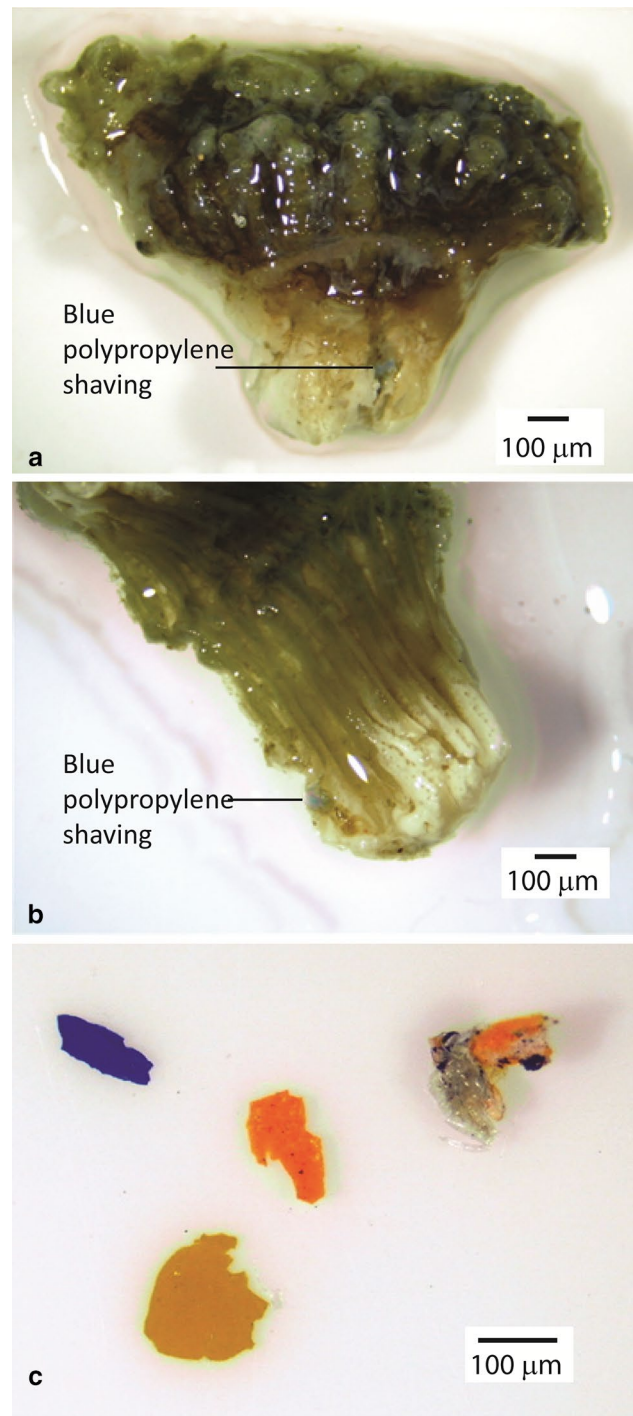


Fig. 1 a, b Microplastics present in the mouth and among the mesenteries of coral polyps and c plastic fragments found in plankton tows in reef waters

active feeding period per day). Consistent with our finding that polyp ingestion of plastics was variable both within and between colonies; rates of plastic ingestion by colonies were also variable (as indicated by the relatively large error bars in Fig. 2). However, we observed approximately

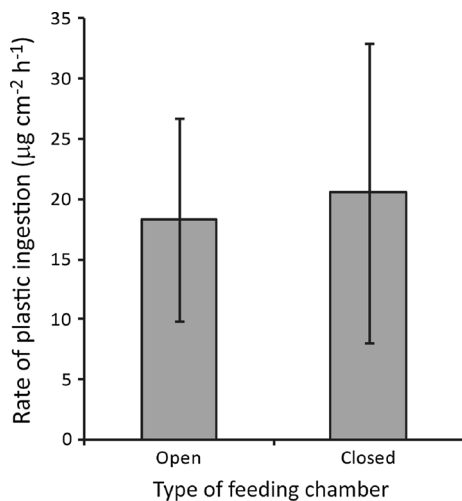


Fig. 2 Rate of microplastic ingestion by fragments of *Dipsastrea pallida* during feeding incubations in open and closed feeding chambers. Error bars show standard error and $n = 3$ for the open chambers and $n = 6$ for the closed chambers ($n =$ replicate trials)

