Species-specific impact of microplastics on coral physiology

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Highlights

- ~~2 species of~~ corals were exposed to ~~2 different polymers and shapes (spheres and fibres) of~~ microplastic ~~types~~ at ambient and elevated temperatures
- ~~We assessed effects of microplastics on~~ gross photosynthesis, net respiration, and photosynthetic yields ~~of photosystem II were assessed~~
- Responses were species, microplastic type, and temperature -dependent ~~and microplastic-specific~~
- ~~Fibres decreased microplastic fibres caused a 41% reduction in~~ photosynthetic ability ~~at ambient temperature over 12 days~~ for *Acropora* sp.
- No stress response occurred at elevated temperature for either species.

Abstract

There is evidence that microplastic (MP) pollution can negatively influence coral health; however, mechanisms are unknown and most studies have used MP exposure concentrations that are considerably higher than current environmental conditions. Furthermore, whether MP exposure influences coral susceptibility to

other stressors such as ocean warming is unknown. Our objective was to determine the physiology response of corals exposed to MP concentrations that have been observed *in-situ* at ambient and elevated temperature that replicates ocean warming. Here, two sets of short-term experiments were conducted at ambient and elevated temperature, exposing the corals *Acropora sp.* and *Seriatopora hystrix* to microspheres and microfibres. Throughout the experiments, gross photosynthesis and *net* respiration was quantified using a 4-chamber coral respirometer, and photosynthetic yields of photosystem II were measured using Pulse-Amplitude Modulated (PAM) fluorometry. Results indicate the effect of MP exposure is dependent on MP type, coral species, and temperature. MP fibres (but not spheres) reduced photosynthetic capability of *Acropora sp.*, with a 41% decrease in photochemical efficiency *at ambient temperature over 12 days*. No additional stress response was observed at elevated temperature; photosynthetic performance significantly increased in *Seriatopora hystrix* exposed to MP *spheres*. These findings show that a disruption to coral photosynthetic ability can occur at MP concentrations that have been observed in the marine environment and that MP pollution impact on corals remains an important aspect for further research.

Graphical abstract

Keywords: Microplastic; Reef-building corals; Ocean warming; Photosynthesis; Stress; Respiration

Main finding summary:

Photosynthetic ability of *Acropora sp.* exposed to microfibres was significantly lower compared to *Seriatopora hystrix* with a 41% decrease at ambient temperature. No stress response occurred at elevated temperature.

1. Introduction

Plastic is durable, lightweight and inexpensive to produce, becoming a favourable every-day material and causing the “age of plastics”, with production increasing from 0.5 million tonnes/yr in 1960 to 348 million tonnes/yr in 2017 (Avio et al., 2017; PlasticsEurope (Association of Plastics Manufacturers), 2018). These properties have ensured plastic waste has developed into a serious threat to the marine environment (Derraik, 2002; Ryan et al., 2009). An estimated 60-80% of the world's litter is plastic and approximately 10% of annual plastic production enters the sea from land-based sources that includes rivers, wastewater discharges and storm water runoff (Derraik, 2002; Ryan et al., 2009). Marine plastic pollution is having detrimental repercussions on the marine environment, contaminating ecosystems and reaching the world's most remote locations, such as Antarctica (Cincinelli et al., 2017; Munari et al., 2017; Ryan et al., 2009; Walker, 2018). Impacts include entanglement and death of marine wildlife, loss of aesthetic value and an increase in economic costs for remediation (Avio et al., 2017; Derraik, 2002). It is well known that larger pieces of plastics are a threat to marine life, although there is still relatively little information on the impact of MPs on marine ecosystems such as coral reefs (Chae and An, 2017; Derraik, 2002; Halden, 2010; Meeker et al., 2009; PlasticsEurope (Association of Plastics Manufacturers), 2018).

Microplastics (MPs), plastic fragments defined as <5 mm, are more difficult to manage than macroplastics due to their size and are of high environmental concern (Avio et al., 2015; Cincinelli et al., 2017; Wright et al., 2013). MPs have been found within numerous organisms and can elicit substantial impacts such as reducing feeding, immunity and survival within laboratory exposure studies (Lusher et al., 2013; Murray and Cowie, 2011; Provencher et al., 2014; Setälä et al., 2014; Sussarellu et al., 2016). While exposure and ingestion of MPs occurs in numerous marine organisms, the implications of this exposure at levels that have been observed *in situ* on overall health and survival are unknown (Fossi et al., 2012; Wright et al., 2013). Several laboratory studies suggest that leaching of constituent contaminants including plastic additives and monomers from MPs are capable of causing endocrine disruption and bioaccumulation (Oehlmann et al., 2008; Talsness, 2009). However, there is no evidence of endocrine disruption from substances sorbed to MPs at environmentally relevant concentrations.

The small size of MPs is one of the main factors contributing to their accessibility to lower trophic organisms (Arossa et al., 2019; Browne et al., 2008; Garnier et al., 2019; Lusher et al., 2013; Setälä et al., 2014). Plastic pollution origin is mainly terrestrial and therefore coastal ecosystems such as coral reefs are particularly at risk (Reichert et al., 2018). Impacts of MPs to coral reefs is of increasing concern because of their high biodiversity and significant economic value (Hamilton et al., 2017; Richmond, 1993). A key concern is that impacts of climate change-related warming may be accentuated by pollutants such as MP exposure (Hughes et al., 2017). Exposure of corals to MPs may happen in numerous ways, especially at low tide when floating plastic can come into contact with corals on shallow reefs (Hall et al., 2015). Previous studies have shown that corals are non-

selective feeders, with common scleractinian corals ingesting a range of food from bacteria to mesozooplankton within a size range of 0.2-1,000µm and a preference for smaller particles (Anthony, 1999; Hall et al., 2015; Mills et al., 2004). As MPs are within the size range that corals ingest, and there is evidence that corals do ingest MPs (Allen et al., 2017; Hall et al., 2015; Hankins et al., 2018; Reichert et al., 2018), investigation of the effects of MP exposure in corals is a priority.

MPs (at high concentration) can disturb the initiation of symbiotic relationships in certain coral species which plays an important role in coral ability to adapt to environmental change (Okubo et al., 2018). Therefore, as MP pollution continues to rise, coral exposure to MPs may reach high levels in the future, potentially reducing coral resilience to environmental change and making reefs more vulnerable (LaJeunesse et al., 2018; Okubo et al., 2018). There is little literature on the responses and defence mechanisms of marine organisms when ingesting MPs, but studies have investigated the production of reactive oxygen species (ROS) and enzymes including superoxide dismutase (SOD) due to MP exposure. Evidence from organisms (photosynthetic and non-photosynthetic) indicate that the overproduction of ROS is significant after MP exposure and can cause oxidative damage (Bhattacharya et al., 2010; Chen et al., 2017; Paul-Pont et al., 2016). In the case of the coral holobiont, this could lead to decreased photosynthetic efficiencies and a breakdown in the host-symbiont relationship, exacerbating coral bleaching responses.

