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The fundamental links between climate change and marine plastic pollution

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28

29 Authors' contributions

30 HVF and HJK conceived the paper. HVF drafted the manuscript with HJK and NHJ. All authors
31 contributed technical content and edited versions of the manuscript. HVF carried out Web of Science
32 search and produced the corresponding figure. NHJ produced all other figures with HVF and HJK,
33 with technical input from all authors.

34

35 **Abstract**

36 Plastic pollution and climate change have commonly been treated as two separate issues and
37 sometimes are even seen as competing. Here we present an alternative view that these two issues are
38 fundamentally linked. Primarily, we explore how plastic contributes to greenhouse gas (GHG)
39 emissions from the beginning to the end of its life cycle. Secondly, we show that more extreme
40 weather and floods associated with climate change, will exacerbate the spread of plastic in the natural
41 environment. Finally, both issues occur throughout the marine environment, and we show that
42 ecosystems and species can be particularly vulnerable to both, such as coral reefs that face disease
43 spread through plastic pollution and climate-driven increased global bleaching events. A Web of
44 Science search showed climate change and plastic pollution studies in the ocean are often siloed, with
45 only 0.4 % of the articles examining both stressors simultaneously. We also identified a lack of
46 regional and industry-specific life cycle analysis data for comparisons in relative GHG contributions
47 by materials and products. Overall, we suggest that rather than debate over the relative importance of
48 climate change or marine plastic pollution, a more productive course would be to determine the
49 linking factors between the two and identify solutions to combat both crises.

50

51 **Keywords: Greenhouse gases; Pollution; Policy; Ocean; Ecosystems**

52

53

54 **Introduction**

55 Plastic, its uses and impacts as a pollutant, are often the focus of discussion within the spheres
56 of research, media and policy; yet this is mostly approached as a separate issue from the growing
57 climate crisis. Recently the public's eagerness to help solve marine plastic pollution has intensified
58 and sparked controversy as a distraction from the greater and more pressing issue of climate change
59 (Stafford and Jones, 2019). However, plastic pollution has an equally global distribution; it is found
60 across all regions of the ocean, from shallow coastal areas to the deepest regions sampled to date and
61 in the most remote and sensitive locations on Earth (Free et al., 2014; Napper et al., 2020; Obbard et
62 al., 2014; Woodall et al., 2014). As marine plastic pollution is ubiquitous and globally irreversible, it
63 meets two of the three conditions for a chemical pollution planetary boundary threat (Villarrubia-
64 Gómez et al., 2018) that can compromise biological and anthropogenic systems and processes
65 (Beaumont et al., 2019; McIlgorm et al., 2011; Rochman et al., 2016). Climate change is a major
66 global threat, already affecting every region across the world and displaying increased ocean
67 temperatures, sea-level rise, ocean acidification, and more frequent and extreme weather events that
68 are causing widespread ecological and socio-economic harm that is predicted to intensify (IPCC,
69 2021, 2019; Ummenhofer and Meehl, 2017; Vicedo-Cabrera et al., 2021; Vitousek et al., 2017).

70 The ocean and its ecosystems and species are commonly the focus of plastic pollution studies;
71 however, most of these studies do not consider the additional impact of climate change. Here we bring
72 together evidence to show that marine plastic pollution and climate change are fundamentally linked
73 in three overarching ways. First, plastic production relies heavily on fossil fuel extraction and the
74 consumption of finite resources. The end-of-life (EOL) processes for plastic waste have differing and
75 sometimes undetermined contributions to global greenhouse gas emissions (GHG) and further, plastic
76 alternatives like bio-based plastics are set to increase in production, yet their sustainability and GHG
77 contribution is also in question. Second, climate currently influences the distribution of plastic
78 pollution and will spread further with climate-driven increased extreme weather events and flooding.
79 Third, global warming alone has demonstrable catastrophic consequences for the marine environment,

80 whilst the impacts of plastic pollution are also building evidence as being harmful to species and
81 ecosystems. The present and future impacts of the co-occurrence of both issues in marine ecosystems
82 is largely still unexplored, as they are in other systems, such as terrestrial and freshwater. Here our
83 review focuses on the more abundant marine plastic pollution literature as a focus to unpack the ways
84 in which plastic pollution and climate change are linked and offer solutions to combat both.

85

86 **1. Plastic contributes to climate change**

87 Plastics are largely derived from fossil fuels and continue to emit greenhouse gases (GHGs) at
88 each stage of their life cycle, from extraction up to and including their EOL (Zheng and Suh, 2019).
89 Plastic production increased from two million metric tons (Mt) in 1950 to an estimated 380 million
90 Mt in 2015, a compound annual growth rate of 8.4 % (Geyer et al., 2017). The demand for plastics
91 illustrates the need for cheap, lightweight materials in our day to day lives. However, global growth in
92 demand for plastics is set to continue as economies develop further. The expansion of plastic
93 production is estimated to emit over 56 billion Mt of carbon-dioxide-equivalent (CO₂e) in GHGs
94 between 2015 – 2050, which is 10 – 13 % of the entire remaining carbon budget (Hamilton et al.,
95 2019). The contribution of plastic to climate change can be categorised in three ways: 1) plastic
96 production, transport and use; 2) plastic disposal, mis-managed waste and degradation; and 3) bio-
97 based plastics.