the same mean plastic ingestion rate using two different types of feeding chambers (open vs. closed, Fig. 2, Welch two-sample t test for unequal samples sizes; $t_{6,8} = 0.16$, $p = 0.88$). This suggests that the variation in feeding rates is not driven by our measuring techniques but, rather, reflects differences in feeding ‘effort’ among coral samples. This interpretation is supported by evidence from previous studies that feeding capacity is highly species specific, and changes in feeding effort are likely responsible for changes in plankton capture rate with depth (Palardy et al. 2005). Additionally, regardless of chamber type, the buoyancy of the microplastics decreased the likelihood of particles remaining within reach of coral polyps during active feeding, and this buoyancy is likely to have contributed to variation among colonies in their plastic ingestion rates. It is noteworthy to consider the potential for increased ingestion of microplastics by corals in the natural environment, as the buoyancy of microplastics decreases with increased biofilm formation and biofouling (Reisser et al. 2013), and only clean (unfouled) plastics were used in this study.

The rates of feeding reported here are broadly comparable to published rates of coral feeding on plankton and suspended particulate matter, which range from 160 to 4,000 $\mu\text{g cm}^{-2} \text{ day}^{-1}$ (or 24–600 $\mu\text{g C cm}^{-2} \text{ day}^{-1}$ based on a prey carbon content of 0.15 $\mu\text{g C prey}^{-1}$, (Ferrier-Pagès et al. 2011)). However, few polyps (7 % of the polyps which had ingested fragments) were able to ingest more than one plastic particle during the 12 h incubation, compared with ingestion of plankton between 2 and 50 items per polyp per hour (Ferrier-Pagès et al. 2011). Since the percentage of polyps that ingested plastics were

relatively low, it is unclear whether intake of plastic particles inhibited further feeding. We suggest that quantifying coral feeding on natural plankton after feeding on plastics would be an appropriate experiment to test this hypothesis. In addition, further research is required to quantify how plastic feeding rates vary according to plastic concentrations in seawater, and whether plastic ingestion rates differ in the presence and absence of natural plankton and other particulate food sources for corals.

Due to their buoyancy and varying density, microplastics have the potential to become widely distributed in the marine environment (Andrady 2011). Although the presence of microplastics in Australian waters is poorly studied, and the overall abundance of plastic debris on the GBR is currently unknown, microplastic pollution up to 26,898 particles per km^{-2} has been documented in the South Pacific subtropical gyre (Eriksen et al. 2013). On the GBR, increased coastal development and tourism activities increase the risk of litter transport into the marine environment (Gregory 1999), which is a particularly high concern for the GBR (Hardesty and Wilcox 2011). In this study, subsurface plankton tows revealed that microplastics are present in reef waters, with up to two plastic fragments found (size 100–500 μm) per $\sim 11,000$ L seawater (Fig. 1c). Infrared spectroscopic analyses identified these fragments as polyurethane, polystyrene and polyester (Fig. 3, Table 2), plastics that are commonly found in marine paints and fishing floats. The majority of microplastics found were <1 mm, and often fibrous. The abundance of these fibres may indicate that the source of this microplastic contamination is due to fragmentation, rather than pre-production resin pellets or scrubbers from cleaning products. These results are similar to findings from plankton tow surveys conducted around Australia, excluding the GBR, which discovered that sampled microplastics were predominately the result of the breakdown of larger plastic items (e.g. packaging and fishing items) (Reisser et al. 2013).

Corals may be exposed to plastics in a variety of ways, particularly at low tide when floating plastics are likely to come into contact with corals on shallow reef-crests and flats. Although microplastics were only present in GBR waters in relatively low concentrations, our estimates are likely to underestimate actual plastic concentrations because we could not have detected particles smaller than 300 μm in diameter, and we only tested the subset of microscopic particles from the plankton tows that we suspected to be plastic based on visual estimation (and, hence, possibly missed particles that resembled materials of biogenic origin like cellulose and shell fragments). We find strong evidence that corals are capable of ingesting microplastics, and that they retain these plastics within their gut cavity for at least 24 h. However, at this time, it is