Recently, MPs have been identified to compromise coral health, by reducing growth and altering photosynthetic performance (especially maximum photochemical efficiency), with species-specific responses observed (Reichert et al., 2019). However this was observed at a MP concentration of 200 particles L⁻¹ which does not represent current environmental levels, similar to many lab-based exposure studies. For example, several investigations into MP concentration on coral reefs (including in the South China Sea, Great Barrier Reef and the Maldives) found a range of 0-45 MP items L⁻¹ *in situ* (Ding et al., 2019; Huang et al., 2019; Nie et al., 2019; Saliu et al., 2018); yet previous studies have tended to use concentrations two to seven orders-of-magnitude higher than environmental quantities (Lenz et al., 2016). Here, we explore whether MP exposure, at environmentally relevant concentrations, will cause a reduction in coral physiology or photosynthetic efficiencies, and whether this is exacerbated by thermal perturbation.

2. Materials and Methods

Two twelve-day experiments were conducted at the University of Edinburgh, to study the impact of two different types MPs (see section 2.1) on the photosynthetic capability and respiration of two species of coral (*Acropora sp.* and *Seriatopora hystrix*) at ambient and elevated temperatures. The first experiment exposed fragments of *Acropora sp.* and *Seriatopora hystrix* to MPs at ambient temperature, 26°C. The second set of experiments used new fragments and the same setup at

ambient temperature (26°C) after the tanks had full water changes and had been cleaned, with the temperature elevating from 26°C to 32°C by 0.5°C every two days. Both experiments also had control set-ups where coral fragments were not exposed to MP but to ambient and elevating temperatures.

2.1 Preliminary set-up

i) Preparation of corals

Corals of the genus *Acropora* and *Seriatopora hystrix* were used for this investigation. *Acropora* sp. is an important dominant reef-building genus and one of the most abundant and species-rich groups of corals in the world. *Acropora* sp. is typically sensitive to anthropogenic ecosystem change (Greer et al., 2009). *S. hystrix* is a branching coral, widely distributed in the Indo-Pacific and thought to be more resilient to environmental change (Anderson, 2014). Corals raised in aquaria were provided by the Tropical Marine Centre, Manchester, UK and were cut using clippers into 110 fragments ~30 mm long per species. Fragments were glued to coral plugs and acclimatised to tank conditions at 26°C for at least 14 days.

ii) Microplastics

Polystyrene is one of the most used plastics globally, typically seen in packaging and was chosen as it is a commonly found plastic polymer in MP sampling at sea and beaches (Barnes et al., 2009; Browne et al., 2010). Fibres are also one of the most found marine MP types, with an important source originating through sewage contaminated by fibres from washing clothes (Browne et al., 2011; Claessens et al., 2011). Polystyrene spheres produced for the NERC RealRiskNano Project (size range 500-1000 µm, MP1), as described by Al-Sid-Cheikh et al. (2018) and microfibres (size range 0.05-1cm, MP2) extracted from tumble dryer lint were used for experimentation. 50ml stock solutions were made of each respective MP with artificial seawater (Tropic Marin) in 100 ml beakers, wrapped in aluminium foil and kept in a fridge to prevent biofilm growth and degradation of MPs. Stocks were mixed by magnetic stirrers for 10 minutes before being added to tanks. As extrapolated by Lenz et al. (2016), MP concentration in various marine environments ranges from approximately 1 µg/L – 1 ng/L. However, previous MP concentrations for coral studies range from 2.5-395 mg/L. Therefore, stocks were added to experimental flasks to a final concentration of 0.1 mg/L as a more environmentally relevant concentration but also to be comparable to previous coral exposure studies (Lenz et al., 2016).

2.2 Tank set-up, water chemistry and microplastic treatments

Four tanks were utilised with each experiment being a closed system to prevent contamination. Each tank had one heater, circulation pump and lights with a 12:12 photoperiod, PAR 50µmols. Salinity was maintained at 36 ppt. An Orion Star A211 pH meter was used with Orion 8302BNUMD ROSS Ultra pH/ATC Triode to monitor

pH daily. Five replicate fragments of each genus were placed into each tank which had different treatments: two control (CTR) tanks, one polystyrene sphere (MP1) treatment and one MP fibre (MP2) treatment. This was repeated at elevated temperature conditions.

2.3 Non-invasive assessment of coral health

Chlorophyll *a* fluorescence is a rapid and non-invasive technique for assessing the photosynthetic apparatus status of coral *Symbiodinaceae* and any effects of contaminants that may inhibit Photosystem (PS) II electron transport (Elahifard et al., 2013; Jones et al., 2000; Schreiber, 2004), with many studies using Pulse-Amplitude Modulated (PAM) fluorometry in coral research (Jones et al., 2000, 1998; Jones and Hoegh-Guldberg, 2001; Owen et al., 2003; Ralph et al., 2001; Schreiber, 2004; Warner et al., 1996). PAM fluorometry has also been utilised to determine whether a compound, such as MPs, have phytotoxic interactions (additive, synergistic or antagonistic) with species (Elahifard et al., 2013; Franqueira et al., 2000).

F_q'/F_m' is correlated with the quantum yield of photochemistry in PSII and reflects the probability that the PSII reaction centres will utilise the available excitation energy for photochemistry (Jones et al., 2000). Photoinhibition of photosynthesis is synonymous with changes in chlorophyll fluorescence characteristics, including a decrease of photosynthetic electron transport activity and a loss of quantum yield (Jones and Hoegh-Guldberg, 2001). F_q'/F_m' was the chosen chlorophyll *a* parameter for this study as it has been used throughout literature as a reliable method to measure photochemical efficiency (Brack and Frank, 1998; Krause and Weis, 1991; Schreiber et al., 1993). A Diving-PAM MK2 fluorometer (Walz) was used for all measurements. Chlorophyll *a* fluorescence was stimulated by a pulse modulated red LED at 650 nm, and corals were quasi-dark adapted (Hennige et al., 2008) before saturation pulse measurements ($Y_{(III)}$) were taken each day to quantify fluorescence yield (F_m' and F') and derive F_q'/F_m' (Table 1) (Hennige et al., 2008). It should be noted that when collecting F_q'/F_m' data using a PAM fluorometer, different areas of the coral were sampled each day, which may have caused some additional variation. In addition, weekly rapid light curves were conducted on each coral fragment to determine the relative Electron Transport Rate (rETR) (Genty et al., 1989). Maximum rETR was compared between variables within experiments. Measurement definitions and their abbreviations are summarised in Table 1.

