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Microplastic pollution in a rapidly changing world: Implications for remote and vulnerable marine ecosystems

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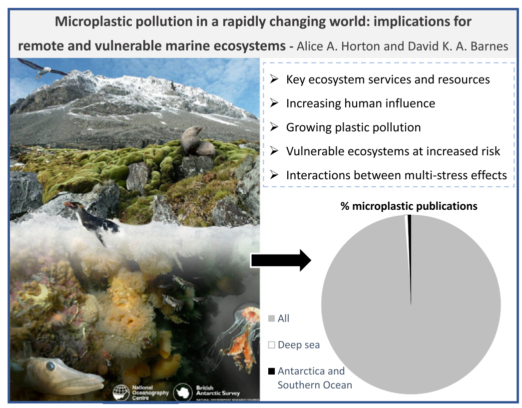
HIGHLIGHTS

- Growing human influence in remote regions is likely to magnify ecosystem impacts.
- Remote ecosystems may be more vulnerable to harm by microplastics.
- Microplastics are a complex physical, chemical and biological stressor.
- These areas provide key ecosystem services and valuable resources.
- Research should consider multi-stress impacts of microplastics with global change.

GRAPHICAL ABSTRACT



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ABSTRACT

Ecosystems in remote regions tend to be highly specific, having historically evolved over long timescales in relatively constant environmental conditions, with little human influence. Such regions are amongst those most physically altering and biologically threatened by global climate change. In addition, they are increasingly receiving anthropogenic pollution. Microplastic pollution has now been found in these most remote places on earth, far from most human activities. Microplastics can induce complex and wide-ranging physical and chemical effects but little to date is known of their long-term biological impacts. In combination with climate-induced stress, microplastics may lead to enhanced multi-stress impacts, potentially affecting the health and resilience of species and ecosystems. While species in historically populated areas have had some opportunity to adapt to mounting human influence over centuries and millennia, the relatively rapid intensification of widespread anthropogenic activities in recent decades has provided species in previously 'untouched' regions little such opportunities. The characteristics of remote ecosystems and the species therein suggest that they could be more sensitive to the combined effects of microplastic pollution, global physical change and other stressors than elsewhere. Here we discuss how species and ecosystems within two remote yet contrasting regions, coastal Antarctica and the deep sea, might be especially vulnerable to harm from microplastic pollution in the context of a rapidly changing environment.

1. Introduction

Plastic waste has become a highly abundant and growing problem across global environments, as a result of increasing plastic manufacture,

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disposal and anthropogenic activities. Microplastics (plastic particles <5 mm) in particular are highly dispersive, and have now caught both scientific and public awareness (Hale et al., 2020; Horton et al., 2017). Since the early 1970s we have been aware of the presence of microplastics within the environment (Buchanan, 1971; Carpenter and Smith, 1972). However, only in recent years have we become aware of, and begun to investigate, the geographical spread, accumulation and ecological implications of this persistent contamination (Thompson, 2015; Thompson et al., 2004). Although plastic pollution is most evident near urban centres, there is growing evidence of microplastics reaching remote and so called 'pristine' environments, including polar sea ice and snow, deep sea sediments and remote alpine regions (Allen et al., 2019; Bergmann et al., 2019; Peeken et al., 2018; Van Cauwenberghe et al., 2013).

With increasing environmental microplastic concentrations there is a higher likelihood of ecosystem exposure, and thus a higher chance of interaction, ingestion and hazardous effects across food webs. Microplastics have the potential to impact biota in a variety of different ways. As with macroplastics and macrofauna, at this proportionally smaller scale, microplastics can lead to the entanglement and physical hindrance of organisms such as zooplankton (Ziajahromi et al., 2017). If ingested, microplastics can lead to gut blockages and thus starvation or reduced energy budgets (Cole et al., 2015; Wright et al., 2013). Further, plastics are comprised of a cocktail of different chemicals, including polymers, dyes and plasticisers, all of which may have toxic properties (Rochman et al., 2019; Zimmermann et al., 2019). Oxidative stress is a commonly observed response to microplastic exposure (Jeong et al., 2017; Qiao et al., 2019; Yu et al., 2018). In addition to chemicals, plastics can act as a vector for organism transport, which thus could introduce non-native species and disease (Kirstein et al., 2016; Reisser et al., 2014). Despite these potential effects it is important to note that, with a few exceptions (Gray and Weinstein, 2017; Jemec et al., 2016), the majority of laboratory studies have not found microplastics to be inherently toxic with acute exposure. However, it has been suggested that chronic sub-lethal harm to lower trophic organisms exposed over longer, more realistic environmental timescales, could have knock-on effects for ecosystems, potentially leading to trophic cascades (Botterell et al., 2019; Galloway et al., 2017). It is further worth noting that such analyses are often based on species and ecosystems that may be considered adaptable or geographically widespread, such as those along temperate coasts.

To date, studies within remote regions have mainly focussed on identifying the abundance, sources and accumulation patterns of microplastics, although studies do exist which have found microplastics throughout remote food webs (Barnes et al., 2018; Jones-Williams et al., 2020; Sfriso et al., 2020). The implications for which trophic levels, ecological guilds, functional traits or taxa (e.g. species) are most sensitive within ecosystems, or why, are not well understood. Are there reasons to consider that isolated and remote ecosystems may be particularly sensitive to microplastic pollution? Unlike elsewhere, remote biota may be mainly native (i.e. have fewer non-indigenous species), endemic, and species considered representative of Vulnerable Marine Ecosystems (VMEs), but are typically poorly known. For example, of >1000 marine species recorded from the mid ocean archipelago of the South Orkney Islands, all are native, more than half endemic to the Southern Ocean, and many are VMEs (Barnes et al., 2009b).

Sensitive species can be defined as those which are highly specific and range-restricted, with low adaptive capability and opportunity, and are thus susceptible to local environmental changes and pollution (Pearson et al., 1983). Biome-specific and range-restricted species are the least likely to be able to adapt or migrate in the face of external environmental pressures (Malcolm et al., 2006). Within diverse communities, it is often the rare and geographically restricted species which are key to supporting ecosystem function and processes. This is due to their distinct functional traits, often complementary to other species within the community, maintaining community resilience (Mouillot et al., 2013). While examples of species that are sensitive to one or more parameters exist across all environments, a greater proportion of sensitive species within a community leads to a greater vulnerability for the local ecosystem as a whole. Vulnerability for any group of organisms can be seen as a combination of exposure, sensitivity to stress, dispersal ability, ecological resilience and resistance to stress, and adaptive capability and opportunity (which includes effective population size and distribution) (Berry et al., 2013). In some communities, the majority of species have similar individual sensitivities in the form of very narrow climate envelopes, for example in terms of temperature (Peck, 2005). Such sensitivity can be compounded if, in the same region, few taxa have high dispersal life stages, such as planktonic larvae (Peck et al., 2006). Where whole communities are highly specific, the ability of these populations to either adapt to rapid environmental changes, or to migrate to avoid unfavourable conditions is reduced, such as in the climate-stressed Southern Ocean (Morley et al., 2019). Amongst the most vulnerable ecosystems are those which are geographically remote, which until recently had little anthropogenic influence, and often contain a large number of endemic and sensitive species. Here we discuss two remote, similarly constant and cold, yet still contrasting regions: Antarctica and the deep sea. In comparison to the growing research efforts on microplastics in other environments, these regions have received little attention to date with respect to microplastic contamination (Fig. 1).

2. Coastal Antarctica and Southern Ocean Islands

Environments around Antarctica can be considered globally important in many different ways. Societally this has included harvesting (whales, seals, fish, squid and krill), tourism (which continues to increase), climate regulation (by acting as a major carbon sink for greenhouse gases) and as a key area for Earth Systems science (for example, pivotal in detection of ozone losses and sea level responses to climate change). The Southern Ocean is also the 'engine' driving global heat and oxygen distribution throughout the world's seafloor habitats, is home to the largest concentration of endemic species and provides seasonal food for a major proportion of global higher marine predators (whales, seals and seabirds) (Griffiths, 2010; Macdonald and Wunsch, 1996).