98

99 **1.1 Production, transport and processing**

100 In 2015, the primary production of plastic emitted the equivalent of more than a billion metric
101 tons of carbon dioxide (CO₂), equal to over 3 % of global fossil fuel emissions (Geyer, 2020). In
102 comparison, agriculture contributes 10 – 15% of GHG emissions (Houser and Stuart, 2020). Plastic
103 refining is also one the most GHG expensive industries in the manufacturing sector and produced
104 184.3 – 213.0 million Mt CO₂e globally in 2015 (Hamilton et al., 2019). This is owing to the energy
105 intensive process of cracking, a petrochemical process in which saturated hydrocarbons are broken

106 down into smaller, often unsaturated, hydrocarbons known as olefins, that are then made into plastic
107 resins (Hamilton et al., 2019; Ren et al., 2006). Indirect emissions or potential savings during the
108 plastic life cycle also need to be considered (Fig. 1). For example, plastic items can enable greenhouse
109 gas (GHG) savings where their lightweight properties release lower CO₂ emissions during transport,
110 relative to other materials such as glass, wooden or metal items (Andrady and Neal, 2009; Stefanini et
111 al., 2020). The extraction phase of fossil fuels contributes to GHG emissions through indirect
112 emissions such as methane leakage, land clearance for extraction infrastructure, and the subsequent
113 transport of the fuels to refineries (Hamilton et al., 2019). The extraction and transportation of natural
114 gas for plastic production is estimated to emit 12.5 – 13.5 million Mt CO₂e in the United States alone
115 (Hamilton et al. 2019).

116

117 **1.2 Plastic disposal, mis-managed waste and degradation**

118 Life Cycle Assessments are increasingly used to evaluate environmental and economic
119 impacts of various plastic waste management systems (Bernardo et al., 2016). One such assessment
120 found that the EOL section accounts for 9 % of total GHG emissions of the entire life cycle of plastic
121 (Zheng and Suh, 2019). The EOL section, is commonly comprised of recycling, landfill and
122 incineration, which vary in the amount of GHG emissions produced. For example, the comparison
123 between incineration or landfill in terms of emissions depends on the efficiency of incineration and if
124 it is carried out with or without energy recovery in comparison with current energy grid portfolios
125 (Eriksson and Finnveden, 2009). Whilst recycling is considered more sustainable, it also faces a
126 number of challenges such as large energy requirements, costliness and can result in low-quality
127 plastics (Al-Salem et al., 2009; Denison, 1996; Rahimi and Garcíá, 2017; Shen and Worrell, 2014).
128 When using 100 % renewable energy throughout the process, recycling of plastics could allow for a
129 77 % reduction in GHG emissions from that of virgin plastic production (Zheng and Suh, 2019). Out
130 of the three main disposal options, plastic waste incineration is generally considered to have the
131 largest climate impact (Eriksson and Finnveden, 2009). In 2015, US emissions from plastic

132 incineration was 5.9 million Mt of CO₂ and these are expected to increase to 91 million Mt by 2050
133 (Hamilton et al., 2019).

134 All conventional plastic ever made is still with us on the planet, except if it has been burnt
135 (Thompson et al., 2005). Almost a third of plastic waste (32 million Mt) from 93 % of the world's
136 population was classified as mismanaged in 2010 (e.g., entering the environment in an uncontrolled
137 fashion) and is predicted reach to up to 90 million Mt/year entering aquatic systems by 2030 under
138 business as usual scenarios (Borrelle et al., 2020; Jambeck et al., 2015). Plastic degrades and
139 fragments into smaller and smaller pieces over time to eventually form microplastics (<5 mm) and
140 nanoplastics (<1000 nm) (Napper and Thompson, 2020). Research into the degradation of
141 microplastic into micro- and nano-particles is still in its infancy, however attempts to quantify and
142 extrapolate degradation rates have not been published. The amount of time a plastic item takes to
143 degrade is highly dependent on polymer and typical thickness and mass. For example, high density
144 polyethylene (HDPE) has been estimated to have a half-life of between 58 years (for a plastic bottle)
145 and 1200 years (for plastic piping) (Chamas et al., 2020). Plastic additives like nonylphenol and
146 bisphenol may leach from plastic during weathering into the environment and be taken up by marine
147 organisms (Koelmans et al., 2014). The toxicity of these chemicals can vary and has caused
148 environmental and human health concerns (Bejgarn et al., 2015; Gunaalan et al., 2020; North and
149 Halden, 2013).

150 Degradation of plastic can be further retarded if plastic reaches deeper marine environments
151 due to lower temperatures, oxygen and UV-B levels (Andrady, 2011). During degradation, both virgin
152 and aged plastic continue to emit direct and indirect GHGs indefinitely, with the most common
153 plastics emitting methane and ethylene (Royer et al., 2018). Polyethylene, accounting for 36 % of all
154 plastic types (Geyer et al., 2017), is the most prolific emitter of methane and ethylene out of a number
155 of plastics tested. Due to its relatively weaker structure and exposed hydrocarbon branches, low
156 density polyethylene (LDPE) produced more GHGs than plastics with a more compact structure (e.g
157 HDPE) (Royer et al., 2018). While plastics release GHGs in most environments, this rate of release
158 can vary. For example, LDPE releases ~76 times the amount of ethylene while incubated in air

159 compared to water (Royer et al., 2018). As plastic degrades into smaller pieces and increases with
160 greater surface-to-volume and edge length-to-volume ratios, GHG production will accelerate (Royer
161 et al., 2018).

162

163 **1.3 Bio-based plastics**

164 Increased awareness of mismanaged waste and its impact on the environment has led to a
165 growing interest in creating a circular economy for plastics and the use of alternatives to fossil fuels as
166 raw materials (Berriman, 2020; Nielsen et al., 2020). One of these pathways has been the emergence
167 of bio-based plastics as a more sustainable alternative to fossil fuel-based plastics. In 2019, the
168 contribution of bio-based plastics to global plastic production was ~ 1 %, yet this is expected to
169 increase (European Bioplastics, 2019). Bio-based plastics are made from renewable plant feedstocks
170 and offer lower GHG emissions in their overall life cycle compared to conventional plastics (Fig. 2)
171 (Zheng and Suh 2019). However, this is highly dependent on their raw materials, composition, EOL
172 management and crucially, the carbon storage potential lost from their associated land use change
173 (Hottle et al., 2013; Kakadellis and Rosetto, 2021; Piemonte and Gironi, 2011; Zheng and Suh, 2019).
174 Spierling et al. (2018) calculated a potential saving of 241 to 316 million Mt CO₂e annually by
175 substituting 65.8 % of all conventional plastics with bio-based plastics.