2.4 Respirometry

A 4-chamber coral respirometer was used at the beginning and end of each experiment to quantify gross photosynthesis and net respiration (Hennige et al., 2008; Lesser, 1997; Levy et al., 2006; Mass et al., 2007). Fragments were placed in 230 ml incubation chambers each fitted with oxygen optodes (Presens) and connected to a temperature-compensated oxygen analyser. Corals were acclimated

in the respirometer for 30 minutes with measurements in light and dark conditions running for 30 minutes each. Respirometry analysis was undertaken at day 1 and 12 of each experiment.

2.5 Statistical analysis

The combined effects of interactions between treatment (control, MP1 and MP2) and temperature (ambient and elevated), and treatment and species on F_q'/F_m' , gross photosynthesis and net respiration were assessed using two-way analysis of variance (ANOVA), followed by Tukey's HSD post hoc test. Analysis of data collected at the end of the 12-day experiments was conducted. Where necessary, data was transformed using arcsine of square root (proportion data) or inverse transformation to conform to the parametric test assumptions. Before the parametric analysis, Shapiro-Wilk and Levene tests were applied to assess the normality and homogeneity of variance, respectively, of data distribution. Parametric assumptions were met for all analysis. Two-way ANOVAs were considered statistically significant if $p \leq 0.05$. All statistical analysis was conducted using R (R Core Team, 2013).

3. Results

The presence microplastics significantly affected the physiology of corals depending on species and temperature interactions. The specific results are presented in the following subtopics.

3.1 Species specific impacts of microplastics to coral (photo)physiology

There was a statistically significant interaction between the effects of species and treatment on F_q'/F_m' at the end of the 12 day experiment (ANOVA, $F(2,62)=5.925, p=0.004$) as shown in Fig.1 A-D). In particular, F_q'/F_m' of corals exposed to fibres (MP2) was significantly lower for *Acropora* sp. compared to *S.hystrix* (Tukey's multiple comparison test, $p=0.008$). For *Acropora* sp. exposed to spheres (MP1), F_q'/F_m' was significantly higher compared to controls (Tukey's multiple comparison test, $p=0.040$) and fibres (MP2) (Tukey's multiple comparison test, $p=0.001$).

There was a statistically significant interaction between the effects of species and treatment on gross photosynthesis (ANOVA, $F(2,45)=7.091, p=0.002$), (Fig. 2 A-

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D). For *S.hystrix*, gross photosynthesis was considerably higher for spheres (MP1) than fibres (MP2), with a significant difference between the effects of MP1 and MP2 (Tukey's multiple comparison test, $p=0.027$) (Fig. 2 B and D)). Analysis of net respiration showed no statistically significant interactions or effects of treatments (ANOVA, $F(2,56)=1.33, p=0.273$) but a significant difference between species (ANOVA, $F(1,56)=7.37, p=0.009$).

3.2 Temperature specific impacts of microplastics to coral (photo)physiology

There was a statistically significant interaction between the effects of temperature and treatment on F_q'/F_m' (ANOVA, $F(2,62)=4.320, p=0.018$), (Fig.1 A-D). A significantly higher F_q'/F_m' was observed for corals exposed to spheres (MP1) at elevated temperature compared to ambient temperature (Tukey's multiple comparison test, $p=0.006$). F_q'/F_m' of corals exposed to fibres (MP2) was also significantly higher at elevated temperatures (Tukey's multiple comparison test, $p<0.001$). In addition, at elevated temperature, there was a significant difference between control and spheres (MP1) for both coral species (Tukey's multiple comparison test, $p=0.080$) (Fig.1 C-D)), with lower F_q'/F_m' observed for control corals.

Likewise, there was a statistically significant interaction between the effects of temperature and treatment on gross photosynthesis. (ANOVA, $F(2,45)=3.708, p=0.032$) (Fig. 2 A-D). Corals exposed to spheres (MP1) had significantly higher gross photosynthesis at elevated temperature compared to ambient temperature (Tukey's multiple comparison test, $p=0.034$), in addition to a significantly higher gross photosynthesis compared to corals exposed to fibres (MP2) fibres (MP2) ($p=0.045$) at elevated temperature (Tukey's multiple comparison test, Fig.2 C-D)). This is due to gross photosynthesis being particularly high for *S.hystrix* at elevated temperature (Fig.2 D).

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4. Discussion

The short-term exposure to MPs tested here resulted in a species-specific and MP-specific stress response between two reef-building coral species.

F_q'/F_m' of corals exposed to MP fibres was significantly lower for *Acropora* sp. compared to *S.hystrix*, at ambient temperature, with a 41% decrease in F_q'/F_m' for *Acropora* sp. over a 12 day period. However, *Acropora* sp. exposed to MP spheres showed significantly higher F_q'/F_m' compared to control and MP fibre treatments.

At elevated temperature, no negative physiological response was observed for either *S.hystrix* or *Acropora* sp. At elevated temperature, no negative

physiological response was observed for either species. *S.hystrix* F_q/F_m' and gross photosynthesis was significantly higher when exposed to MP spheres.

This study supports current literature that negative impacts of MPs are species specific. This study supports current literature that negative impacts of MPs are species specific (Reichert et al., 2019, 2018), but importantly, also shows these results at concentrations that replicate environmental levels. Our results further highlight the need for more investigations to fully understand observed physiological responses.

At ambient temperature, the significantly reduced photosynthetic efficiency of PSII (F_q'/F_m') for *Acropora* sp. may have occurred for several reasons. When photosynthetic efficiency (F_q'/F_m') is considered with the negative gross photosynthetic values observed, it can be concluded that photosynthetic ability of *Acropora* sp. decreased when exposed to fibres. A decrease in the capacity of PSII may have been caused by the stress production of reactive oxygen species (ROS). This has been previously observed in *Pocillopora damicornis*, as well as the suppression of its detoxification and immune system when exposed to MPs (Tang et al., 2018). An increase in ROS production either directly, or indirectly such as via organic radical formation, can result in heightened oxidative stress and biological damage due to limiting the fixation of CO₂ and therefore inhibiting the repair of PSII (Bhattacharya et al., 2010; Livingstone, 2003; Takahashi and Murata, 2008). A difference in respiratory ability was also observed for *Acropora* sp., exposed to MPs having higher net respiration levels. Heightened respiratory activity is known to occur under stressful conditions in corals and anemones (Edmunds, 2005; Leggat et al., 2011; Nii and Muscatine, 1997), supporting the hypothesis that interactions with MPs is energetically costly and may prevent normal coral functioning. These are speculations however and further study is necessary.