As a result of anthropogenically-induced change, polar environments are changing at an unprecedented rate, and proportionally much faster than other environments globally (Clark et al., 2015). This includes air and sea temperature rises, wind strengthening, the extent of marine ice, acidification and freshening, amongst others (Bracegirdle et al., 2008; Shadwick et al., 2013). Physical change around the polar regions to date has been extremely complex in both time and space, especially in the Southern Ocean. Most obvious around Antarctica has been drastic reductions in marine ice, in terms of glacier retreat, ice shelf disintegration and, most recently, seasonal sea ice losses (Parkinson, 2019). A growing research presence and tourism industry also mean that direct anthropogenic impacts are increasing, in the form of a growing number of visitors, permanent or temporary structures, pollution and vectors for non-indigenous species (Hughes et al., 2020). Plastics are yet another of these diverse recent polar stressors.

It is clear that microplastics are present within Antarctica, both in coastal waters and sediments. The fronts of the Antarctic Circumpolar Current (ACC) form a strong, but not impermeable, barrier (Clarke et al., 2005). A study of sea surface water around Antarctica found that concentrations of floating plastics were an order of magnitude higher in samples north of the Subtropical Front (STF) compared to those taken south of the STF. This result thus suggests that the STF prevents a large proportion of floating plastic particles from reaching the Southern Ocean (Suaria et al., 2020). Microplastic pollution has nonetheless been detected at various locations around the Antarctic continent, at comparable concentrations to those found in marine and coastal environments in other locations (Munari et al., 2017; Reed et al., 2018),

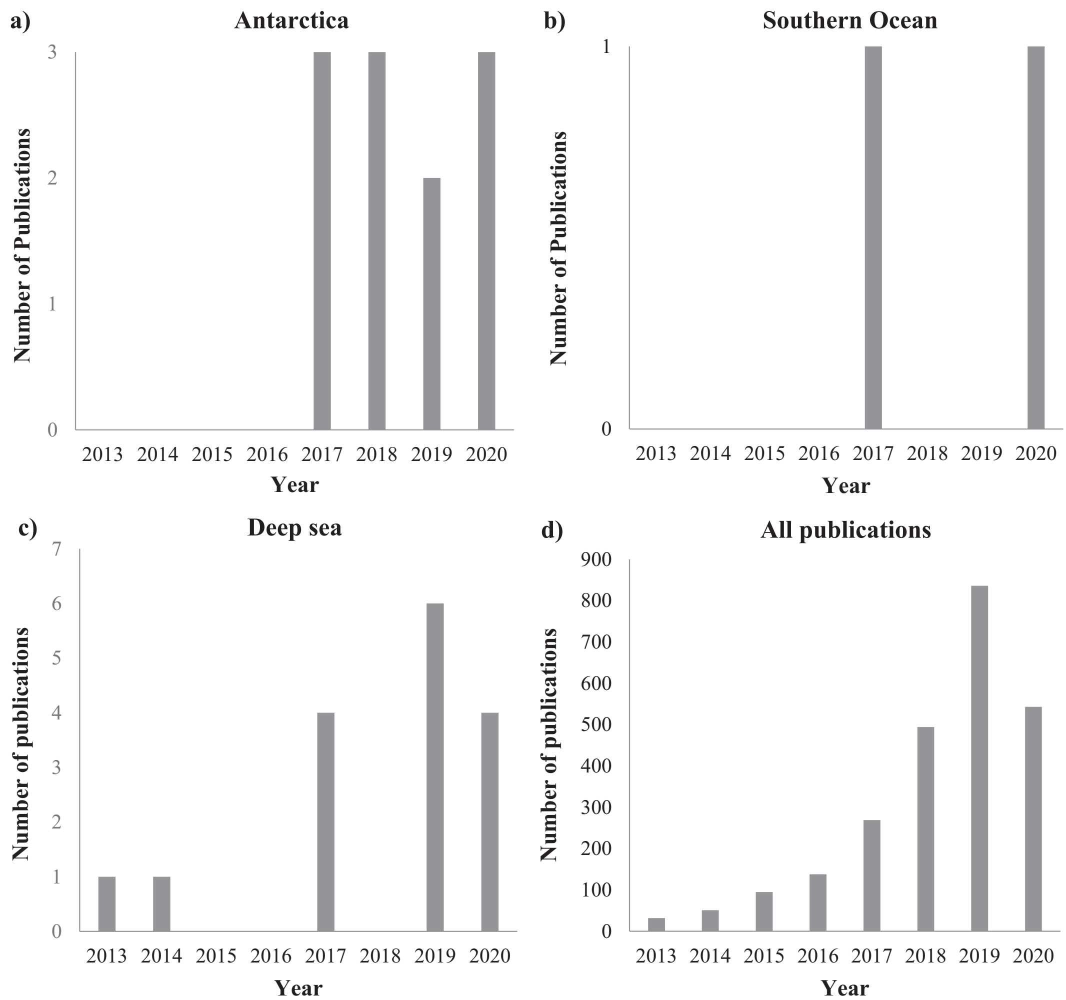

Fig. 1. Number of peer-reviewed publications on microplastics; data produced by searching on Web of Science (accessed 9th June 2020) using search by publication title for specific regions: a) Antarctica (search term '(microplastic* OR nanoplastic*) AND Antarctic*'), b) Southern Ocean (search term '(microplastic* OR nanoplastic*) AND Southern Ocean'), c) deep sea (search term '(microplastic* OR nanoplastic*) AND deep sea'), d) all publications (search term 'microplastic* OR nanoplastic*'). Using these search terms there were no results for Antarctica, Southern Ocean or deep sea before 2013, therefore these dates were also selected for fig. d) as a comparison.

suggesting direct inputs to this region. The highest concentrations observed can be linked to specific areas of anthropogenic activity such as research stations, highlighting the relative importance of local sources (Reed et al., 2018). This is especially the case for wastewater input to coastal waters from ships and research stations, which is often untreated, or insufficiently treated (Hughes and Thompson, 2004; Waller et al., 2017). However, such work mainly highlights localised hotspots rather than background levels, which are equally important when considering chronic ecosystem exposure.

Recent studies showing that microplastics can be easily transported by air to remote regions indicate that diffuse transport of microplastics on air currents could act as a contributor to other remote areas, including Antarctica, although to our knowledge this remains to be investigated on this continent (Bergmann et al., 2019). In the case of macroplastics, Barnes et al. (2018) observed a clear exponential year-on-year increase in the number of items found on remote and isolated beaches throughout the South Atlantic Ocean. Potentially a slightly different trend was observed by Waluda et al. (2020) who found that in some locations number of items increased but mass decreased (which could imply that plastics have degraded and fragmented in situ), while in other locations number decreased but mass increased. This indicates a complex temporal and location-specific relationship between the mass and number of beached plastics. Plastics on beaches will ultimately fragment to smaller components, including microplastics (Fig. 2), thus contributing further to the microplastic burden in coastal sediments and waters (Barnes et al., 2009a). It has been shown that microplastics can further degrade to form nanoplastics (<1 μm) (Enfrin et al., 2020; Lambert and Wagner, 2016). Analytical limitations have thus far hindered the accurate measurement of nanoplastics within the environment, although it is recognised that these are likely to pose the greatest ecological risk. This is therefore a key area for future research (Jeong et al., 2016; Shen et al., 2019; Sjollema et al., 2016).

There are good reasons to hypothesise that Antarctic communities may be especially sensitive to microplastic pollution compared to even range-restricted members of communities elsewhere (Waller et al., 2017). These communities, as in most other remote locations, have evolved in a context of long-term environmental consistency (e.g. dark and/or cold), with little anthropogenic disturbance. Further, in Antarctica, the context of environmental change is different (Peck et al., 2006). For example, with sea temperature, a 1 °C increase in the Southern Ocean as predicted within the next 50 years (IPCC, 2014) would represent the biggest change for millions of years. North of the ACC, 1 °C changes occur over hours, even in the Arctic (Peck et al., 2006). Another contextual difference is the pace of change relative to organism lifespans. Extremely seasonal food supplies and low temperatures drive typically slow development, growth, time to reproduction and generational turnover. Antarctic species are also considered to have narrow temperature (and other condition) tolerances (Morley

Fig. 2. Drift plastics wash ashore at remote St Helena. They degrade within the environment to a variety of smaller sizes due to exposure to UV and leaching of additives, diversifying potential influence on food webs (photo credit David K. A. Barnes).

et al., 2019; Peck, 2005). With permanent human presence only established on the Antarctic mainland within the last century, organisms have had little time to adapt to the resulting rapid physical and chemical changes to their environment. One key uncertainty is the lack of knowledge about the types of habitats, the species occupying these, and the physical and genetic links between isolated communities within this region (Clark et al., 2015).