176 As bio-based plastics are derived from biomass, land is needed to cultivate and grow the raw
177 materials needed for manufacture. To satisfy the land requirement to replace plastics used for
178 packaging globally, 61 million ha would be needed for planting bio-based plastic feedstock, an area
179 larger than France (Brizga et al., 2020). The land required would also be damaging to biodiversity.
180 Globally, land use change has been estimated to reduce the number of species by 13.6 %, with
181 agriculture as a major driver (Newbold et al., 2015). A life cycle assessment that took land use change
182 from biofuels into consideration through GHG emission equivalents, found total emissions to be
183 comparable between plastic made from both sugarcane (biofuel) and crude oil (fossil fuel) (Liptow
184 and Tillman, 2012). However, this is a rare example where bio-based and fossil-based plastic have

185 been compared, with the global warming potential of land use change considered. Firmer guidelines
186 on the methodologies used to conduct LSAs across these various plastic products are needed to allow
187 for increased studies that can make stronger comparisons in sustainability and GHG contribution
188 (Spierling et al., 2018).

189 Bio-based plastics are not necessarily biodegradable; some are, but some only biodegrade under
190 specific industrial conditions (Geyer, 2020) (Fig. 2). In fact, the term ‘bioplastics’ is often used to
191 describe both bio-based plastic and biodegradable plastic. Napper and Thompson (2019) showed that
192 when left in the natural environment (marine, soil and outside), single use carrier bags (including those
193 of oxo-biodegradable, compostable and HDPE formulations materials), as expected, did not
194 demonstrate substantial biodegradation over a three-year period. Polylactic acid (PLA), derived from
195 renewable sources like corn-starch, only will biodegrade under industrial composting conditions,
196 however as a pollutant in the marine environment, its degradation rate is similar to that of HDPE
197 (Chamas et al., 2020). However, just because something is biodegradable, does not mean it can be
198 thrown into the environment instead of managed properly – and clearer direction for disposal of
199 biodegradable plastics is needed. For example, in Germany 63 % of consumers that disposed of
200 compostable bio-based plastic incorrectly (e.g. recycled instead of composted), while only 10 % of
201 consumers disposed of fossil fuel-based plastic packaging incorrectly (Taufik et al., 2020). To dispose
202 of bio-based plastics correctly a consumer will need an understanding of the item type, whether local
203 authorities can and will collect that material as organic for compost or as material for recycling, and its
204 suitability for home-composting or need for relocation to another facility (e.g. industrial composting).

205 Recent research shows biodegradable bio-based plastics stimulate microbial metabolism, which
206 can release CO₂ into the water column from buried carbon (Sanz-Lázaro et al., 2021). While
207 biodegradable plastics can mitigate issues related to persistence in the environment by biodegrading,
208 this biodegradation should occur under controlled conditions in a compost setting to be able to reap
209 the benefits of the compost produced. Alongside research on the impacts of traditional plastics,
210 biodegradable plastics should continue to be evaluated for their impact on our waste management
211 systems and impact on the environment.

212 The EOL management for bio-based plastics is also highly varied in the release of GHG
213 emissions depending on whether they are biodegradable, compostable or non-biodegradable, and how
214 they are managed (Hottle et al., 2017; Zheng and Suh, 2019). It is therefore important not to consider
215 bio-based plastics as a “silver bullet” solution to marine plastic pollution. Instead, a shift from a linear
216 to a life-cycle approach is needed when thinking about manufacture and design, while encouraging
217 reduced levels of consumption and waste at both individual and industrial levels.

218

219 **2. Climate change impacts plastic pollution**

220 Microplastics are now being transported through the atmosphere in a manner similar to
221 biogeochemical cycles (Brahney et al., 2021; Evangelidou et al., 2020) and can be transported over tens
222 of kilometres to near-pristine and remote areas (Allen et al., 2019). Evidence is also building of
223 interconnectedness between the freshwater, terrestrial and marine realms and are becoming
224 established as a part of the carbon cycle (Stubbins et al., 2021). For example, microplastic can be
225 transported from rivers to the ocean (Napper et al., 2021) and back onto land from the marine
226 environment via sea spray (Allen et al., 2020). Studies show that climate change will further impact
227 plastic pollution fluxes and concentrations in its global distribution. For example, Arctic sea ice is a
228 major microplastic sink, with densities of between 38 to 234 microplastic particles per cubic metre
229 (Obbard et al., 2014; Peeken et al., 2018). As sea ice volume is expected to decrease through melting
230 due to warming temperatures, microplastics will be released into the marine environment (Obbard et
231 al., 2014).

232 Climate change is already causing increased extreme weather events (Coumou and
233 Rahmstorf, 2012; IPCC, 2021, 2019), including tropical storms, which can disperse mis-managed
234 waste between terrestrial, freshwater and marine environments (Lo et al., 2020; Wang et al., 2019).
235 After a typhoon in Sanggou Bay, China, the abundance of microplastics increased within seawater
236 and sediments by as much as 40 % (Wang et al., 2019). Further inputs of terrestrial plastic into aquatic
237 environments is likely increased by stronger winds, more frequent rain events and sea level rise may

238 release plastics trapped in coastal sediments and increase the risk of flooding (Galgani et al., 2015;
239 Van Sebille et al., 2020; Welden and Lusher, 2017). Roebroek et al. (2021) demonstrated that
240 flooding of global rivers has the potential to further worsen riverine plastic pollution, with flood risk
241 areas often becoming sites with high plastic mobilisation during flooding events. Increased rainfall,
242 associated with monsoons, is estimated to increase estimated monthly river plastic inputs into the
243 ocean. Napper et al. (2021) estimated the microplastic concentration entering the Bay of Bengal from
244 the Ganges at approximately 1 billion microplastics per day during the pre-monsoon season and 3
245 billion post-monsoon season.