Coral exposure to microfibres can cause other stress responses that impair coral functioning further. Firstly, the interaction with microfibres may inhibit heterotrophic feeding. MPs have been observed to block normal food supply with continuous ingestion and egestion of MPs leading to little to no nutrients being obtained (Chapron et al., 2018; Reichert et al., 2019). Fibres have been observed within the coral polyp, wrapped by mesenterial tissue causing extraction by the coral to be difficult (Allen et al., 2017; Hall et al., 2015). In addition, MPs may become trapped in the mucus layer of corals and have the potential to trigger stress responses through further mucus production (Hall et al., 2015; Reichert et al., 2018). These responses are all energetically costly, especially an increase in mucus production, which can use half of the carbon assimilated from photosynthesis (Wild et al., 2004). As microfibres are thought to be the most abundant MP type in marine environments, it is likely that coral-microfibre interactions are already occurring, albeit at low levels (Browne et al., 2011; Thompson et al., 2004; Wright et al., 2013). Fibres can also become entangled with other fibres, particles or tissue, making

egestion even more demanding or impossible compared with other MP types such as spheres. Ingestion of MP fibres in particular can therefore cause blockages and feeding difficulties in addition to impeding normal digestion of natural food as mesenterial tissues are the primary tissue involved in digestion (Goldberg, 2002). The stress response observed for *Acropora* sp. at ambient temperature may have long-term effects including reduced growth, fecundity, ability to repair, and survival. *Acropora* sp. are typically a more sensitive species and form important frameworks for reefs. As MP pollution levels continue to rise, this may therefore threaten reef composition by reducing photosynthetic ability and growth of sensitive coral species.

The results observed here were species specific, with *S. hystrix* showing no change in physiology when exposed to MPs at ambient temperature, supporting previous studies at higher MP concentrations (Mouchi et al., 2019; Reichert et al., 2019). This may be due to differences in feeding capacity and behaviour, with *Acropora* interacting with MPs more (Hall et al., 2015). Furthermore, MPs can disturb the anthozoan-algae symbiotic relationship in both coral and anemones, suppressing the uptake of *Symbiodinaceae* (Okubo et al., 2018). The symbiotic alga-coral relationship may have been disturbed in *Acropora* sp., with the host producing stress responses that impacts downstream on the *Symbiodinaceae*, reducing photosynthetic capability (Okubo et al., 2018). *Symbiodinaceae* differ in sensitivity and therefore some species may be more sensitive to MP disturbance. *Acropora* sp. are typically more sensitive to environmental change compared to other corals. This may explain the species-specific responses observed, but a wider range of species must be tested under long-term MP exposures at ambient temperatures.

It was expected that elevated temperatures would accentuate the negative physiological impacts of MP exposure on corals (Biscre et al., 2017), yet this was not observed. *Acropora* sp. showed no change in photosynthetic or respiratory ability, yet *S. hystrix* had considerably higher photosynthetic ability (F_q'/F_m' and gross photosynthesis) when exposed to either type of MP. MPs may destabilise the functioning of the symbiotic alga-host relationship by inducing the production of ROS (Dubinsky and Stambler, 1996; Okubo et al., 2018). However, acclimation to thermal stress can occur through production of oxidative enzymes to inactive damaging oxygen radicals or heat shock proteins that refold denatured cellular and structural proteins (Coles and Brown, 2003; Hofmann and Todgham, 2010; Weis, 2010). A speculation for why these results were observed is that through these mechanisms (acclimation), the coral may become more resistant to the damage caused by MP exposure with temperature (within time scales of experiments here). At ambient temperature, the photosynthetic capability of *Acropora* sp. was lowered as a result of exposure to MP fibres which may have been caused by ROS production and/or damage to PSII. However, at elevated temperature, acclimation may not only protect the holobiont from thermal stress but also ROS induced damage from the presence and damage of MPs. Physiological changes to corals due to stress, where the host switches to a primarily heterotrophic nutrition has been previously observed during bleaching events (Grottoli et al., 2006). If MP exposure was maintained in the long-term, physiological acclimation may manifest as a shift towards more

thermotolerant *Symbiodinaceae* or change in the associated microbial community (Ainsworth and Hoegh-Guldberg, 2009; Fine and Loya, 2002; Reshef et al., 2006), highlighting an important focus for future research.

5. Conclusions

Ultimately, our findings support the general view that MP exposure induces a negative impacts on the coral holobiont's photophysiology, albeit with species and MP type specificity. In particular, photosynthetic capability of *Acropora sp.*, a globally important reef-building genus, was compromised even at ambient temperature. This investigation contributes to our understanding of the physiological effects of MPs by carrying out experiments at more environmentally-relevant concentrations at both ambient and elevated temperatures. Explanations for the results observed highlight the complex response mechanisms of corals to MP exposure and show the need for more research in this area. Future studies at both ambient and elevated temperatures should take a holistic view, interrogating impacts on the coral host and associated symbionts and bacterial communities. In addition, to further investigate impact mechanisms, a range of microplastic concentrations are needed. Importantly, research is needed *in situ* to determine MP concentration on coral reefs to inform future exposure studies and assess the extent of potential MP stress for coral reef management.

Figures and Tables

Table 1: Abbreviations and their definitions relevant for PAM fluorometry measurements

ABBREVIATION	DEFINITION
PAR	Photosynthetically active radiation
PSII	Photosystem II is a specialised protein complex that uses light energy to drive the transfer of electrons from water, resulting in the production of oxygen in photosynthesis
F'	Fluorescence yield – under actinic light
F _m '	The maximum fluorescence yield - under actinic light
F _q '	Fluorescence quenched (F _m ' – F')
F _q '/F _m '	Effective photochemical efficiency of PSII photochemistry (or effective

	quantum yield) at any given actinic irradiance, determined by $(F_m' - F') / F_m'$.
Maximum relative ETR	<p>The approximation of the maximum electron transport rate ($\mu\text{mol electrons m}^{-2} \text{ s}^{-1}$) determined by(Genty et al., 1989):</p> $\text{relative ETR} = \Phi_{\text{PSII}} \times \text{PAR}$ <p>where effective quantum yield Φ_{PSII} is determined by(Genty et al., 1989):</p> $\Phi_{\text{PSII}} = \frac{[F_m' - F]}{F_m'}$ <p>with F being the minimum florescence for light-adapted samples</p>

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Figure 1: The changes in average F_q/F_m' over the 12 day period for *Acropora sp.* and *Seriatopora sp.* at A-B) ambient temperature (26°C) and C-D) elevated temperature (26 - 32°C) with standard error bars. MP1 = corals exposed to polystyrene spheres and MP2 = corals exposed to microplastic fibres.