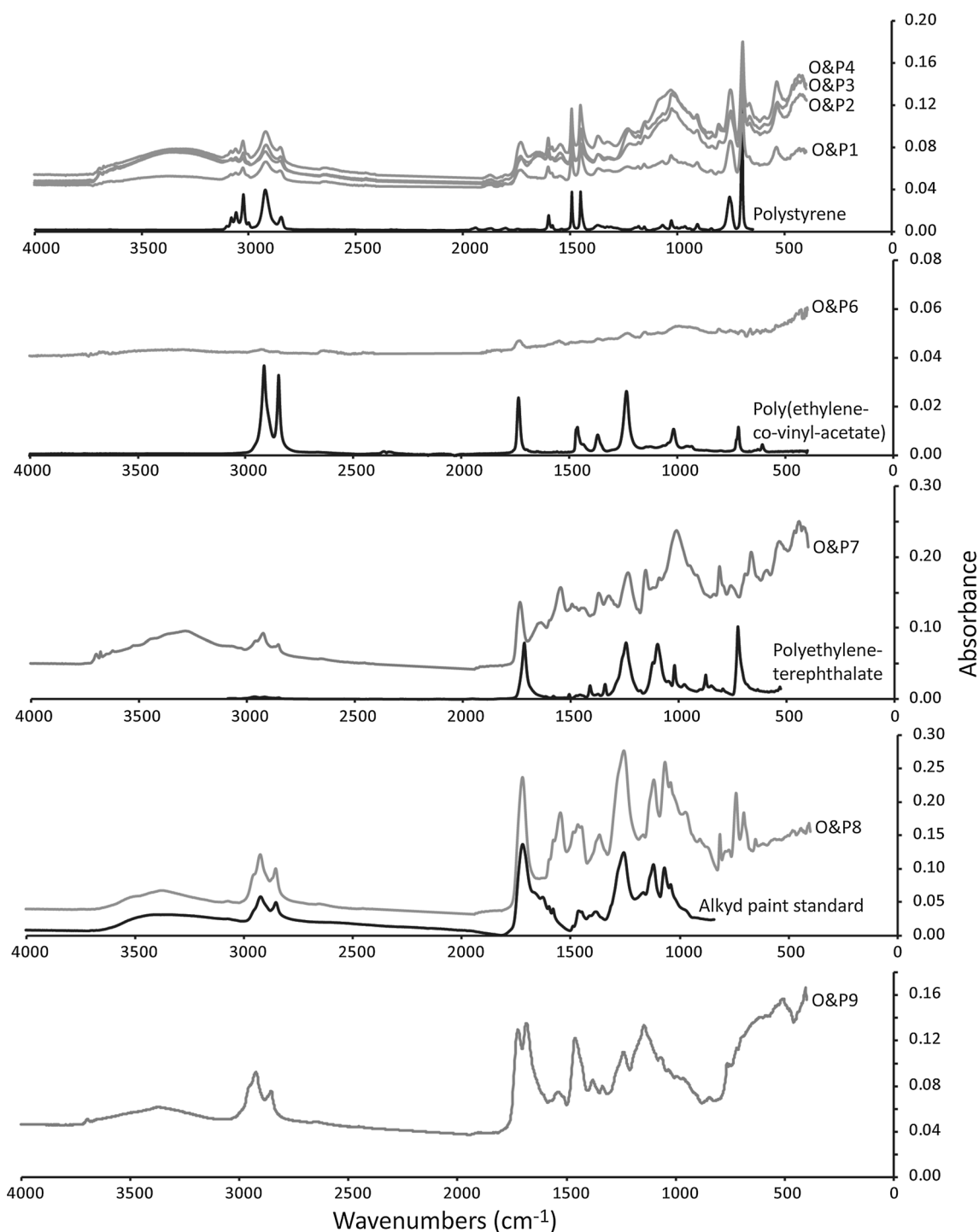


Fig. 3 Fourier transform infrared (FT-IR) spectra from microplastics found in surface waters adjacent to Orpheus and Pelorus Islands. Spectra from these microplastic samples are shown in *grey* and refer-

ence spectra (from polymers of known identity) are shown in *black*. Identification characteristics for the different sample polymers are described in Table 1

uncertain exactly how microplastic ingestion affects coral energetics and growth, or whether and how this ingestion influences reef growth in general. Future work should

investigate microplastic digestion as the next step towards understanding how microplastics potentially impact coral health. Overall, these findings highlight the importance of