246

247 **3. Impacts of climate change and plastic pollutions co-occur in the marine** 248 **environment**

249 Between 4.8 - 12.7 million Mt of plastic waste was estimated to have entered the ocean in
250 2010 from coastal countries (Jambeck et al., 2015). The impacts that this plastic pollution has on the
251 marine environment has been increasingly explored in recent decades (Derraik, 2002; Thushari and
252 Senevirathna, 2020), yet there is a lack of studies that predict how this might interact with the
253 consequences of climate change to cause harm to marine organisms and ecosystems. This is clear
254 from a simple Web of Science search; we show in the last 10 years 6,327 papers addressed plastic
255 pollution in the marine environment, 45,752 papers addressed climate change in the marine
256 environment and only 208 addressed both (Fig. 3, search terms provided in Supplementary Material).
257 As both lines of research continue to develop, plastic pollution research could benefit from lessons
258 learned from climate change research to aid in establishing a stronger understanding on the current
259 status and impacts of plastic pollution urgently needed for decision-making (Fig. 3).

260 Although more pronounced in plastics studies, early climate studies often manipulated stressors
261 beyond anticipated projections, which help identify worst-case scenario impacts, but are of limited
262 relevance for understanding proximate and foreseeable climate impacts (Wernberg et al., 2012).
263 Plastic studies are commonly conducting experiments and showing lethal effects in organisms

264 subjected to much higher concentrations of microplastics than how they presently occur in natural
265 environments (Burns and Boxall, 2018).

266

267 **3.1 Marine species and ecosystems are presently vulnerable to both crises**

268 An example of a species notably vulnerable from the effects of both climate change and
269 marine plastic pollution are marine turtles. Marine turtles exhibit temperature-dependent sex
270 determination at their embryonic stage, during incubation on temperate and tropical beaches. This
271 raises concerns with regard to global warming, sea level rise and increased storminess (Patrício et al.,
272 2021). Some turtle rookeries around the world are demonstrating the effects of increasing global
273 temperatures through skewed sex ratios towards females, which threatens populations (Chatting et
274 al., 2021; Laloë et al., 2016; Marcovaldi et al., 2016). Green turtles (*Chelonia mydas*) from warmer
275 nesting beaches on the northern Great Barrier Reef, showed extremely biased sex ratios, with 99.1 %
276 of juvenile, 99.8 % of subadult, and 86.8 % of adult-sized turtles being female (Jensen et al., 2018).
277 Microplastics have the potential to increase the temperatures of incubating clutches (Beckwith, 2019).
278 However, strategies to mitigate this are being explored with promising results (Clarke et al., 2021).
279 Larger marine plastic debris threaten marine turtles through direct ingestion, which can cause
280 debilitation and death through internal injury and intestinal blockage (Nelms et al., 2016),
281 entanglement (Duncan et al., 2017), and can affect hatchling survival (Triessnig et al., 2012).
282 Although all seven species of marine turtle were demonstrated to have ingested synthetic particles at
283 concentrations higher than marine mammals (Duncan et al., 2019), the population-level impacts of
284 plastic pollution on marine turtles is still largely unknown (Senko et al., 2020).

285 Marine plastic pollution alongside climate change impacts destabilises ecosystems vulnerable
286 to climate change (Fig. 4). For example on coral reefs, coral bleaching events, resulting from global
287 warming and increasing ocean temperatures are becoming more frequent (Hughes et al., 2018a) and
288 are predicted to become annual occurrences on many reefs this century (van Hooidonk et al. 2020).
289 Coral bleaching events are causing mass coral mortality (Hughes et al., 2017; Raymundo et al., 2019;

290 Sheppard et al., 2017), species assemblages shifts (Hughes et al., 2018b; Stuart-Smith et al., 2018)
291 and numerous local species extinctions (Graham et al. 2006, Bento et al. 2016). Coral reefs are under
292 pressure from a number of threats that combined, have proven detrimental to coral reef resilience
293 (Baumann et al., 2019; Ortiz et al., 2018; Riegl et al., 2012). The extent to which climate change
294 threats to corals might be exacerbated by plastic pollution is currently unknown, yet some studies
295 have found plastic to be detrimental to coral health. Laboratory experiments have shown plastic
296 ingestion can negatively affect gamete fertilisation (Berry et al., 2019), as well as inducing other
297 species-specific responses, such as reduced growth and photosynthetic performance (Reichert et al.,
298 2019). Field studies have shown that the presence of plastic debris can increase direct physical
299 damage (Valderrama Ballesteros et al., 2018) and disease likelihood in corals (Lamb et al., 2018).
300 While the direct effects of plastic pollution to coral reefs have not been shown to compare to
301 population-scale climate-driven impacts, plastics may act as an additional stressor, particularly at
302 local scales.

303 Other vulnerable and remote environments, rarely impacted by anthropogenic pressures in the
304 past, are now under unavoidable threat from climate change and marine plastic pollution. Marine
305 Protected Areas (MPAs) are a widespread tool used to protect such environments, but are still and will
306 increasingly be impacted by plastic pollution (Burt et al., 2020; Liubartseva et al., 2019; Nelms et al.,
307 2020; Ryan and Schofield, 2020) and climate change (Andrello et al., 2015; Sheppard et al., 2017).
308 Although MPAs are ineffective in stopping the flow of plastic pollution in oceanic currents or the
309 impacts of climate change, they can be effective in mitigating climate change by protecting carbon
310 assimilation and storage habitats (Roberts et al., 2017; Sala et al., 2021).