The Southern Ocean pelagic ecosystem hinges on a few key taxa, especially diatoms (e.g. *Eucampia*, *Fragilariopsis*, *Pseudonitzschia*, and *Thalassionema* spp.) and Antarctic krill (*Euphausia superba*) (Waller et al., 2017). While common and abundant throughout Southern Ocean surface waters, endemic krill are nonetheless sensitive to environmental changes (Atkinson et al., 2019; Rogers et al., 2020). Even without considering plastic exposure, krill are anticipated to be amongst the hardest-hit species in relation to changing environmental conditions, specifically ocean acidification and sea ice loss (Morley et al., 2019; Obryk et al., 2016). The latter, and raised temperatures, they will have experienced in the last interglacial (120–140 kya) but pH may approach levels not experienced for >50 million years (Orr et al., 2005; Pearson and Palmer, 1999). Krill which have been exposed experimentally to microplastics have not shown acute toxicity responses, but sublethal impacts could be important and are considered a priority for investigation (Dawson et al., 2018a). These authors subsequently observed that the gastric mill of krill can degrade ingested microplastics into nanoplastics. While in this instance the biological consequences were not investigated, nanoplastics can be translocated into tissues and thus this process may lead to greater retention and bioaccumulation, with implications for trophic transfer (Dawson et al., 2018b). Indeed within the environment, studies of gentoo penguin and King Penguin scat have found high concentrations of microplastics, inferred to be ingested via trophic transfer from krill (Bessa et al., 2019) or from fish (Le Guen et al., 2020). Antarctic benthic macroinvertebrates have also been observed to ingest microplastics, with 83% of samples containing microplastics, representing a range of species and feeding habits. Filter feeders and grazers were shown to contain the highest abundances (Sfriso et al., 2020). These studies highlight the widespread ingestion of microplastics by organisms at all levels throughout the Antarctic food web.

Other than the above detailed studies, little is known about microplastic impacts on Antarctic pelagic food webs, and even less is known about their interaction with continental shelf benthos. This environment is particularly important because this is where the vast majority of all described Antarctic species live, most of it endemics, rarities and VMEs (SCAR-Marine Biodiversity Information Network). With growing anthropogenic pressures, it is therefore critical that the combined effects of microplastics with other local stressors in these areas are sought to be better understood, such that mitigations, or even prevention of release, might be achieved.

3. Deep sea

Like the Southern Ocean, the deep sea is far from sight but is globally important. It is by far the largest habitat on Earth and is a major sink of dissolved greenhouse gas, methane oxidation, nutrient regeneration, fish stocks, energy reserves (oil and gas), key minerals and metals, as well a source for new pharmaceutical compounds (Thurber et al., 2014). Accessing some of these resources is highly contentious, none more so than deep seafloor mining in the high seas (i.e. beyond national Exclusive Economic Zones), which seems likely to begin on a massive scale imminently (Hylton, 2020).

The region encompassing Antarctica and the coastal Southern Ocean is highly contrasting in characteristics to the deep sea: they experience different degrees of connectivity, histories, sunlight and seasonality. However, these environments do share some parallels. For example, their biota are equally poorly known and show some similarities (e.g. absence of reptiles, rarity of durophagus predators, presence of giant arthropods and richness of polychaetes) (Moran and Woods, 2012). Despite this comparability, many of the biota are equally distinct, as the deep sea hosts few suspension feeders, nor vast zooplankton populations as found in Southern Ocean ecosystems.

Deep-sea ecosystems, here considered as >1000 m as defined by Glover and Smith (2003) are, like much of Antarctica, far from hotspots of human activity. Except for localised impacts of trawling and underwater mining or drilling, and severe incidents such as oil spills, deep sea environments are generally not subject to strong anthropogenic influences (Ahnert and Borowski, 2000; Glover and Smith, 2003). However, plastics seem to be an exception given their abundance and easily-dispersed nature, with much of the 'lost' ocean plastic (>99%) likely to have sunk away from the surface and towards the ocean depths (Egger et al., 2020; Koelmans et al., 2017). Recent studies have shown widespread evidence of macroplastic and microplastic pollution within the deep sea, with evidence to suggest that plastics can rapidly reach the deep ocean floor and have been present there for a number of decades (Chiba et al., 2018; Courtene-Jones et al., 2020; Pham et al., 2014). In fact, some plastics in the deep sea have been found fully intact decades after deposition, without evidence of mechanical, chemical or photodegradation (Krause et al., 2020). With the increasing 'plastic footprint' of human society, the persistence of plastics, and in line with observations in other environments, deep-sea plastic contamination continues to increase (Bergmann and Klages, 2012; Galgani et al., 1996). The deep sea is recognised to be a significant sink for microplastics given that if they reach sediments there, they are unlikely to resuspend and disperse elsewhere (Pohl et al., 2020; Woodall et al., 2014). In fact, some of the highest microplastic concentrations ever recorded (1.9 million particles per m^2) have been recently reported within deep-sea sediments (Kane et al., 2020). It is likely that many deep-sea hotspots of microplastics align with high biological productivity as these regions will also correspond to those with high sedimentation of organic matter (Chiba et al., 2018; Kane et al., 2020; Pohl et al., 2020).

The accumulation of microplastics within deep-sea sediments, especially corresponding with deposition of detritus, has inevitably led to benthic organism exposure and ingestion. Given that many deep-sea species are sessile, with no pelagic life stage, they are unlikely to be able to actively move from contaminated sites (Danovaro et al., 2017). Ingestion of microplastics has been shown in a number of deep-sea taxa representing a range of feeding mechanisms from detritivores to predators, suggesting that plastic is both directly and indirectly ingested (i.e. via trophic transfer) (Courtene-Jones et al., 2019; Courtene-Jones et al., 2017). Despite the increasing volumes of plastic predicted to be reaching the ocean depths, a study using historically-collected samples found that although microplastic ingestion was evident across a range of invertebrates, there was no significant variation in abundance within organisms since the 1970s, suggesting a consistent level of ingestion since then (Courtene-Jones et al., 2019). Given that concentrations within local sediment, and thus exposure, have increased over this time frame (Courtene-Jones et al., 2020), this could imply that maximum internal accumulation was achieved even at very low microplastic densities (such as in the 1970s), for example due to slow gut transit time.

The deep-sea environment is generally thought to be fairly homogenous, with >90% characterised by a muddy silty environment and low productivity, despite hosting high biodiversity (Glover and Smith, 2003). However, analysis of deep-sea benthic samples across multiple spatial scales suggests that this perceived homogeneity may be superficial and an artefact of sample paucity. Most species, genera and families are spread extremely patchily, revealing that there probably are small but considerable differences in habitat, which are very important to a 'choosy' biota there (Durden et al., 2015; Kaiser et al., 2007). Abyssal plain environments are also punctuated by 'island communities' clustered within isolated hotspots such as hydrothermal vents and submarine canyons, hosting highly specific organisms with a lower diversity, at high densities (Glover and Smith, 2003; Rogers et al., 2012). Therefore, in order to better understand deep-sea organism exposure, we need a greater understanding of the distribution and hotspots of both benthic communities and microplastics, information we are currently lacking.

As with Antarctic species, deep-sea species have adapted over millennia to specific environmental conditions: in this case dark, consistent temperatures and salinities, low food levels and high pressures, and are highly vulnerable to environmental change (Ashford et al., 2019; Danovaro et al., 2017). Deep-sea fauna are key to maintaining global biogeochemical cycling, carbon sequestration, nutrient cycling and thus primary and secondary productivity. Studies have shown that deep-sea community functioning and efficiency are exponentially linked to biodiversity, a relationship not seen in the majority of other ecosystems, highlighting that a reduction in biodiversity could have severe consequences for ecosystem functioning (Danovaro et al., 2008). Also similar to Antarctic ecosystems, deep-sea organisms within communities are characterised by slow growth and delayed and low levels of reproduction, although primarily due to limited availability of food (Glover and Smith, 2003). This low generational turnover could lead them to be less resilient and adaptable to the influx of anthropogenic contaminants including microplastics and any associated chemicals (Peck, 2011).