Table 2 Identification of microplastic polymer type by ATR-FTIR spectroscopy from samples collected in waters adjacent to Orpheus and Pelorus Islands (“O” and “P”, respectively; central Great Barrier Reef)

| Sample | Polymer type and characteristics |
|---------|--|
| O&P 1–4 | Polystyrene—peaks at 700, 760, 1,490 cm^{-1} |
| O&P 5 | Degraded polystyrene—weak peaks at 700, 760, 1,490 cm^{-1} |
| O&P 6 | Uncertain—weak spectrum with moderate match to poly(ethylene-co-vinyl-acetate) or poly(vinyl-acetate-co-ethylene), weak peaks at 1,730 and 1,235 cm^{-1} |
| O&P 7 | Polyester—strong bands near 1,720 cm^{-1} combined with a strong band in mid 1200 s. Note ‘polyester’ is a broad class of polymers, sample spectrum is shown in reference to polyethylene terephthalate |
| O&P 8 | Strong match to alkyd–melamine binder polymer in spectral library. Likely a paint chip or painted item. Sample spectrum is shown in reference to an alkyd paint sample |
| O&P 9 | Polyurethane—peaks at 1,250, 1,470, 1,530 and 1,690 cm^{-1} . Reference spectrum not available |

understanding the mechanisms of dispersal of microplastics, and the need for further investigation of whether and how microplastic contamination influences the physiology, growth and survival of marine organisms.