Figure 2: The average gross photosynthesis (O_2 production) and net respiration (O_2 consumption) of corals at the end of the 12-day experiment for *Acropora sp.* and *Seriatopora sp.*

Seriatopora sp. at A-B) ambient temperature (26°C) and C-D) elevated temperature (26 - 32°C) with standard error bars.

MP1

= corals exposed to polystyrene spheres and MP2 = corals exposed to microplastic fibres.

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References

- Ainsworth, T., Hoegh-Guldberg, O., 2009. Bacterial communities closely associated with coral tissues vary under experimental and natural reef conditions and thermal stress. *Aquat. Biol.* 4, 289–296. doi:10.3354/ab00102
- Al-Sid-Cheikh, M., Rowland, S.J., Stevenson, K., Rouleau, C., Henry, T.B., Thompson, R.C., 2018. Uptake, Whole-Body Distribution, and Depuration of Nanoplastics by the Scallop *Pecten maximus* at Environmentally Realistic Concentrations. *Environ. Sci. Technol.* 52, 14480–14486. doi:10.1021/acs.est.8b05266
- Allen, A.S., Seymour, A.C., Rittschof, D., 2017. Chemoreception drives plastic consumption in a hard coral. *Mar. Pollut. Bull.* 124, 198–205. doi:10.1016/j.marpolbul.2017.07.030
- Anderson, M., 2014. The effects of temperature on gene expression in the Indo-Pacific reef-building coral *Seriatopora hystrix*: insight from aquarium studies in Southern Taiwan. *Int. J. Mar. Sci.* doi:10.5376/ijms.2014.04.0050
- Anthony, K.R.N., 1999. Coral suspension feeding on fine particulate matter. *J. Exp.*

485 Mar. Bio. Ecol. 232, 85–106. doi:10.1016/S0022-0981(98)00099-9
 486 Arossa, S., Martin, C., Rossbach, S., Duarte, C.M., 2019. Microplastic removal by
 487 Red Sea giant clam (*Tridacna maxima*). Environ. Pollut. 252, 1257–1266.
 488 doi:10.1016/j.envpol.2019.05.149
 489 Avio, C.G., Gorbi, S., Lilan, M., Benedetti, M., Fattorini, D., D'Errico, G., Pauletto, M.,
 490 Bargelloni, L., Regoli, F., 2015. Pollutants bioavailability and toxicological risk
 491 from microplastics to marine mussels. Environ. Pollut. 198, 211–222.
 492 doi:10.1016/j.envpol.2014.12.021
 493 Avio, C.G., Gorbi, S., Regoli, F., 2017. Plastics and microplastics in the oceans:
 494 From emerging pollutants to emerged threat. Mar. Environ. Res. 128, 2–11.
 495 doi:10.1016/j.marenvres.2016.05.012
 496 Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and
 497 fragmentation of plastic debris in global environments. Philos. Trans. R. Soc.
 498 Lond. B. Biol. Sci. 364, 1985–98. doi:10.1098/rstb.2008.0205
 499 Bhattacharya, P., Lin, S., Turner, J.P., Ke, P.C., 2010. Physical adsorption of
 500 charged plastic nanoparticles affects algal photosynthesis. J. Phys. Chem. C
 501 114, 16556–16561. doi:10.1021/jp1054759
 502 Biscéré, T., Lorrain, A., Rodolfo-Metalpa, R., Gilbert, A., Wright, A., Devissi, C.,
 503 Peignon, C., Farman, R., Duvieilbourg, E., Payri, C., Houlbrèque, F., 2017.
 504 Nickel and ocean warming affect scleractinian coral growth. Mar. Pollut. Bull.
 505 120, 250–258. doi:10.1016/j.marpolbul.2017.05.025
 506 Brack, W., Frank, H., 1998. Chlorophyll a fluorescence: a tool for the investigation of
 507 toxic effects in the photosynthetic apparatus. Ecotoxicol. Environ. Saf. 40, 34–
 508 41. doi:10.1006/eesa.1997.1639
 509 Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T.,
 510 Thompson, R., 2011. Accumulation of Microplastic on Shorelines Worldwide:
 511 Sources and Sinks. Environ. Sci. Technol. 45, 9175–9179.
 512 doi:10.1021/es201811s
 513 Browne, M.A., Dissanayake, A., Galloway, T.S., Lowe, D.M., Thompson, R.C., 2008.
 514 Ingested Microscopic Plastic Translocates to the Circulatory System of the
 515 Mussel, *Mytilus edulis* (L.). Environ. Sci. Technol. 42, 5026–5031.
 516 doi:10.1021/es800249a
 517 Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial Patterns of Plastic
 518 Debris along Estuarine Shorelines. Environ. Sci. Technol. 44, 3404–3409.
 519 doi:10.1021/es903784e
 520 Chae, Y., An, Y.J., 2017. Effects of micro- and nanoplastics on aquatic ecosystems:
 521 Current research trends and perspectives. Mar. Pollut. Bull. 124, 624–632.
 522 doi:10.1016/j.marpolbul.2017.01.070
 523 Chapron, L., Peru, E., Engler, A., Ghiglione, J.F., Meistertzheim, A.L., Pruski, A.M.,
 524 Purser, A., Vétion, G., Galand, P.E., Lartaud, F., 2018. Macro- and microplastics
 525 affect cold-water corals growth, feeding and behaviour. Sci. Rep. 8, 15299.
 526 doi:10.1038/s41598-018-33683-6
 527 Chen, Q., Gundlach, M., Yang, S., Jiang, J., Velki, M., Yin, D., Hollert, H., 2017.
 528 Quantitative investigation of the mechanisms of microplastics and nanoplastics
 529 toward zebrafish larvae locomotor activity. Sci. Total Environ. 584–585, 1022–
 530 1031. doi:10.1016/j.scitotenv.2017.01.156
 531 Cincinelli, A., Scopetani, C., Chelazzi, D., Lombardini, E., Martellini, T., Katsoyiannis,
 532 A., Fossi, M.C., Corsolini, S., 2017. Microplastic in the surface waters of the
 533 Ross Sea (Antarctica): Occurrence, distribution and characterization by FTIR.
 534 Chemosphere 175, 391–400. doi:10.1016/j.chemosphere.2017.02.024