One species that are extremely abundant within the deep sea (and globally), yet sensitive to temperature shifts, are nematodes (*C. elegans*) (Danovaro et al., 2017). Considering they have also been shown to respond negatively to microplastic exposure with respect to health and life history (Lei et al., 2018a; Lei et al., 2018b), nematodes within the deep sea are likely to be sensitive to the combined effects of microplastics and global climate change. However, with methods only recently developing to enable analysis of the smallest microplastics <50 μm (those that would be available for ingestion by nematodes), neither interaction nor harm of nematodes has yet been reported within the environment (O'Connor et al., 2020; Song et al., 2015; Wiggin and Holland, 2019). Corals occur in both deep sea and Antarctic systems and, at least for coral species in warm waters, are known to ingest microplastics and be demonstrably negatively impacted both in terms of energy levels, growth and pathogen frequencies (Lamb et al., 2018; Reichert et al., 2019).

There have been few experimental studies on deep-sea organisms due to the extreme challenges of maintaining these organisms within a controlled laboratory setting. This is primarily due to the fact that these organisms cannot survive at the comparatively low pressures at or near the surface (Danovaro et al., 2017). It is possible to carry out in-situ experiments using experimental chambers deployed within the deep sea (e.g. Witte et al. (2003)), however these are very costly to implement and maintain. Where laboratory studies have been carried out, these usually involve microbial communities rather than invertebrates (Main et al., 2015). For deep-sea research, the difficulty of access, specimen retrieval and experimentation, coupled with interpreting the effects of multiple stressors, cannot be underestimated. Long-term monitoring may be the best indicator of change in relation to anthropogenic disturbance, although this can be difficult to attribute to a specific cause. With a comparative 'head start' on microplastic exposure research (Fig. 1) and some physical and biological similarities to the Antarctica and coastal Southern Ocean, research on how deep-sea species have been affected could help to inform future Antarctic research in this field.

4. Microplastics contribute to multi-stress impacts

Within the environment, it is rare for one anthropogenic influence or stressor to occur in isolation. Rather, stressors including warming, ocean acidification, chemical and particulate pollution (to name a few) will often co-occur as they often have a driver in common. For example, industrial or transportation activities leading to greenhouse gas emissions will often also produce microplastics (and other pollutants) as a result of these activities (Welden and Lusher, 2017). In the field of ecotoxicology, it is well-recognised that different chemicals and substances will interact to produce toxicological consequences which can vary from the expected effects of combined exposure to those substances. This may range from a chemical reducing or inhibiting the effect of another (antagonism) to a chemical disproportionately enhancing the effect of another (synergism) (Cedergreen, 2014; Jonker et al., 2005). These effects may not be limited to chemical mixtures, and such interactions have been suggested for microplastics in the presence of chemicals, or combined exposure to different types of microplastics (Pacheco et al., 2018; Ziajahromi et al., 2017). Plastics in themselves are complex composites, and so can have both physical and chemical effects. Different polymers and particle types may lead to different toxicity responses, or may have no toxic effect, and so wider conclusions on toxicity cannot be made based on exposure to one microplastic type alone (Rochman et al., 2019).

Due to the complexities of defining, handling and identifying microplastics as a pollutant, the ability to collect reliable and conclusive ecosystem-scale data from both laboratory experiments and field-based observations has thus-far been limited. For this reason, inferences have primarily been made based on individual species responses, and the possibility or likelihood of subsequent knock-on effects. In contrast, for climate stress, assemblage and community-scale effects are already being reported, with responses including life span, activity timing and duration, migration (range shift and compression), bleaching (coral reefs) and changes in species abundances and interactions (IPCC, 2014; Morley et al., 2019).

While both climate stress and microplastics may impact on similar physiological processes, their effects can be contrasting. For example, Kratina et al. (2019) highlight that increased temperatures generally lead to increased metabolism, while microplastics can reduce metabolism. This opens up questions about their interactive effects, with their research showing that combined temperature increases and microplastics led to an overall reduction in metabolism (Kratina et al., 2019). This implies that microplastics produce the dominant negative effect at higher temperatures, and that microplastic impacts can be temperature dependent. The relative importance of microplastics as a stressor, and their contribution to multi-stress impacts through interactions with other stressors, is further complicated by the variety of local species responses to the same change in a given parameter, such as temperature. Even species which are similar in terms of functional traits, guilds, trophic positions and taxonomic affinities, can respond differently to a small sea temperature increase (Ashton et al., 2017). Decreased oceanic pH (associated with increasing CO_2 concentrations) and microplastics are both associated with similar effects, including negative effects on survival, growth and reproduction (Kroeker et al., 2010). Combined effects are generally more significant than these stressors in isolation, with more significant negative effects seen at low pH and high microplastic exposure concentrations (Wang et al., 2020). These studies highlight that climate-related stressors have the potential to exacerbate the negative ecological effects of microplastics, decreasing organism resilience and thus enhancing multi-stress impacts (Fonte et al., 2016; Jaikumar et al., 2018; Kratina et al., 2019; Wang et al., 2020). However, these studies (as most do) focus on single species. What is much-needed is not only data on a greater diversity of species and communities, but also on species within assemblages or community settings (i.e. in situ), to examine microplastic effects on changing interaction strengths (e.g. altering the outcomes of competition or predation). These would help in making predictions of the combined effects of these stressors at the ecosystem scale.

In addition to direct impacts, there are indirect ways in which microplastics may affect ecosystems. For example, primary production can be affected both by climate change and microplastics, for example by altering algal growth and reproduction, or inhibiting photosynthesis (Mao et al., 2018; Sjollema et al., 2016; Wu et al., 2019; Zhang et al., 2017). This could lead to consequences for primary consumers and thus the whole trophic web (Shen et al. 2020). This may be especially significant in Antarctic waters in which most of the food web are heavily dependent on seasonal primary production. Therefore it is critical that we assess not just the effects of microplastics under currently realistic environmental conditions, but also under predicted future conditions under the current scenarios of global climatic change (Convey and Peck, 2019).

The theory of microplastics acting as a 'Trojan Horse' facilitating the bioavailability of externally-associated chemical contaminants appears to be polymer and chemical-specific and is not always well-supported (Horton et al., 2020; Horton et al., 2018; Koelmans et al., 2016). However, the plastics themselves do contain chemicals that can cause toxicity, including plasticisers and dyes (Zimmermann et al., 2019). Further, microplastics are rarely released into the environment alone. For example, where there are wastewater inputs to the environment, microplastics will be input with detergents and sewage pathogens (Ram and Kumar, 2020). Especially widely-used in Antarctica, personal protective equipment (PPE) will usually be made from synthetic polymer-based fabrics, often treated with water repellents such as per/polyfluorinated compounds (PFCs), and flame retardants such as polybrominated diphenyl ethers (PBDEs). Regardless of their binding to each other, the co-occurrence of these contaminants has implications for their toxicity. Gutt et al. (2015) and Rogers et al. (2020) both attempt to understand the implications of many simultaneous stressors on the Southern Ocean and how biota will respond, but plastic is considered little in either.

5. How to assess change?

Two of the most remote global environments are now on the frontline of rapid change. Environmental change and ecosystem responses can be assessed through a combination of two key approaches: observations vs experimental studies. Field surveys and time-series monitoring enable assessment of microplastic abundance, accumulation, fate, and organism ingestion within the natural environment, and how this is changing with time. For example, sediment cores can reveal how recently, rapidly and extensively microplastics have accumulated, but not any effect they may be having on ecosystems. Analysis of the microplastic abundance within faunal samples from habitats of different exposure histories (for example with increasing distance from retreating glaciers or human activities) could show the relative uptake by differing taxa, functional traits, ecological guilds and trophic levels. It is key that surveys are undertaken using quantitative, randomised and statistically robust sampling designs. Linking such data to other environmental variables (temperature, salinity, UV light, climate, sedimentation, productivity, and especially proximity to human activities such as research activities, tourism and resource exploitation) will aid detection of subtle, complex and interacting influences.