References

- Andrady AL (2011) Microplastics in the marine environment. *Mar Pollut Bull* 62:1596–1605. doi:[10.1016/j.marpolbul.2011.05.030](https://doi.org/10.1016/j.marpolbul.2011.05.030)
- Anthony KRN (1999) Coral suspension feeding on fine particulate matter. *J Exp Mar Biol Ecol* 232:85–106. doi:[10.1016/S0022-0981\(98\)00099-9](https://doi.org/10.1016/S0022-0981(98)00099-9)
- Anthony KRN, Fabricius KE (2000) Shifting roles of heterotrophy and autotrophy in coral energetics under varying turbidity. *J Exp Mar Biol Ecol* 252:221–253. doi:[10.1016/S0022-0981\(00\)00237-9](https://doi.org/10.1016/S0022-0981(00)00237-9)
- Ashton K, Holmes L, Turner A (2010) Association of metals with plastic production pellets in the marine environment. *Mar Pollut Bull* 60:2050–2055. doi:[10.1016/j.marpolbul.2010.07.014](https://doi.org/10.1016/j.marpolbul.2010.07.014)
- Besseling E, Wang B, Lürling M, Koelmans AA (2014) Nanoplastic affects growth of *S. obliquus* and reproduction of *D. magna*. *Environ Sci Technol* 48:12336–12343. doi:[10.1021/es503001d](https://doi.org/10.1021/es503001d)
- Browne MA, Dissanayake A, Galloway TS, Lowe DM, Thompson RC (2008) Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). *Environ Sci Technol* 42:5026–5031. doi:[10.1021/es800249a](https://doi.org/10.1021/es800249a)
- Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, Thompson R (2011) Accumulation of microplastic on shorelines worldwide: sources and sinks. *Environ Sci Technol* 45:9175–9179. doi:[10.1021/es201811s](https://doi.org/10.1021/es201811s)
- Budd AF, Fukami H, Smith ND, Knowlton N (2012) Taxonomic classification of the reef coral family Mussidae (Cnidaria: Anthozoa: Scleractinia). *Zool J Linn Soc* 166:465–529. doi:[10.1111/j.1096-3642.2012.00855.x](https://doi.org/10.1111/j.1096-3642.2012.00855.x)
- Carpenter EJ, Smith JKL (1972) Plastics on the Sargasso sea surface. *Science* 175:1240–1241. doi:[10.1126/science.175.4027.1240](https://doi.org/10.1126/science.175.4027.1240)
- Claessens M, De Meester S, Van Landuyt L, De Clerck K, Janssen CR (2011) Occurrence and distribution of microplastics in marine sediments along the Belgian coast. *Mar Pollut Bull* 62:2199–2204. doi:[10.1016/j.marpolbul.2011.06.030](https://doi.org/10.1016/j.marpolbul.2011.06.030)
- Cole M, Lindeque P, Fileman E, Halsband C, Goodhead R, Moger J, Galloway TS (2013) Microplastic ingestion by zooplankton. *Environ Sci Technol* 47:6646. doi:[10.1021/es400663f](https://doi.org/10.1021/es400663f)
- Endo S et al (2005) Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: variability among individual particles and regional differences. *Mar Pollut Bull* 50:1103–1114. doi:[10.1016/j.marpolbul.2005.04.030](https://doi.org/10.1016/j.marpolbul.2005.04.030)
- Eriksen M et al (2013) Plastic pollution in the South Pacific subtropical gyre. *Mar Pollut Bull* 68:71. doi:[10.1016/j.marpolbul.2012.12.021](https://doi.org/10.1016/j.marpolbul.2012.12.021)
- Fendall LS, Sewell MA (2009) Contributing to marine pollution by washing your face: microplastics in facial cleansers. *Mar Pollut Bull* 58:1225–1228. doi:[10.1016/j.marpolbul.2009.04.025](https://doi.org/10.1016/j.marpolbul.2009.04.025)
- Ferrier-Pagès C, Witting J, Tambutté E, Sebens KP (2003) Effect of natural zooplankton feeding on the tissue and skeletal growth of the scleractinian coral *Stylophora pistillata*. *Coral Reefs* 22:229–240. doi:[10.1007/s00338-003-0312-7](https://doi.org/10.1007/s00338-003-0312-7)
- Ferrier-Pagès C, Hoogenboom M, Houlbrèque F (2011) The role of plankton in coral trophodynamics. In Springer Netherlands, Dordrecht doi:[10.1007/978-94-007-0114-4_15](https://doi.org/10.1007/978-94-007-0114-4_15)
- Goldberg WM (2002) Gastrodermal structure and feeding responses in the scleractinian *Mycetophyllia reesi*, a coral with novel digestive filaments. *Tissue Cell* 34:246–261. doi:[10.1016/S0040-8166\(02\)00008-3](https://doi.org/10.1016/S0040-8166(02)00008-3)
- Gregory MR (1996) Plastic ‘scrubbers’ in hand cleansers: a further (and minor) source for marine pollution identified. *Mar Pollut Bull* 32:867–871. doi:[10.1016/S0025-326X\(96\)00047-1](https://doi.org/10.1016/S0025-326X(96)00047-1)
- Gregory MR (1999) Plastics and South Pacific Island shores: environmental implications. *Ocean Coast Manag* 42:603–615. doi:[10.1016/S0964-5691\(99\)00036-8](https://doi.org/10.1016/S0964-5691(99)00036-8)
- Hardesty BD, Wilcox C (2011) Understanding the types, sources and at-sea distribution of marine debris in Australian waters
- Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for identification and quantification. *Environ Sci Technol* 46:3060–3075. doi:[10.1021/es2031505](https://doi.org/10.1021/es2031505)
- Houlbrèque F, Ferrier-Pages C (2009) Heterotrophy in tropical scleractinian corals. *Biol Rev*. doi:[10.1111/j.1469-185X.2008.00058.x](https://doi.org/10.1111/j.1469-185X.2008.00058.x)
- Houlbrèque F, Delesalle B, Blanchot J, Montel Y, Ferrier-Pages C (2006) Picoplankton removal by the coral reef community of La Prevoyante, Mayotte Island. *Aquat Microb Ecol* 44:59–70. doi:[10.3354/ame044059](https://doi.org/10.3354/ame044059)
- Ivar do Sul JA, Costa MF (2014) The present and future of microplastic pollution in the marine environment. *Environ Pollut* 185:352. doi:[10.1016/j.envpol.2013.10.036](https://doi.org/10.1016/j.envpol.2013.10.036)
- Kaposi KL, Mos B, Kelaher BP, Dworjanyn SA (2014) Ingestion of microplastic has limited impact on a marine larva. *Environ Sci Technol* 48:1638. doi:[10.1021/es404295e](https://doi.org/10.1021/es404295e)
- Koelmans AA, Besseling E, Foekema EM (2014) Leaching of plastic additives to marine organisms. *Environ Pollut* 187:49–54. doi:[10.1016/j.envpol.2013.12.013](https://doi.org/10.1016/j.envpol.2013.12.013)
- Laist DW (1987) Overview of the biological effects of lost and discarded plastic debris in the marine environment. *Mar Pollut Bull* 18:319–326. doi:[10.1016/S0025-326X\(87\)80019-X](https://doi.org/10.1016/S0025-326X(87)80019-X)