535 Claessens, M., Meester, S. De, Landuyt, L. Van, Clerck, K. De, Janssen, C.R., 2011.
 536 Occurrence and distribution of microplastics in marine sediments along the
 537 Belgian coast. *Mar. Pollut. Bull.* 62, 2199–2204.
 538 doi:10.1016/j.marpolbul.2011.06.030
 539 Coles, S.L., Brown, B.E., 2003. Coral bleaching--capacity for acclimatization and
 540 adaptation. *Adv. Mar. Biol.* 46, 183–223. doi:10.1016/S0065-2881(03)46004-5
 541 Davies, S.W., Ries, J.B., Marchetti, A., Castillo, K.D., 2018. Symbiodinium functional
 542 diversity in the Coral *Siderastrea siderea* Is influenced by thermal stress and
 543 reef environment, but not ocean acidification. *Front. Mar. Sci.* 5, 1–14.
 544 doi:10.3389/fmars.2018.00150
 545 Derraik, J.G., 2002. The pollution of the marine environment by plastic debris: A
 546 review. *Mar. Pollut. Bull.* doi:10.1016/S0025-326X(02)00220-5
 547 Ding, J., Jiang, F., Li, J., Wang, Zongxing, Sun, C., Wang, Zhangyi, Fu, L., Ding,
 548 N.X., He, C., 2019. Microplastics in the Coral Reef Systems from Xisha Islands
 549 of South China Sea. *Environ. Sci. Technol.* 53, 8036–8046.
 550 doi:10.1021/acs.est.9b01452
 551 Dubinsky, Z., Stambler, N., 1996. Marine pollution and coral reefs. *Glob. Chang.*
 552 *Biol.* 2, 511–526. doi:10.1111/j.1365-2486.1996.tb00064.x
 553 Edmunds, P.J., 2005. Effect of elevated temperature on aerobic respiration of coral
 554 recruits. *Mar. Biol.* 146, 655–663. doi:10.1007/s00227-004-1485-5
 555 Elahifard, E., Ghanbari, A., Hasan, M., Mohassel, R., Zand, E., Mirshamsi, A.,
 556 Abbaspoor, M., 2013. Measuring chlorophyll fluorescence parameters for rapid
 557 detection of ametryn resistant. *Plant Knowl. J.* 2, 76–82.
 558 Fine, M., Loya, Y., 2002. Endolithic algae: an alternative source of photoassimilates
 559 during coral bleaching. *Proc. R. Soc. London. Ser. B Biol. Sci.* 269, 1205–1210.
 560 doi:10.1098/rspb.2002.1983
 561 Fossi, M.C., Panti, C., Guerranti, C., Coppola, D., Giannetti, M., Marsili, L., Minutoli,
 562 R., 2012. Are baleen whales exposed to the threat of microplastics? A case
 563 study of the Mediterranean fin whale (*Balaenoptera physalus*). *Mar. Pollut. Bull.*
 564 64, 2374–2379. doi:10.1016/j.marpolbul.2012.08.013
 565 Franqueira, D., Orosa, M., Torres, E., Herrero, C., Cid, A., 2000. Potential use of
 566 flow cytometry in toxicity studies with microalgae. *Sci. Total Environ.* 247, 119–
 567 126. doi:10.1016/S0048-9697(99)00483-0
 568 Garnier, Y., Jacob, H., Guerra, A.S., Bertucci, F., Lecchini, D., 2019. Evaluation of
 569 microplastic ingestion by tropical fish from Moorea Island, French Polynesia.
 570 *Mar. Pollut. Bull.* 140, 165–170. doi:10.1016/J.MARPOLBUL.2019.01.038
 571 Genty, B., Briantais, J., Baker, N., 1989. The relationship between the quantum yield
 572 of photosynthetic electron transport and quenching of chlorophyll fluorescence.
 573 *Biochim. Biophys. Acta - Gen. Subj.* 990, 87–92.
 574 Goldberg, W.M., 2002. Gastrodermal structure and feeding responses in the
 575 scleractinian *Mycetophyllia reesi*, a coral with novel digestive filaments. *Tissue*
 576 *Cell* 34, 246–261. doi:10.1016/S0040-8166(02)00008-3
 577 Greer, L., Jackson, J.E., Curran, H.A., Guilderson, T., Teneva, L., 2009. How
 578 vulnerable is *Acropora cervicornis* to environmental change? Lessons from the
 579 early to middle Holocene. *Geology* 37, 263–266. doi:10.1130/G25479A.1
 580 Grottoli, A.G., Rodrigues, L.J., Palardy, J.E., 2006. Heterotrophic plasticity and
 581 resilience in bleached corals. *Nature* 440, 1186–1189.
 582 Halden, R.U., 2010. Plastics and health risks. *Annu. Rev. Public Health* 31, 179–94.
 583 doi:10.1146/annurev.publhealth.012809.103714
 584 Hall, N.M., Berry, K.L.E., Rintoul, L., Hoogenboom, M.O., 2015. Microplastic