311 Polar regions, considered a relatively pristine environment with a highly sensitive ecosystem,
312 now have substantial microplastics accumulated in sea ice and sediments and are being consumed by
313 sea bird populations (Amélineau et al., 2016; Munari et al., 2017; Obbard et al., 2014). The presence
314 of microplastic particles in these environments is an additional threat to the fragile, already climate-
315 sensitive ecosystems containing organisms with low genetic differentiation, making them particularly
316 vulnerable to environmental change (Rowlands et al., 2021). Additionally, microplastics could also

317 decrease surface albedo of the snow and ice and accelerate melting, adding to another ramification of
318 global warming (Evangelidou et al., 2020). There are also concerns for poorly known deep sea
319 ecosystems that are increasingly recognised as sinks for plastic pollution (Woodall et al., 2014), with
320 their key functions in carbon storage and nutrient cycling threatened by climate change (Sweetman et
321 al., 2017). As with many of these remote and vulnerable environments, the combined impacts are not
322 yet understood.

323 Changes to community composition, ecosystem function and even biogeochemical cycles due
324 to both climate change and marine plastic pollution are occurring on global scales, the future
325 consequences from combinations of these effects are uncertain. Range shifts and the facilitation of
326 invasive species are already a demonstrable consequence of climate change. As temperate regions
327 have become warmer, tropical species shift their ranges poleward (Bates et al., 2014; Edwards et al.,
328 2013; Vergés et al., 2019). For example, in the shallow Mediterranean Israeli shelf, non-native
329 warmer water marine mollusc species have colonised habitats to the detriment of native species and
330 formed an irreversible novel ecosystem (Albano et al., 2021). Similarly, marine plastic debris can
331 facilitate trans-oceanic travel for invasive species as debris items are commonly colonised by a
332 diverse assemblages of encrusting organisms like coralline algae, barnacles and bivalve molluscs
333 (Gregory, 2009). Marine plastic debris also hosts unique assemblages of marine microbial
334 communities known as the “Plastisphere” (Cornejo-D’Ottone et al., 2020; Zettler et al., 2013), which
335 will become more abundant with predicted increases in plastic production and mis-managed waste
336 (Borrelle et al., 2020). Increased coastal development and climate change-driven storms have
337 increased the frequency of biological rafting events, where storms can disperse colonised plastic
338 material from coasts into the open ocean (Carlton et al., 2017). Both climate change and plastic
339 pollution therefore enhance the mobility of invasive species on a global scale, which can lead to
340 altered community assemblages, native species extinctions and potentially further reaching
341 consequences.

342 The effects of both global warming and microplastics may additively impact ocean primary
343 production. Research surrounding the interactions of phytoplankton, marine microbes and marine

344 plastic pollution is in its early stages, but suggests that plastic can disrupt biogeochemical cycles like
345 the biological carbon pump, essential to maintaining the ocean's role as a carbon sink (Stoett and
346 Vince, 2019). Sjollema et al. (2016) showed that microplastics disrupt microalgal (or phytoplankton)
347 growth at very high concentrations of microplastics yet did not find significant impacts on
348 photosynthetic rates. Other experiments show an interactive effect of temperature and CO₂ on the
349 toxicity of nanoplastics to microalgae, with toxicity attenuated under simultaneous increases in CO₂
350 and temperature (Yang et al., 2020). A climate change driven decline in primary production has been
351 projected under all emissions scenarios (Couespel et al., 2021). Primary consumers, such as
352 zooplankton will be impacted by this reduction in phytoplankton, which directly relates to predicted
353 reductions in fish biomass (Couespel et al., 2021). Gove et al. (2019) showed how coastal ocean
354 surface convergence features known as bio-slicks spatially concentrate phytoplankton and
355 zooplankton, but also microplastics. Zooplankton included larval fish that ingest these non-nutritious
356 prey-sized plastics, at a time when food is critical for their survival. The projected decrease in primary
357 production because of climate change and ingestion of microplastics by higher trophic levels could
358 therefore have significant additive impacts on the productivity of marine food webs and should be a
359 focus of future research.

360

361 **3.2 Direct testing of the plastic pollution and climate change interaction**

362 Studies that have directly tested the interaction of marine plastic pollution and climate
363 change-related impacts under controlled laboratory conditions found a range of outcomes. For
364 example, Weber et al. (2020) found no interaction upon exposing mussels to temperature stress
365 combined with microplastic exposure treatments. However, individually the treatments caused
366 detrimental effects to the organism, such as thermal stress affecting energy reserves, oxidative stress,
367 and immune function (Weber et al., 2020). Wang et al. (2020) found significant inhibition of digestive
368 enzymes in mussels, upon exposure to microplastics, which was exacerbated by conditions that
369 mimicked future ocean acidification (Wang et al., 2020). Litchfield et al. (2020) found that rates of
370 decomposition of seagrass and kelp were enhanced with thermal stress conditions under various

371 climate change scenarios but were slowed with exposure to more plastic pollution, while the
372 combination of the two displayed a neutralising effect.

373 McCormick et al. (2020) is a rare example of where plastic pollution and climate change
374 interactions were tested in the field. The authors exposed juvenile fish to microplastics and observed
375 their behaviour within coral reef habitat of varying levels of degradation, expected under climate
376 change conditions. The study found that fish consuming microplastic and those experiencing habitat
377 degradation exhibited risk-prone behaviour, leading to reduced survival, with microplastic exposure
378 having the greater impact of the two (McCormick et al., 2020). Evidently, further studies that directly
379 test the interaction between climate change conditions and marine plastic pollution, both in the lab
380 and the field, are needed to explore the extent of the impact that these co-occurring conditions will
381 have at the scale of individual, population, and ecosystem scales.