Experimental exposure studies can be carried out within a controlled field or laboratory setting under varying environmental conditions (e.g. different temperature, pH and light conditions). These studies allow identification of responses and underlying biological mechanisms, to enable an understanding of specific individual and community responses to microplastics. Such studies are especially valuable as they can be used to investigate responses under the different environmental conditions and additional stressors that may be encountered now or in the future, thus developing predictive capacity. However, it should be borne in mind that due to the highly-specific environments inhabited by these organisms, experimental studies may be very difficult to implement. This may be easier for Antarctic organisms where the shallower habitats close to research stations are accessible by humans and thus in situ mesocosm studies could be implemented or organisms successfully transported to an experimental facility. Deep sea environments are far less accessible and organisms much more difficult to maintain outside of their natural environment. In situ, these ecosystems could only be manipulated using remotely-operated machinery, making such research challenging and expensive. It is primarily the specific functional traits of an organism, such as metabolism, feeding ecology and morphology, that will influence its sensitivity (Baas and Kooijman, 2015; Baird and Van den Brink, 2007). Traits-based sensitivity analysis of species with comparable traits from more accessible environments may go some way to aid in the prediction and extrapolation to wider species-level effects in remote deep-sea or Antarctic ecosystems. Where possible, combining data from observational and experimental studies in these regions will enable a greater understanding of the actual exposure and interactions of individual species and communities with microplastics, and the potential for short and long-term ecosystem-scale effects.

6. Long-term implications and outlook

Despite increased societal awareness and efforts at waste reduction and remediation, in line with the increasing production and disposal of plastics, microplastic pollution is likely to increase within remote (and wider) environments for some time. A number of effective reduction and recycle campaigns are being put in place for some products, however much progress is required. Public attention (which is often brief) is spread amongst a growing diversity of serious environmental issues and for most people, making the 'right' choice must be balanced with making the easiest or most economically viable choice.

The spread, abundance and incorporation of microplastics into food webs have been widely documented, but the nature of their impact on populations, species and communities is still largely obscure. Despite the vastly different environments that they inhabit, shared characteristics of Antarctic and deep sea species (slow growth, low metabolism, low reproductive rate, reduced dispersal capabilities and sensitivity to change) mean that many species are unlikely to be able to adapt quickly and are therefore threatened by environmental change and pollution. Of course other remote environments will have different characteristics entirely, for example tropical coral reefs, which are not characterised by low temperatures, low metabolism or slow growth, but have equally specific requirements and are similarly sensitive to current climactic changes, especially with respect to temperature and pH (Hoegh-Guldberg et al., 2007). Given the increasing abundance and distribution of microplastics within the environment, this is an additional stressor that is largely being overlooked in remote environments (Fig. 1) and must be considered when assessing ecosystem resilience in our rapidly and drastically changing world.

Given the wide and growing array of serious environmental stressors, it is unlikely that microplastics are, or will be, the most significant environmental threat now or into the future. Yet, there is nonetheless evidence to suggest that the presence of microplastics alone may cause harm, or that the combination of microplastics with other environmental stressors may pose unpredictable hazards. While environmental concentrations are currently generally lower than those that cause harm to organisms, due to the persistence and continued input of plastics, concentrations are likely to continue to increase for some time into the future (Adam et al., 2019). Going forward, it is important to understand which types and forms of (micro)plastics are the most hazardous to ecosystems, and the mechanisms of harm. Linking the abundance and distribution of microplastics to human activities will aid efforts to reduce or avoid use, and thus mitigate effects. This is especially the case for remote environments where anthropogenic activities are low compared to more populated areas, but where contamination may have more significant ecological effects and thus interventions may have greater impact.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Adam, V., Yang, T., Nowack, B., 2019. Toward an ecotoxicological risk assessment of microplastics: comparison of available hazard and exposure data in freshwaters. Environ. Toxicol. Chem. 38, 436–447.

Ahnert, A., Borowski, C., 2000. Environmental risk assessment of anthropogenic activity in the deep-sea. J. Aquat. Ecosyst. Stress. Recover. 7, 299–315.

Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., Binet, S., Galop, D., 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat. Geosci. 12, 339–344.

Ashford, O.S., Kenny, A.J., Barrio Froján, C.R.S., Downie, A.-L., Horton, T., Rogers, A.D., 2019. On the influence of vulnerable marine ecosystem habitats on peracarid crustacean assemblages in the Northwest Atlantic fisheries organisation regulatory area. Front. Mar. Sci. 6.

Ashton, G.V., Morley, S.A., Barnes, D.K.A., Clark, M.S., Peck, L.S., 2017. Warming by 1°C drives species and assemblage level responses in Antarctica's marine shallows. Curr. Biol. 27, 2698–2705.e3.

Atkinson, A., Hill, S.L., Pakhomov, E.A., Siegel, V., Reiss, C.S., Loeb, V.J., Steinberg, D.K., Schmidt, K., Tarling, G.A., Gerrish, L., Sailley, S.F., 2019. Krill (*Euphausia superba*) distribution contracts southward during rapid regional warming. Nat. Clim. Chang. 9, 142–147.

Baas, J., Kooijman, S.A., 2015. Sensitivity of animals to chemical compounds links to metabolic rate. Ecotoxicology 24, 657–663.

Baird, D.J., Van den Brink, P.J., 2007. Using biological traits to predict species sensitivity to toxic substances. Ecotoxicol. Environ. Saf. 67, 296–301.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009a. Accumulation and fragmentation of plastic debris in global environments. Phil. Trans. R. Soc. B Biol. Sci. 364, 1985–1998.

Barnes, D.K.A., Kaiser, S., Griffiths, H.J., Linse, K., 2009b. Marine, intertidal, freshwater and terrestrial biodiversity of an isolated polar archipelago. J. Biogeogr. 36, 756–769.

Barnes, D.K.A., Morley, S.A., Bell, J., Brewin, P., Brigden, K., Collins, M., Glass, T., Goodall-Copestake, W.P., Henry, L., Laptikhovsky, V., Piechaud, N., Richardson, A., Rose, P., Sands, C.J., Schofield, A., Shreeve, R., Small, A., Stamford, T., Taylor, B., 2018. Marine plastics threaten giant Atlantic Marine Protected Areas. Curr. Biol. 28, R1137–R1138.

Bergmann, M., Klages, M., 2012. Increase of litter at the Arctic deep-sea observatory HAUSGARTEN. Mar. Pollut. Bull. 64, 2734–2741.

Bergmann, M., Mützel, S., Primpke, S., Tekman, M.B., Trachsel, J., Gerdts, G., 2019. White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Sci. Adv. 5, eaax1157.

Berry, P., Ogawa-Onishi, Y., McVey, A., 2013. The vulnerability of threatened species: adaptive capability and adaptation opportunity. Biology 2, 872–893.

Bessa, F., Ratcliffe, N., Otero, V., Sobral, P., Marques, J.C., Waluda, C.M., Trathan, P.N., Xavier, J.C., 2019. Microplastics in gentoo penguins from the Antarctic region. Sci. Rep. 9, 14191.

Botterell, Z.L.R., Beaumont, N., Dorrington, T., Steinke, M., Thompson, R.C., Lindeque, P.K., 2019. Bioavailability and effects of microplastics on marine zooplankton: a review. Environ. Pollut. 245, 98–110.

Bracegirdle, T.J., Connolley, W.M., Turner, J., 2008. Antarctic climate change over the twenty first century. J. Geophys. Res. Atmos. 113.

Buchanan, J., 1971. Pollution by synthetic fibres. Mar. Pollut. Bull. 2, 23.

Carpenter, E.J., Smith, K., 1972. Plastics on the Sargasso Sea surface. Science 175, 1240–1241.

Cedergreen, N., 2014. Quantifying synergy: a systematic review of mixture toxicity studies within environmental toxicology. PLoS One 9.

Chiba, S., Saito, H., Fletcher, R., Yogi, T., Kayo, M., Miyagi, S., Ogido, M., Fujikura, K., 2018. Human footprint in the abyss: 30 year records of deep-sea plastic debris. Mar. Policy 96, 204–212.

Clark, G.F., Raymond, B., Riddle, M.J., Stark, J.S., Johnston, E.L., 2015. Vulnerability of Antarctic shallow invertebrate-dominated ecosystems. Austral Ecol. 40, 482–491.