585 ingestion by scleractinian corals. *Mar. Biol.* 162, 725–732. doi:10.1007/s00227-
 586 015-2619-7
 587 Hamilton, R.J., Almany, G.R., Brown, C.J., Pita, J., Peterson, N.A., Howard Choat,
 588 J., 2017. Logging degrades nursery habitat for an iconic coral reef fish. *Biol.*
 589 *Conserv.* 210, 273–280. doi:10.1016/j.biocon.2017.04.024
 590 Hankins, C., Duffy, A., Drisco, K., 2018. Scleractinian coral microplastic ingestion:
 591 Potential calcification effects, size limits, and retention. *Mar. Pollut. Bull.* 135,
 592 587–593. doi:10.1016/J.MARPOLBUL.2018.07.067
 593 Hennige, S.J., Smith, D.J., Perkins, R., Consalvey, M., Paterson, D.M., Suggett,
 594 D.J., 2008. Photoacclimation, growth and distribution of massive coral species in
 595 clear and turbid waters. *Mar. Ecol. Prog. Ser.* 369, 77–88.
 596 doi:10.3354/meps07612
 597 Hofmann, G.E., Todgham, A.E., 2010. Living in the Now: Physiological Mechanisms
 598 to Tolerate a Rapidly Changing Environment. *Annu. Rev. Physiol.* 72, 127–145.
 599 doi:10.1146/annurev-physiol-021909-135900
 600 Huang, Y., Yan, M., Xu, K., Nie, H., Gong, H., Wang, J., 2019. Distribution
 601 characteristics of microplastics in Zhubi Reef from South China Sea. *Environ.*
 602 *Pollut.* doi:10.1016/j.envpol.2019.113133
 603 Hughes, T.P., Barnes, M.L., Bellwood, D.R., Cinner, J.E., Cumming, G.S., Jackson,
 604 J.B.C., Kleypas, J., Van De Leemput, I.A., Lough, J.M., Morrison, T.H., Palumbi,
 605 S.R., Van Nes, E.H., Scheffer, M., 2017. Coral reefs in the Anthropocene.
 606 *Nature* 546, 82–90. doi:10.1038/nature22901
 607 Jones, R.J., Hoegh-Guldberg, O., 2001. Diurnal changes in the photochemical
 608 efficiency of the symbiotic dinoflagellates (Dinophyceae) of corals:
 609 Photoprotection, photoinactivation and the relationship to coral bleaching. *Plant,*
 610 *Cell Environ.* 24, 89–99. doi:10.1046/j.1365-3040.2001.00648.x
 611 Jones, R.J., Hoegh-Guldberg, O., Larkum, A.W.D., Schreiber, U., 1998.
 612 Temperature-induced bleaching of corals begins with impairment of the CO₂
 613 fixation mechanism in zooxanthellae. *Plant, Cell Environ.* 21, 1219–1230.
 614 doi:10.1046/j.1365-3040.1998.00345.x
 615 Jones, R.J., Ward, S., Amri, A.Y., Hoegh-Guldberg, O., 2000. Changes in quantum
 616 efficiency of Photosystem II of symbiotic dinoflagellates of corals after heat
 617 stress, and of bleached corals sampled after the 1998 Great Barrier Reef mass
 618 bleaching event. *Mar. Freshw. Res.* 51, 63–71. doi:10.1071/MF99100
 619 Krause, G.H., Weis, E., 1991. Chlorophyll Fluorescence and Photosynthesis: The
 620 Basics. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* 42, 313–349.
 621 doi:10.1146/annurev.pp.42.060191.001525
 622 LaJeunesse, T.C., Parkinson, J.E., Gabrielson, P.W., Jeong, H.J., Reimer, J.D.,
 623 Voolstra, C.R., Santos, S.R., 2018. Systematic Revision of Symbiodiniaceae
 624 Highlights the Antiquity and Diversity of Coral Endosymbionts. *Curr. Biol.* 28,
 625 2570–2580.e6. doi:10.1016/J.CUB.2018.07.008
 626 Leggat, W., Seneca, F., Wasmund, K., Ukani, L., Yellowlees, D., Ainsworth, T.D.,
 627 2011. Differential Responses of the Coral Host and Their Algal Symbiont to
 628 Thermal Stress. *PLoS One* 6, e26687. doi:10.1371/journal.pone.0026687
 629 Lenz, R., Enders, K., Nielsen, T.G., 2016. Microplastic exposure studies should be
 630 environmentally realistic. *Proc. Natl. Acad. Sci. U. S. A.* 113, E4121–E4122.
 631 doi:10.1073/pnas.1606615113
 632 Lesser, M.P., 1997. Oxidative stress causes coral bleaching during exposure to
 633 elevated temperatures. *Coral Reef* 16, 187–192.
 634 Levy, O., Achituv, Y., Yacobi, Y.Z., Dubinsky, Z., Stambler, N., 2006. Diel tuning of

coral metabolism: physiological responses to light cues. *J. Exp. Biol.* 209, 273–283.
 Livingstone, D.R., 2003. Oxidative stress in aquatic organisms in relation to pollution and aquaculture. *Rev. Med. Vet. (Toulouse)*. 427–430.
 Lusher, A.L., McHugh, M., Thompson, R.C., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. *Mar. Pollut. Bull.* 67, 94–99. doi:10.1016/J.MARPOLBUL.2012.11.028
 Mass, T., Einbinder, S., Brokovich, E., Shashar, N., Vago, R., Erez, J., Dubinsky, Z., 2007. Photoacclimation of *Stylophora pistillata* to light extremes: Metabolism and calcification. *Mar. Ecol. Prog. Ser.* 334, 93–102. doi:10.3354/meps334093
 Meeker, J.D., Sathyanarayana, S., Swan, S.H., 2009. Phthalates and other additives in plastics: human exposure and associated health outcomes. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 364, 2097–113. doi:10.1098/rstb.2008.0268
 Mills, M.M., Lipschultz, F., Sebens, K.P., 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
 Mouchi, V., Chapron, L., Peru, E., Pruski, A.M., Meistertzheim, A.-L., Vétion, G., Galand, P.E., Lartaud, F., 2019. Long-term aquaria study suggests species-specific responses of two cold-water corals to macro-and microplastics exposure. *Environ. Pollut.* 253, 322–329. doi:10.1016/J.ENVPOL.2019.07.024
 Munari, C., Infantini, V., Scoponi, M., Rastelli, E., Corinaldesi, C., Mistri, M., 2017. Microplastics in the sediments of Terra Nova Bay (Ross Sea, Antarctica). *Mar. Pollut. Bull.* 122, 161–165. doi:10.1016/j.marpolbul.2017.06.039
 Murray, F., Cowie, P.R., 2011. Plastic contamination in the decapod crustacean *Nephrops norvegicus* (Linnaeus, 1758). *Mar. Pollut. Bull.* 62, 1207–1217. doi:10.1016/J.MARPOLBUL.2011.03.032
 Nie, H., Wang, J., Xu, K., Huang, Y., Yan, M., 2019. Microplastic pollution in water and fish samples around Nanxun Reef in Nansha Islands, South China Sea. *Sci. Total Environ.* 696, 134022. doi:10.1016/J.SCITOTENV.2019.134022
 Nii, C.M., Muscatine, L., 1997. Oxidative stress in the symbiotic sea anemone *Aiptasia pulchella* (Carlgren, 1943): Contribution of the animal to superoxide ion production at elevated temperature. *Biol. Bull.* 192, 444–456. doi:10.2307/1542753
 Oehlmann, J., Oetken, M., Schulte-Oehlmann, U., 2008. A critical evaluation of the environmental risk assessment for plasticizers in the freshwater environment in Europe, with special emphasis on bisphenol A and endocrine disruption. *Environ. Res.* 108, 140–149. doi:10.1016/j.envres.2008.07.016
 Okubo, N., Takahashi, S., Nakano, Y., 2018. Microplastics disturb the anthozoan-algae symbiotic relationship. *Mar. Pollut. Bull.* 135, 83–89. doi:10.1016/j.marpolbul.2018.07.016
 Owen, R., Knap, A., Ostrander, N., Carbery, K., 2003. Comparative Acute Toxicity of Herbicides to Photosynthesis of Coral Zooxanthellae. *Environmental Contamination and Toxicology* 54, 541–548. doi:10.1007/s00128-003-0020-6
 Paul-Pont, I., Lacroix, C., González Fernández, C., Hégaret, H., Lambert, C., Le Goïc, N., Frère, L., Cassone, A.L., Sussarellu, R., Fabioux, C., Guyomarch, J., Albertosa, M., Huvet, A., Soudant, P., 2016. Exposure of marine mussels *Mytilus* spp. to polystyrene microplastics: Toxicity and influence on fluoranthene bioaccumulation. *Environ. Pollut.* 216, 724–737. doi:10.1016/j.envpol.2016.06.039