382

383

384 **4. Integrated Approaches**

385 Reduced demand for virgin polymers can reduce the sector's dependency on fossil fuels,
386 prioritising reuse and recycling of polymers. Where reuse is not feasible, we should continue to
387 recycle plastic until the structural or chemical properties deteriorate (Lamberti et al., 2020). The
388 infrastructure around extraction, production and especially the EOL stages of plastics must be
389 addressed to reduce the general environmental impacts of plastic. GHG emissions from plastics could
390 be reduced through incorporating low-carbon energy throughout industrial processes during their life
391 cycle. While reducing global consumption of virgin polymers, research should continue to explore
392 whether an increase in bio-based plastic production can be done sustainably (Lamberti et al., 2020;
393 Zheng and Suh, 2019). For example, using waste biomass and forest residues to curb land-use
394 requirements has been suggested to improve GHG footprint for bio-based plastic (Lamberti et al.,
395 2020; Repo et al., 2012; Zheng and Suh, 2019). At both industrial and governmental levels greater
396 effort should be taken to minimise any leakage and/or waste at any stage of the plastic life cycle.

397 The size of the societal, economic, and commercial shift needed to avoid the worsening
398 impacts of the climate and plastic pollution crises, requires both a top-down and bottom-up approach.
399 Both global and national economies must shift to a circular economy, decoupling growth from the use
400 of finite resources. Despite the necessity of this shift, our global society has become less circular over
401 the past two years (from 9.1 % to 8.6 %; measured by divided global cycled materials with material
402 inputs) (Haigh et al., 2021). Further, re-emphasis of the importance of reducing or reusing plastic and
403 bio-based plastics is needed to reduce our reliance on single-use products. If growth in single-use
404 plastic continues, it could account for 5 to 10 % of global GHG emissions by 2050 (Charles et al.,
405 2021).

406 By finding solutions to tackle climate change, we may also help in mitigating marine plastic
407 pollution. For example, the conservation and restoration of blue carbon coastal habitats, including salt
408 marshes and seagrass meadows that support high sediment accumulation rates and are also able to
409 bury and trap plastics, whilst sequestering large amounts of carbon in their sediments (Martin et al.,
410 2020). Mangroves are an example of a blue carbon habitat efficient in the burial and retention of
411 plastic litter, where the plastic can remain undegraded for decades, and also act as a barrier against its
412 dispersal into the marine environment (Martin et al., 2020, 2019). The removal of these vital coastal
413 blue carbon habitats globally would equate to 1 Pg of CO₂ emissions annually (Duarte et al., 2013),
414 whilst also potentially losing a natural mechanism containing the spread of plastic. Although recent
415 evidence has shown marine debris can have detrimental ecological effects on these ecosystems (Giles
416 et al., 2021), the burial of plastic prevents the spread of plastic to the wider ocean and the dynamics of
417 this novel ecosystem service requires further investigation. Additionally, macroplastic can be ejected
418 out of the sea via seagrass “neptune balls”, showing another example of how these coastal habitats
419 could be key to benefitting both issues (Martin et al., 2019; Sanchez-Vidal et al., 2021).

420 Action on climate change has been compromised by uncertainty, aspects of human
421 psychology (Ross et al., 2016), and the need for acts of good global citizenship versus national
422 interest. Plastic pollution is unequivocally due to human actions, decisions and behaviour (Pahl et al.,
423 2017), with few ‘plastics deniers’ that compare to ‘climate change deniers’. Marine litter is clearly

424 visible in our coastal environments and seeing it can have a measurable negative effect on an
425 individual's wellbeing (Wyles et al., 2016). People's commitment to tackle marine plastic pollution
426 through beach cleans is associated with increased environmental awareness (Wyles et al., 2017).
427 Therefore, engagement in such activities can be a gateway to the issue of climate change. Further,
428 science-based solutions to marine conservation are often poorly documented, it is therefore important
429 to highlight marine conservation successes to inspire public action and provide exemplars to
430 conservation professionals and policy makers (Knowlton, 2021). There is considerable opportunity to
431 build on the success in mobilising action on plastic pollution for subsequent action on the impacts of
432 climate change in the ocean.