Clarke, A., Barnes, D.K.A., Hodgson, D.A., 2005. How isolated is Antarctica? Trends Ecol. Evol. 20, 1–3.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Galloway, T.S., 2015. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. Environ. Sci. Technol. 49, 1130–1137.

Convey, P., Peck, L.S., 2019. Antarctic environmental change and biological responses. Sci. Adv. 5, eaaz0888.

Courtene-Jones, W., Quinn, B., Gary, S.F., Mogg, A.O., Narayanaswamy, B.E., 2017. Microplastic pollution identified in deep-sea water and ingested by benthic invertebrates in the Rockall Trough, North Atlantic Ocean. Environ. Pollut. 231, 271–280.

Courtene-Jones, W., Quinn, B., Ewins, C., Gary, S.F., Narayanaswamy, B.E., 2019. Consistent microplastic ingestion by deep-sea invertebrates over the last four decades (1976–2015), a study from the North East Atlantic. Environ. Pollut. 244, 503–512.

Courtene-Jones, W., Quinn, B., Ewins, C., Gary, S.F., Narayanaswamy, B.E., 2020. Microplastic accumulation in deep-sea sediments from the Rockall Trough. Mar. Pollut. Bull. 154, 111092.

Danovaro, R., Gambi, C., Dell'Anno, A., Corinaldesi, C., Fraschetti, S., Vanreusel, A., Vincx, M., Gooday, A.J., 2008. Exponential decline of deep-sea ecosystem functioning linked to benthic biodiversity loss. Curr. Biol. 18, 1–8.
Danovaro, R., Corinaldesi, C., Dell'Anno, A., Snelgrove, P.V., 2017. The deep-sea under global change. Curr. Biol. 27, R461–R465.
Dawson, A., Huston, W., Kawaguchi, S., King, C., Cropp, R., Wild, S., Eisenmann, P., Townsend, K., Bengtson Nash, S., 2018a. Uptake and depuration kinetics influence microplastic bioaccumulation and toxicity in Antarctic Krill (*Euphausia superba*). Environ. Sci. Technol. 52, 3195–3201.
Dawson, A.L., Kawaguchi, S., King, C.K., Townsend, K.A., King, R., Huston, W.M., Bengtson Nash, S.M., 2018b. Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill. Nat. Commun. 9, 1001.
Durden, J.M., Bett, B.J., Jones, D.O., Huvenne, V.A., Ruhl, H.A., 2015. Abyssal hills–hidden source of increased habitat heterogeneity, benthic megafaunal biomass and diversity in the deep sea. Prog. Oceanogr. 137, 209–218.
Egger, M., Sulu-Gambari, F., Lebreton, L., 2020. First evidence of plastic fallout from the North Pacific Garbage Patch. Sci. Rep. 10, 7495.
Enfrin, M., Lee, J., Gibert, Y., Basheer, F., Kong, L., Dumée, L.F., 2020. Release of hazardous nanoplastic contaminants due to microplastics fragmentation under shear stress forces. J. Hazard. Mater. 384, 121393.
Fonte, E., Ferreira, P., Guilhermino, L., 2016. Temperature rise and microplastics interact with the toxicity of the antibiotic cefalexin to juveniles of the common goby (*Pomatoschistus microps*): post-exposure predatory behaviour, acetylcholinesterase activity and lipid peroxidation. Aquat. Toxicol. 180, 173–185.
Galgani, F., Souplet, A., Cadiou, Y., 1996. Accumulation of debris on the deep sea floor off the French Mediterranean coast. Mar. Ecol. Prog. Ser. 142, 225–234.
Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evol. 1, 116.
Glover, A.G., Smith, C.R., 2003. The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. Environ. Conserv. 30, 219–241.
Gray, A.D., Weinstein, J.E., 2017. Size- and shape-dependent effects of microplastic particles on adult daggerblade grass shrimp (*Palaemonetes pugio*). Environ. Toxicol. Chem. 36, 3074–3080.
Griffiths, H.J., 2010. Antarctic marine biodiversity–what do we know about the distribution of life in the Southern Ocean? PLoS One 5.
Gutt, J., Bertler, N., Bracegirdle, T.J., Buschmann, A., Comiso, J., Hosie, G., Isla, E., Schloss, I.R., Smith, C.R., Tournadre, J., 2015. The Southern Ocean ecosystem under multiple climate change stresses-an integrated circumpolar assessment. Glob. Chang. Biol. 21, 1434–1453.
Hale, R.C., Seeley, M.E., La Guardia, M.J., Mai, L., Zeng, E.Y., 2020. A global perspective on microplastics. J. Geophys. Res. Oceans 125, e2018JC014719.
Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., Hatziolos, M.E., 2007. Coral reefs under rapid climate change and ocean acidification. Science 318, 1737–1742.
Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., Svendsen, C., 2017. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci. Total Environ. 586, 127–141.
Horton, A.A., Vijver, M.G., Lahive, E., Spurgeon, D.J., Svendsen, C., Heutink, R., van Bodegom, P.M., Baas, J., 2018. Acute toxicity of organic pesticides to *Daphnia magna* is unchanged by co-exposure to polystyrene microplastics. Ecotoxicol. Environ. Saf. 166, 26–34.
Horton, A.A., Newbold, L.K., Palacio-Cortés, A.M., Spurgeon, D.J., Pereira, M.G., Carter, H., Gweon, H.S., Vijver, M.G., van Bodegom, P.M., da Silva, M.A.N., 2020. Accumulation of polybrominated diphenyl ethers and microbiome response in the great pond snail *Lymnaea stagnalis* with exposure to nylon (polyamide) microplastics. Ecotoxicol. Environ. Saf. 188, 109882.
Hughes, K.A., Thompson, A., 2004. Distribution of sewage pollution around a maritime Antarctic research station indicated by faecal coliforms, *Clostridium perfringens* and faecal sterol markers. Environ. Pollut. 127, 315–321.
Hughes, K.A., Pescott, O.L., Peyton, J., Adriaens, T., Cottier-Cook, E.J., Key, G., Rabitsch, W., Tricarico, E., Barnes, D.K.A., Baxter, N., Belchier, M., Blake, D., Convey, P., Dawson, W., Frohlich, D., Gardiner, L.M., González-Moreno, P., James, R., Malumphy, C., Martin, S., Martinou, A.F., Minchin, D., Monaco, A., Moore, N., Morley, S.A., Ross, K., Shanklin, J., Turvey, K., Vaughan, D., Vaux, A.G.C., Werenkraut, V., Winfield, I.J., Roy, H.E., 2020. Invasive non-native species likely to threaten biodiversity and ecosystems in the Antarctic Peninsula region. Glob. Chang. Biol. 26, 2702–2716.
Hylton, W.S., 2020. 20,000 feet under the sea: history's largest mining operation is about to begin. The Atlantic https://www.theatlantic.com/magazine/archive/2020/01/20000-feet-under-the-sea/603040/.
IPCC, 2014. Climate change 2014: synthesis report. In: Team, Core Writing, Pachauri, R.K., Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), p. 151 Geneva, Switzerland.
Jaikumar, G., Baas, J., Brun, N.R., Vijver, M.G., Bosker, T., 2018. Acute sensitivity of three Cladoceran species to different types of microplastics in combination with thermal stress. Environ. Pollut. 239, 733–740.
Jemec, A., Horvat, P., Kunej, U., Bele, M., Krzan, A., 2016. Uptake and effects of microplastic textile fibers on freshwater crustacean *Daphnia magna*. Environ. Pollut. 219, 201–209.
Jeong, C.B., Won, E.J., Kang, H.M., Lee, M.C., Hwang, D.S., Hwang, U.K., Zhou, B., Souissi, S., Lee, S.J., Lee, J.S., 2016. Microplastic size-dependent toxicity, oxidative stress induction, and p-JNK and p-p38 activation in the monogonont rotifer (*Brachionus koreanus*). Environ. Sci. Technol. 50, 8849–8857.
Jeong, C.-B., Kang, H.-M., Lee, M.-C., Kim, D.-H., Han, J., Hwang, D.-S., Souissi, S., Lee, S.-J., Shin, K.-H., Park, H.G., 2017. Adverse effects of microplastics and oxidative stress-induced MAPK/Nrf2 pathway-mediated defense mechanisms in the marine copepod *Paracyclopina nana*. Sci. Rep. 7, 1–11.
Jones-Williams, K., Galloway, T., Cole, M., Stowasser, G., Waluda, C., Manno, C., 2020. Close encounters-microplastic availability to pelagic amphipods in sub-antarctic and antarctic surface waters. Environ. Int. 140, 105792.
Jonker, M.J., Svendsen, C., Bedaux, J.J.M., Bongers, M., Kammenga, J.E., 2005. Significance testing of synergistic/antagonistic, dose level-dependent, or dose ratio-dependent effects in mixture dose-response analysis. Environ. Toxicol. Chem. 24, 2701–2713.
Kaiser, S., Barnes, D.K.A., Brandt, A., 2007. Slope and deep-sea abundance across scales: Southern ocean isopods show how complex the deep sea can be. Deep-Sea Res. II Top. Stud. Oceanogr. 54, 1776–1789.
Kane, I.A., Clare, M.A., Miramontes, E., Wogelius, R., Rothwell, J.J., Garreau, P., Pohl, F., 2020. Seafloor microplastic hotspots controlled by deep-sea circulation. Science 368 (6495), 1140–1145 eaba5899.
Kirstein, I.V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Loder, M., Gerdts, G., 2016. Dangerous hitchhikers? Evidence for potentially pathogenic *Vibrio* spp. on microplastic particles. Mar. Environ. Res. 120, 1–8.
Koelmans, A.A., Bakir, A., Burton, G.A., Janssen, C.R., 2016. Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies. Environ. Sci. Technol. 50, 3315–3326.
Koelmans, A.A., Kooi, M., Law, K.L., Van Sebille, E., 2017. All is not lost: deriving a top-down mass budget of plastic at sea. Environ. Res. Lett. 12, 114028.
Kratina, P., Watts, T.J., Green, D.S., Kordas, R.L., O'Gorman, E.J., 2019. Interactive effects of warming and microplastics on metabolism but not feeding rates of a key freshwater detritivore. Environ. Pollut. 255, 113259.
Krause, S., Molari, M., Gorb, E.V., Gorb, S.N., Kossel, E., Haeckel, M., 2020. Persistence of plastic debris and its colonization by bacterial communities after two decades on the abyssal seafloor. Sci. Rep. 10, 9484.
Kroeker, K.J., Kordas, R.L., Crim, R.N., Singh, G.G., 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecol. Lett. 13, 1419–1434.
Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., True, J.D., Kelly, L.A., Ahmad, A., Jompa, J., Harvell, C.D., 2018. Plastic waste associated with disease on coral reefs. Science 359, 460–462.
Lambert, S., Wagner, M., 2016. Characterisation of nanoplastics during the degradation of polystyrene. Chemosphere 145, 265–268.
Le Guen, C., Suaria, G., Sherley, R.B., Ryan, P.G., Aliani, S., Boehme, L., Brierley, A.S., 2020. Microplastic study reveals the presence of natural and synthetic fibres in the diet of King Penguins (*Aptenodytes patagonicus*) foraging from South Georgia. Environ. Int. 134, 105303.
Lei, L., Liu, M., Song, Y., Lu, S., Hu, J., Cao, C., Xie, B., Shi, H., He, D., 2018a. Polystyrene (nano) microplastics cause size-dependent neurotoxicity, oxidative damage and other adverse effects in *Caenorhabditis elegans*. Environ. Sci. Nano 5, 2009–2020.
Lei, L., Wu, S., Lu, S., Liu, M., Song, Y., Fu, Z., Shi, H., Raley-Susman, K.M., He, D., 2018b. Microplastic particles cause intestinal damage and other adverse effects in zebrafish *Danio rerio* and nematode *Caenorhabditis elegans*. Sci. Total Environ. 619, 1–8.
Macdonald, A.M., Wunsch, C., 1996. An estimate of global ocean circulation and heat fluxes. Nature 382, 436–439.
Main, C.E., Ruhl, H.A., Jones, D.O.B., Yool, A., Thornton, B., Mayor, D.J., 2015. Hydrocarbon contamination affects deep-sea benthic oxygen uptake and microbial community composition. Deep-Sea Res. I Oceanogr. Res. Pap. 100, 79–87.
Malcolm, J.R., Liu, C., Neilson, R.P., Hansen, L., Hannah, L., 2006. Global warming and extinctions of endemic species from biodiversity hotspots. Conserv. Biol. 20, 538–548.
Mao, Y., Ai, H., Chen, Y., Zhang, Z., Zeng, P., Kang, L., Li, W., Gu, W., He, Q., Li, H., 2018. Phytoplankton response to polystyrene microplastics: perspective from an entire growth period. Chemosphere 208, 59–68.
Moran, A.L., Woods, H.A., 2012. Why might they be giants? Towards an understanding of polar gigantism. J. Exp. Biol. 215, 1995–2002.
Morley, S.A., Barnes, D.K.A., Dunn, M.J., 2019. Predicting which species succeed in climate-forced polar seas. Front. Mar. Sci. 5, 507.
Mouillot, D., Bellwood, D.R., Baraloto, C., Chave, J., Galzin, R., Harmelin-Vivien, M., Kulbicki, M., Lavergne, S., Lavorel, S., Mouquet, N., 2013. Rare species support vulnerable functions in high-diversity ecosystems. PLoS Biol. 11.
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.
Obryk, M.K., Doran, P.T., Friedlaender, A.S., Gooseff, M.N., Li, W., Morgan-Kiss, R.M., Priscu, J.C., Schofield, O., Stammerjohn, S.E., Steinberg, D.K., Ducklow, H.W., 2016. Responses of Antarctic marine and freshwater ecosystems to changing ice conditions. Bioscience 66, 864–879.
O'Connor, J.D., Mahon, A.M., Ramsperger, A.F.R.M., Trotter, B., Redondo-Hasselerharm, P.E., Koelmans, A.A., Lally, H.T., Murphy, S., 2020. Microplastics in freshwater biota: a critical review of isolation, characterization, and assessment methods. Global Chall. 4, 1800118.
Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437, 681–686.
Pacheco, A., Martins, A., Guilhermino, L., 2018. Toxicological interactions induced by chronic exposure to gold nanoparticles and microplastics mixtures in *Daphnia magna*. Sci. Total Environ. 628–629, 474–483.
Parkinson, C.L., 2019. A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. Proc. Natl. Acad. Sci. 116, 14414–14423.
Pearson, P.N., Palmer, M.R., 1999. Middle Eocene seawater pH and atmospheric carbon dioxide concentrations. Science 284, 1824–1826.