685 PlasticsEurope (Association of Plastics Manufacturers), 2018. An analysis of
 686 European plastics production, demand and waste data. *Plast. - facts 2018* 1–57.
 687 Provencher, J.F., Bond, A.L., Mallory, M.L., 2014. Marine birds and plastic debris in
 688 Canada: a national synthesis and a way forward. *Environ. Rev.* 23, 1–13.
 689 doi:10.1139/er-2014-0039
 690 R Core Team, 2013. R: A language and environment for statistical computing. R
 691 Found. Stat. Comput. Vienna, Austria.
 692 Ralph, P.J., Gademann, R., Larkum, A.W.D., 2001. Zooxanthellae expelled from
 693 bleached corals at 33°C are photosynthetically competent. *Mar. Ecol. Prog. Ser.*
 694 220, 163–168. doi:10.3354/meps220163
 695 Reichert, J., Arnold, A.L., Hoogenboom, M.O., Schubert, P., Wilke, T., 2019. Impacts
 696 of microplastics on growth and health of hermatypic corals are species-specific.
 697 *Environ. Pollut.* 254, 113074. doi:10.1016/J.ENVPOL.2019.113074
 698 Reichert, J., Schellenberg, J., Schubert, P., Wilke, T., 2018. Responses of reef
 699 building corals to microplastic exposure. *Environ. Pollut.* 237, 955–960.
 700 doi:10.1016/j.envpol.2017.11.006
 701 Reshef, L., Koren, O., Loya, Y., Zilber-Rosenberg, I., Rosenberg, E., 2006. The
 702 Coral Probiotic Hypothesis. *Environ. Microbiol.* 8, 2068–2073.
 703 doi:10.1111/j.1462-2920.2006.01148.x
 704 Richmond, R.H., 1993. Coral reefs: preent problems and future concerns resulting
 705 from anthropogenic disturbance. *Am. Zool.* 33, 524–536.
 706 doi:10.1093/icb/33.6.524
 707 Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the
 708 abundance of plastic debris in the marine environment. *Philos. Trans. R. Soc. B*
 709 *Biol. Sci.* 364, 1999–2012. doi:10.1098/rstb.2008.0207
 710 Saliu, F., Montano, S., Garavaglia, M.G., Lasagni, M., Seveso, D., Galli, P., 2018.
 711 Microplastic and charred microplastic in the Faafu Atoll, Maldives. *Mar. Pollut.*
 712 *Bull.* 136, 464–471. doi:10.1016/J.MARPOLBUL.2018.09.023
 713 Schreiber, U., 2004. Pulse-Amplitude-Modulation (PAM) Fluorometry and Saturation
 714 Pulse Method: An Overview, in: *Chlorophyll a Fluorescence*. Springer
 715 Netherlands, Dordrecht, pp. 279–319. doi:10.1007/978-1-4020-3218-9_11
 716 Schreiber, U., Neubauer, C., Schliwa, U., 1993. PAM fluorometer based on medium-
 717 frequency pulsed Xe-flash measuring light: A highly sensitive new tool in basic
 718 and applied photosynthesis research. *Photosynth. Res.* 36, 65–72.
 719 doi:10.1007/BF00018076
 720 Setälä, O., Fleming-Lehtinen, V., Lehtiniemi, M., 2014. Ingestion and transfer of
 721 microplastics in the planktonic food web. *Environ. Pollut.* 185, 77–83.
 722 doi:10.1016/j.envpol.2013.10.013
 723 Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M.E.J., Le
 724 Goïc, N., Quillien, V., Mingant, C., Epelboin, Y., Corporeau, C., Guyomarch, J.,
 725 Robbens, J., Paul-Pont, I., Soudant, P., Huvet, A., 2016. Oyster reproduction is
 726 affected by exposure to polystyrene microplastics. *Proc. Natl. Acad. Sci. U. S. A.*
 727 113, 2430–5. doi:10.1073/pnas.1519019113
 728 Takahashi, S., Murata, N., 2008. How do environmental stresses accelerate
 729 photoinhibition? *Trends Plant Sci.* 13, 178–182.
 730 doi:10.1016/j.tplants.2008.01.005
 731 Talsness, C., 2009. Components of plastic: experimental studies in animals and
 732 relevance for human health. *Philos. Trans. R. Soc. B Biol. Sci.* 364, 2079–2096.
 733 Tang, J., Ni, X., Zhou, Z., Wang, L., Lin, S., 2018. Acute microplastic exposure
 734 raises stress response and suppresses detoxification and immune capacities in

735 the scleractinian coral *Pocillopora damicornis*. *Environ. Pollut.* 243, 66–74.
 736 doi:10.1016/J.ENVPOL.2018.08.045
 737 Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G.,
 738 McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? *Science*
 739 304, 838. doi:10.1126/science.1094559
 740 Walker, T.R., 2018. Drowning in debris: Solutions for a global pervasive marine
 741 pollution problem. *Mar. Pollut. Bull.* doi:10.1016/j.marpolbul.2017.11.039
 742 Warner, M.E., Fitt, W.K., Schmidt, G.W., 1996. The effects of elevated temperature
 743 on the photosynthetic efficiency of zooxanthellae in hospite from four different
 744 species of reef coral: A novel approach. *Plant, Cell Environ.* 19, 291–299.
 745 doi:10.1111/j.1365-3040.1996.tb00251.x
 746 Weis, V.M., 2010. The susceptibility and resilience of corals to thermal stress:
 747 Adaptation, acclimatization or both?: NEWS and VIEWS. *Mol. Ecol.* 19, 1515–
 748 1517. doi:10.1111/j.1365-294X.2010.04575.x
 749 Wild, C., Huettel, M., Klutner, A., Kremb, S.G., Rasheed, M.Y.M., Jørgensen, B.B.,
 750 2004. Coral mucus functions as an energy carrier and particle trap in the reef
 751 ecosystem. *Nature* 428, 66–70. doi:10.1038/nature02344
 752 Wright, S., Galloway, Tamara Susan, Wright, S.L., Thompson, R.C., Galloway,
 753 Tamara S., 2013. The physical impacts of microplastics on marine organisms: A
 754 review Investigating microplastic contamination in coastal waters View project
 755 Tracking relevant nanomaterial transformations, exposure, uptake and effects in
 756 freshwater and soil systems View pr. *Artic. Environ. Pollut.*
 757 doi:10.1016/j.envpol.2013.02
 758
 759
 760
 761
 762