433

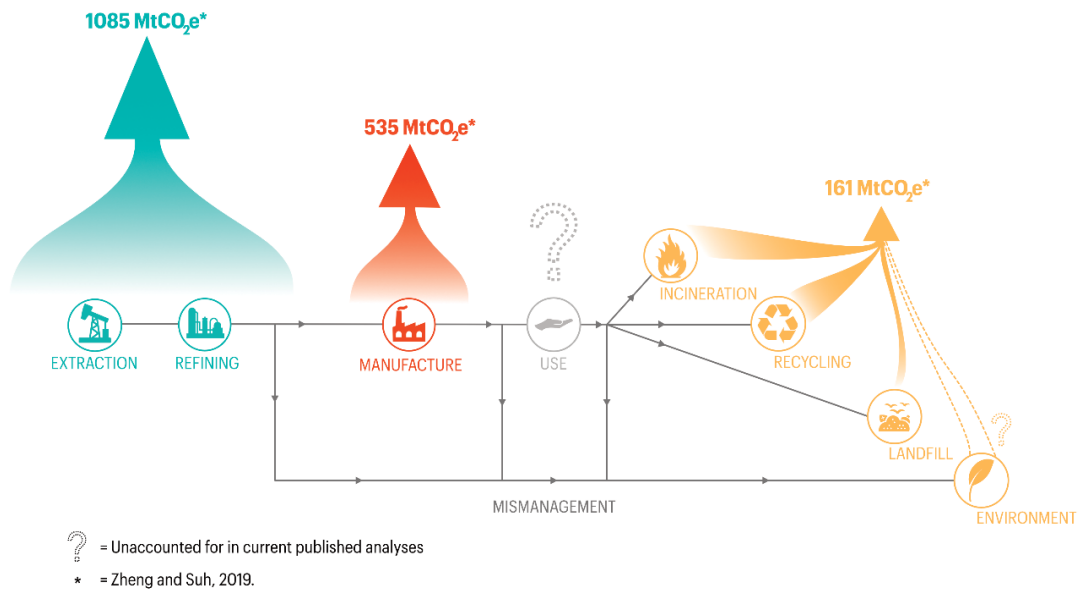
434 **Conclusion**

435 Despite being inherently linked, the plastic pollution and climate change crises are often
436 researched in isolation and even pitted against each other in competition for engagement and funding.
437 There is an increasing co-occurrence of these global issues, along with other stressors that threaten the
438 resilience of species and habitats sensitive to both climate change and plastic pollution. Further
439 research is needed to determine the mechanistic links between these two stressors, their roles in our
440 biogeochemical cycles and how both may interact to negatively impact ecosystems. Whilst we
441 acknowledge that plastic production is not the major contributor to GHG emissions and impacts are
442 largely different between the two crises, when simplified, the root cause is the same, overconsumption
443 of finite resources. A lack of region and industry-specific data is currently limiting our ability to
444 compare relative GHG contributions by materials and products. We have also emphasised that
445 approaches for each can be beneficial to both issues and lessen the overall anthropogenic strain on our
446 natural world. Solutions are undoubtedly complex, yet a coordinated effort to implement shifts
447 towards a circular economy is needed to ease current stressors on the marine environment and avoid
448 worst-case scenario environmental crises. Rather than debate whether climate change or plastic
449 pollution is of greater threat, a more productive course would be to recognise they are fundamentally
450 linked and take a systems approach to tackle both issues to synergistically reduce GHG emissions.

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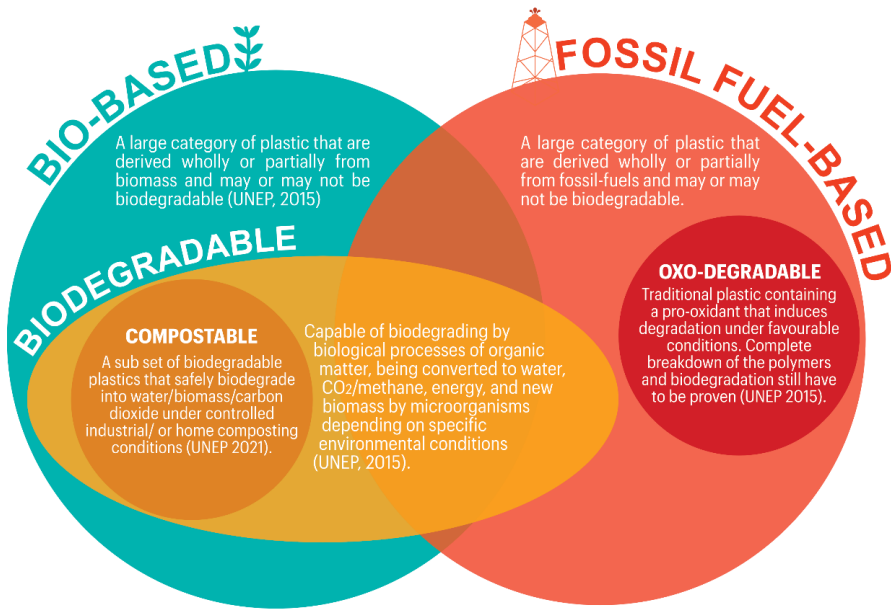
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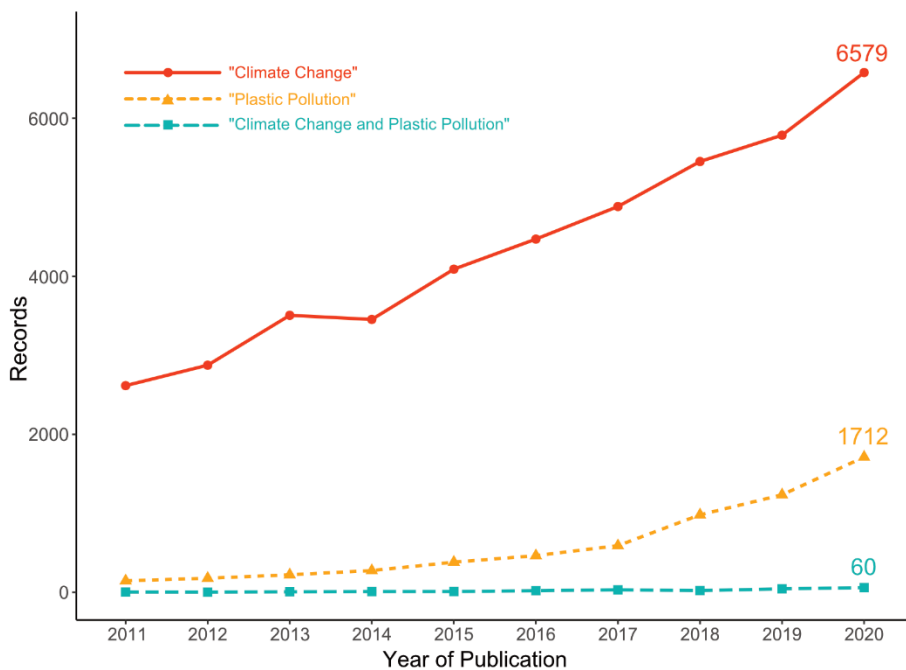
454

455 Fig. 1 The Plastic Lifecycle. Schematic representing the estimated amounts of greenhouse gases
 456 released in CO₂e at each stage of the plastic life cycle. The amount stored during use and released
 457 when plastic ends up in the natural environment is largely unknown. Data taken from Zheng and Suh
 458 (2019).