Pearson, T., Gray, J., Johannessen, P., 1983. Objective selection of sensitive species indicative of pollution-induced change in benthic communities. 2. Data analyses. Marine ecology progress series. Oldendorf 12, 237–255.

Peck, L.S., 2005. Prospects for surviving climate change in Antarctic aquatic species. Front. Zool. 2 9.

Peck, L.S., 2011. Organisms and responses to environmental change. Mar. Genomics 4, 237–243.

Peck, L.S., Convey, P., Barnes, D.K.A., 2006. Environmental constraints on life histories in Antarctic ecosystems: tempos, timings and predictability. Biol. Rev. 81, 75–109.

Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C., Krumpen, T., Bergmann, M., Hehemann, L., Gerdts, G., 2018. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nat. Commun. 9, 1–12.

Pham, C.K., Ramirez-Llodra, E., Alt, C.H.S., Amaro, T., Bergmann, M., Canals, M., Company, J.B., Davies, J., Duineveld, G., Galgani, F., Howell, K.L., Huvenne, V.A.I., Isidro, E., Jones, D.O.B., Lastras, G., Morato, T., Gomes-Pereira, J.N., Purser, A., Stewart, H., Tojeira, I., Tubau, X., Van Rooij, D., Tyler, P.A., 2014. Marine litter distribution and density in European seas, from the shelves to deep basins. PLoS One 9, e95839.

Pohl, F., Eggenhuisen, J.T., Kane, I.A., Clare, M.A., 2020. Transport and burial of microplastics in deep-marine sediments by turbidity currents. Environ. Sci. Technol. 54 (7), 4180–4189.

Qiao, R., Sheng, C., Lu, Y., Zhang, Y., Ren, H., Lemos, B., 2019. Microplastics induce intestinal inflammation, oxidative stress, and disorders of metabolome and microbiome in zebrafish. Sci. Total Environ. 662, 246–253.