- Lewis JB, Price WS (1975) Feeding mechanisms and feeding strategies of Atlantic reef corals. *J Zool* 176:527–544. doi:[10.1111/j.1469-7998.1975.tb03219.x](https://doi.org/10.1111/j.1469-7998.1975.tb03219.x)
- Marsh JA (1970) Primary productivity of reef-building calcareous red algae. *Ecology* 51:255–263. doi:[10.2307/1933661](https://doi.org/10.2307/1933661)
- Mato Y, Isobe T, Takada H, Kanehiro H, Ohtake C, Kaminuma T (2001) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environ Sci Technol* 35:318–324. doi:[10.1021/es0010498](https://doi.org/10.1021/es0010498)
- Mills MM, Lipschultz F, Sebens KP (2004) Particulate matter ingestion and associated nitrogen uptake by four species of scleractinian corals. *Coral Reefs* 23:311–323. doi:[10.1007/s00338-004-0380-3](https://doi.org/10.1007/s00338-004-0380-3)
- Moore CJ (2008) Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. *Environ Res* 108:131–139. doi:[10.1016/j.envres.2008.07.025](https://doi.org/10.1016/j.envres.2008.07.025)
- Murdock GR (1978) Digestion, assimilation, and transport of food in the gastrovascular cavity of a gorgonian octocoral (Cnidaria; Anthozoa). *Bull Mar Sci* 28:354–362
- Palardy JE, Grottoli AG, Matthews KA (2005) Effects of upwelling, depth, morphology and polyp size on feeding in three species of Panamanian corals. *Mar Ecol Prog Ser* 300:79–89. doi:[10.3354/meps300079](https://doi.org/10.3354/meps300079)
- Palardy JE, Rodrigues LJ, Grottoli AG (2008) The importance of zooplankton to the daily metabolic carbon requirements of healthy and bleached corals at two depths. *J Exp Mar Biol Ecol* 367:180–188. doi:[10.1016/j.jembe.2008.09.015](https://doi.org/10.1016/j.jembe.2008.09.015)
- Reisser J, Shaw J, Wilcox C, Hardesty BD, Proietti M, Thums M, Pattiaratchi C (2013) Marine plastic pollution in waters around Australia: characteristics, concentrations, and pathways. *PLoS One*. doi:[10.1371/journal.pone.0080466](https://doi.org/10.1371/journal.pone.0080466)
- Rios LM, Moore C, Jones PR (2007) Persistent organic pollutants carried by synthetic polymers in the ocean environment. *Mar Pollut Bull* 54:1230–1237. doi:[10.1016/j.marpolbul.2007.03.022](https://doi.org/10.1016/j.marpolbul.2007.03.022)
- Sano M, Shimizu M, Nose Y (1987) Long-term effects of destruction of hermatypic corals by *Acanthaster planci* infestation on reef fish communities at Iriomote Island, Japan. *Mar Ecol Prog Ser* 37:191–199. doi:[10.3354/meps037191](https://doi.org/10.3354/meps037191)
- Stella JS, Pratchett MS, Hutchings PA, Jones GP (2011) Coral-associated invertebrates: diversity, ecology importance and vulnerability to disturbance. *Oceanogr Mar Biol*. doi:[10.1201/b11009-3](https://doi.org/10.1201/b11009-3)
- Tanaka K, Takada H, Yamashita R, Mizukawa K, MA Fukuwaka, Watanuki Y (2013) Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. *Mar Pollut Bull* 69:219. doi:[10.1016/j.marpolbul.2012.12.010](https://doi.org/10.1016/j.marpolbul.2012.12.010)
- Teuten EL, Rowland SJ, Galloway TS, Thompson RC (2007) Potential for plastics to transport hydrophobic contaminants. *Environ Sci Technol* 41:7759. doi:[10.1021/es071737s](https://doi.org/10.1021/es071737s)
- Teuten EL et al (2009) Transport and release of chemicals from plastics to the environment and to wildlife. *Philos Trans R Soc Lond B* 364:2027–2045. doi:[10.1098/rstb.2008.0284](https://doi.org/10.1098/rstb.2008.0284)
- Thompson RC et al (2004) Lost at sea: where is all the plastic? *Science* 304:838. doi:[10.1126/science.1094559](https://doi.org/10.1126/science.1094559)
- Titlyanov EA, Titlyanova TV, Leletkin VA, Tsukahara J, Van Woesik R, Yamazato K (1996) Degradation of zooxanthellae and regulation of their density in hermatypic corals. *Mar Ecol Prog Ser* 139:167–178. doi:[10.3354/meps139167](https://doi.org/10.3354/meps139167)
- von Moos N, Burkhardt-Holm P, Köhler A (2012) Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure. *Environ Sci Technol* 46:11327–11335. doi:[10.1021/es302332w](https://doi.org/10.1021/es302332w)
- Zitko V, Hanlon M (1991) Another source of pollution by plastics: skin cleaners with plastic scrubbers. *Mar Pollut Bull* 22:41–42. doi:[10.1016/0025-326x\(91\)90444-w](https://doi.org/10.1016/0025-326x(91)90444-w)