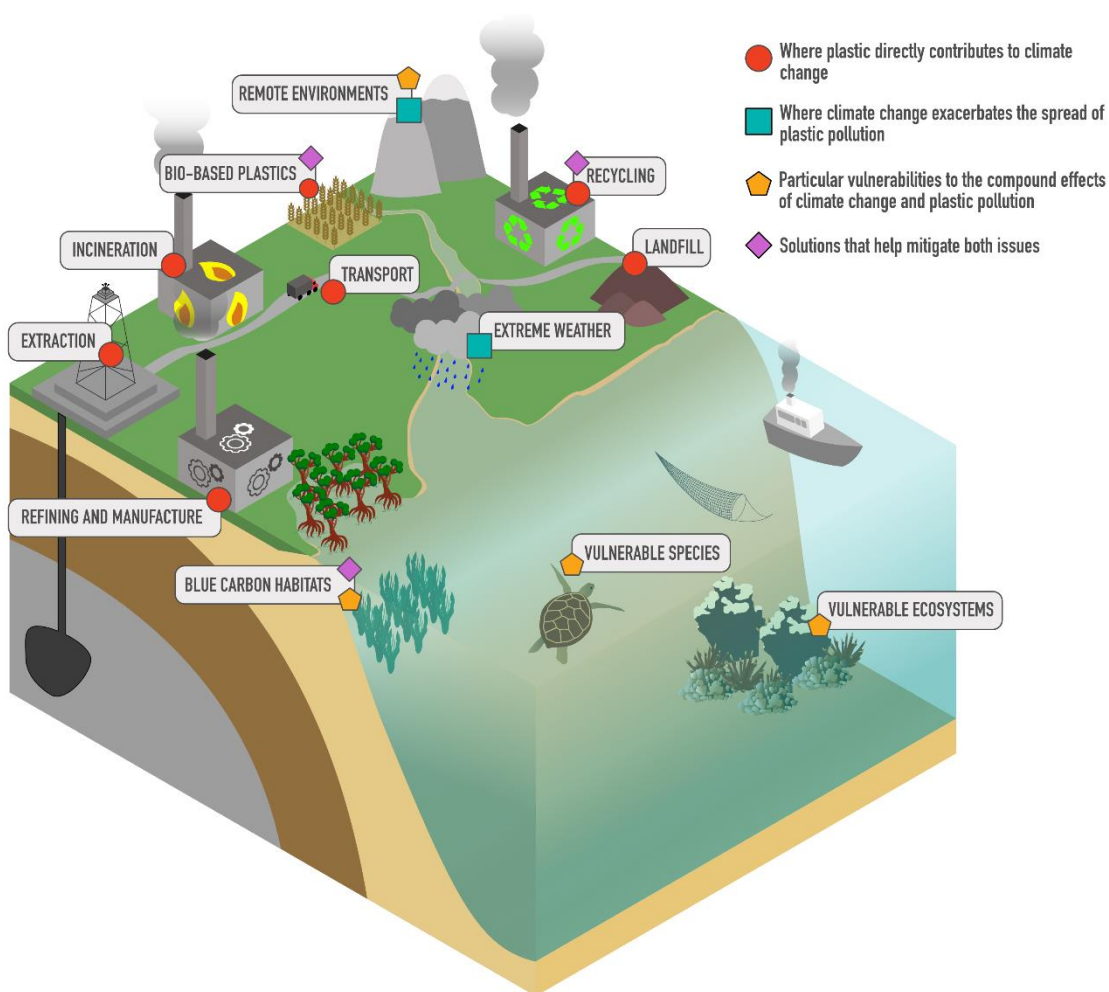
459

460 Fig. 2 Differences and biodegradability of different types of plastics. Here we show the differences
 461 between bio-based and fossil fuel-based plastics and where they overlap in terms of biodegradability.



462

463 Fig. 3 Web of Science search results. The number of records published in the years 2011-2020 that
 464 address climate change in marine systems (top), marine plastic pollution (middle) and both plastic
 465 pollution and climate change in marine systems (bottom).



466

467 Fig. 4 Interactions between plastic and climate. A schematic illustrating points that we make
 468 throughout this article, whereby plastic will affect climate change through the contribution of GHGs
 469 and interact with the impacts of climate change in the natural environment. Coloured shapes indicate
 470 how each component is connected to both plastic pollution and climate change. The various stages of
 471 plastic production from extraction to waste management contribute to GHG emissions, whilst climate
 472 change can cause extreme weather events and accelerate the spread of plastics to vulnerable and
 473 remote environments. Blue carbon habitats play an important role in sequestering carbon, but they can
 474 also bury and trap plastics, preventing further spread.

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Supplementary Material

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Table A.1 Search terms used in Web of Science database to highlight the difference between the number of publications address both plastic pollution and climate change in the marine environment and the number of publications that address either plastic pollution or climate change in the marine environment.

Group of publications	Web of Science search terms
Climate change in the marine environment	("heat stress" OR "thermal stress" OR "temperature rise" OR "acidification" OR "global change" OR "global warming" OR "climate change" OR "sea-level rise") AND ("ocean*" OR "marine" OR "sea") NOT ("plasticity" OR "evolution*")
Plastic pollution in the marine environment	("plastic" OR "plastic pollution" OR "macroplastic" OR "marine debris" OR "microplastic" OR "nanoplastic" OR "marine litter") AND ("ocean*" OR "marine" OR "sea") NOT ("plasticity" OR "evolution*")
Both climate change and plastic pollution in the marine environment	((("plastic" OR "plastic pollution" OR "macroplastic" OR "marine debris" OR "microplastic" OR "nanoplastic" OR "marine litter") AND ("heat stress" OR "thermal stress" OR "temperature rise" OR "acidification" OR "global change" OR "global warming" OR "climate change" OR "sea-level rise")) AND ("ocean*" OR "marine" OR "sea") NOT ("plasticity" OR "evolution*"))

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