Ram, B., Kumar, M., 2020. Correlation appraisal of antibiotic resistance with fecal, metal and microplastic contamination in a tropical Indian river, lakes and sewage. npj Clean Water 3, 3.

Reed, S., Clark, M., Thompson, R., Hughes, K.A., 2018. Microplastics in marine sediments near Rothera research station, Antarctica. Mar. Pollut. Bull. 133, 460–463.

Reichert, J., Arnold, A.L., Hoogenboom, M.O., Schubert, P., Wilke, T., 2019. Impacts of microplastics on growth and health of hermatypic corals are species-specific. Environ. Pollut. 254, 113074.

Reisser, J., Shaw, J., Hallegraeff, G., Proietti, M., Barnes, D.K.A., Thums, M., Wilcox, C., Hardesty, B.D., Pattiaratchi, C., 2014. Millimeter-sized marine plastics: a new pelagic habitat for microorganisms and invertebrates. PLoS One 9.

Rochman, C.M., Brookson, C., Bikker, J., Djuric, N., Earn, A., Bucci, K., Athey, S., Huntington, A., McIlwraith, H., Munno, K., 2019. Rethinking microplastics as a diverse contaminant suite. Environ. Toxicol. Chem. 38, 703–711.

Rogers, A.D., Tyler, P.A., Connelly, D.P., Copley, J.T., James, R., Larter, R.D., Linse, K., Mills, R.A., Garabato, A.N., Pancost, R.D., Pearce, D.A., Polunin, N.V.C., German, C.R., Shank, T., Boersch-Supan, P.H., Alker, B.J., Aquilina, A., Bennett, S.A., Clarke, A., Dinley, R.J.J., Graham, A.G.C., Green, D.R.H., Hawkes, J.A., Hepburn, L., Hilario, A., Huvenne, V.A.I., Marsh, L., Ramirez-Llodra, E., Reid, W.D.K., Roterman, C.N., Sweeting, C.J., Thatje, S., Zwirglmaier, K., 2012. The discovery of new deep-sea hydrothermal vent communities in the Southern Ocean and implications for biogeography. PLoS Biol. 10, e1001234.

Rogers, A.D., Frinault, B.A.V., Barnes, D.K.A., Bindoff, N.L., Downie, R., Ducklow, H.W., Friedlaender, A.S., Hart, T., Hill, S.L., Hofmann, E.E., Linse, K., McMahon, C.R., Murphy, E.J., Pakhomov, E.A., Reygondeau, G., Staniland, I.J., Wolf-Gladrow, D.A., Wright, R.M., 2020. Antarctic futures: an assessment of climate-driven changes in ecosystem structure, function, and service provisioning in the Southern Ocean. Annu. Rev. Mar. Sci. 12, 87–120.

SCAR-Marine Biodiversity Information Network, (SCAR-MarBIN), d. . Accessed: 29/04/2020. www.SCARMarBIN.be.

Sfriso, A.A., Tomio, Y., Rosso, B., Gambaro, A., Sfriso, A., Corami, F., Rastelli, E., Corinaldesi, C., Mistri, M., Munari, C., 2020. Microplastic accumulation in benthic invertebrates in Terra Nova Bay (Ross Sea, Antarctica). Environ. Int. 137, 105587.

Shadwick, E.H., Trull, T.W., Thomas, H., Gibson, J.A.E., 2013. Vulnerability of polar oceans to anthropogenic acidification: comparison of Arctic and Antarctic seasonal cycles. Sci. Rep. 3, 2339.

Shen, M., Zhang, Y., Zhu, Y., Song, B., Zeng, G., Hu, D., Wen, X., Ren, X., 2019. Recent advances in toxicological research of nanoplastics in the environment: a review. Environ. Pollut. 252, 511–521.

Shen, M., Ye, S., Zeng, G., Zhang, Y., Xing, L., Tang, W., Wen, X., Liu, S., 2020. Can microplastics pose a threat to ocean carbon sequestration? Mar. Pollut. Bull. 150, 110712.

Sjollema, S.B., Redondo-Hasselerharm, P., Leslie, H.A., Kraak, M.H., Vethaak, A.D., 2016. Do plastic particles affect microalgal photosynthesis and growth? Aquat. Toxicol. 170, 259–261.

Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Rani, M., Lee, J., Shim, W.J., 2015. A comparison of microscopic and spectroscopic identification methods for analysis of microplastics in environmental samples. Mar. Pollut. Bull. 93, 202–209.

Suaria, G., Perold, V., Lee, J.R., Lebouard, F., Aliani, S., Ryan, P.G., 2020. Floating macro-and microplastics around the Southern Ocean: results from the Antarctic circumnavigation expedition. Environ. Int. 136, 105494.

Thompson, R.C., 2015. Microplastics in the Marine Environment: Sources, Consequences and Solutions. Marine Anthropogenic Litter. Springer, pp. 185–200.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838.

Thurber, A.R., Sweetman, A.K., Narayanaswamy, B.E., Jones, D.O., Ingels, J., Hansman, R., 2014. Ecosystem function and services provided by the deep sea. Biogeosciences 11, 3941–3963.

Van Cauwenberghe, L., Vanreusel, A., Mees, J., Janssen, C.R., 2013. Microplastic pollution in deep-sea sediments. Environ. Pollut. 182, 495–499.

Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., Pacherres, C.O., Hughes, K.A., 2017. Microplastics in the Antarctic marine system: an emerging area of research. Sci. Total Environ. 598, 220–227.

Waluda, C.M., Staniland, I.J., Dunn, M.J., Thorpe, S.E., Grilly, E., Whitelaw, M., Hughes, K.A., 2020. Thirty years of marine debris in the Southern Ocean: annual surveys of two island shores in the Scotia Sea. Environ. Int. 136, 105460.

Wang, X., Huang, W., Wei, S., Shang, Y., Gu, H., Wu, F., Lan, Z., Hu, M., Shi, H., Wang, Y., 2020. Microplastics impair digestive performance but show little effects on antioxidant activity in mussels under low pH conditions. Environ. Pollut. 258, 113691.

Welden, N.A., Lusher, A.L., 2017. Impacts of changing ocean circulation on the distribution of marine microplastic litter. Integr. Environ. Assess. Manag. 13, 483–487.

Wiggin, K.J., Holland, E.B., 2019. Validation and application of cost and time effective methods for the detection of 3–500 μm sized microplastics in the urban marine and estuarine environments surrounding Long Beach, California. Mar. Pollut. Bull. 143, 152–162.

Witte, U., Aberle, N., Sand, M., Wenzhöfer, F., 2003. Rapid response of a deep-sea benthic community to POM enrichment: an in situ experimental study. Mar. Ecol. Prog. Ser. 251, 27–36.

Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C., 2014. The deep sea is a major sink for microplastic debris. R. Soc. Open Sci. 1, 140317.

Wright, S.L., Rowe, D., Thompson, R.C., Galloway, T.S., 2013. Microplastic ingestion decreases energy reserves in marine worms. Curr. Biol. 23, 1031–1033.

Wu, Y., Guo, P., Zhang, X., Zhang, Y., Xie, S., Deng, J., 2019. Effect of microplastics exposure on the photosynthesis system of freshwater algae. J. Hazard. Mater. 374, 219–227.

Yu, P., Liu, Z., Wu, D., Chen, M., Lv, W., Zhao, Y., 2018. Accumulation of polystyrene microplastics in juvenile *Eriocheir sinensis* and oxidative stress effects in the liver. Aquat. Toxicol. 200, 28–36.

Zhang, C., Chen, X., Wang, J., Tan, L., 2017. Toxic effects of microplastic on marine microalgae *Skeletonema costatum*: interactions between microplastic and algae. Environ. Pollut. 220, 1282–1288.

Ziajahromi, S., Kumar, A., Neale, P.A., Leusch, F.D.L., 2017. Impact of microplastic beads and fibers on waterflea (*Ceriodaphnia dubia*) survival, growth, and reproduction: implications of single and mixture exposures. Environ. Sci. Technol. 51, 13397–13406.

Zimmermann, L., Dierkes, G., Ternes, T.A., Völker, C., Wagner, M., 2019. Benchmarking the in vitro toxicity and chemical composition of plastic consumer products. Environ. Sci. Technol. 53, 11467–11477.