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# The fundamental links between climate change and marine plastic pollution

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Authors' contributions

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

## Abstract

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

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

## Introduction

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

The ocean and its ecosystems and species are commonly the focus of plastic pollution studies; however, most of these studies do not consider the additional impact of climate change. Here we bring together evidence to show that marine plastic pollution and climate change are fundamentally linked in three overarching ways. First, plastic production relies heavily on fossil fuel extraction and the consumption of finite resources. The end-of-life (EOL) processes for plastic waste have differing and sometimes undetermined contributions to global greenhouse gas emissions (GHG) and further, plastic alternatives like bio-based plastics are set to increase in production, yet their sustainability and GHG contribution is also in question. Second, climate currently influences the distribution of plastic pollution and will spread further with climate-driven increased extreme weather events and flooding. Third, global warming alone has demonstrable catastrophic consequences for the marine environment, whilst the impacts of plastic pollution are also building evidence as being harmful to species and ecosystems. The present and future impacts of the co-occurrence of both issues in marine ecosystems is largely still unexplored, as they are in other systems, such as terrestrial and freshwater. Here our review focuses on the more abundant marine plastic pollution literature as a focus to unpack the ways in which plastic pollution and climate change are linked and offer solutions to combat both.

## 1. Plastic contributes to climate change

Plastics are largely derived from fossil fuels and continue to emit greenhouse gases (GHGs) at each stage of their life cycle, from extraction up to and including their EOL (Zheng and Suh, 2019). Plastic production increased from two million metric tons (Mt) in 1950 to an estimated 380 million Mt in 2015, a compound annual growth rate of 8.4 % (Geyer et al., 2017). The demand for plastics illustrates the need for cheap, lightweight materials in our day to day lives. However, global growth in demand for plastics is set to continue as economies develop further. The expansion of plastic production is estimated to emit over 56 billion Mt of carbon-dioxide-equivalent ($CO_2e$) in GHGs between 2015 – 2050, which is 10 – 13 % of the entire remaining carbon budget (Hamilton et al., 2019). The contribution of plastic to climate change can be categorised in three ways: 1) plastic production, transport and use; 2) plastic disposal, mis-managed waste and degradation; and 3) bio-based plastics.

### 1.1 Production, transport and processing

In 2015, the primary production of plastic emitted the equivalent of more than a billion metric tons of carbon dioxide ($CO_2$), equal to over 3 % of global fossil fuel emissions (Geyer, 2020). In comparison, agriculture contributes 10 – 15% of GHG emissions (Houser and Stuart, 2020). Plastic refining is also one the most GHG expensive industries in the manufacturing sector and produced 184.3 – 213.0 million Mt $CO_2e$ globally in 2015 (Hamilton et al., 2019). This is owing to the energy intensive process of cracking, a petrochemical process in which saturated hydrocarbons are broken down into smaller, often unsaturated, hydrocarbons known as olefins, that are then made into plastic resins (Hamilton et al., 2019; Ren et al., 2006). Indirect emissions or potential savings during the plastic life cycle also need to be considered (Fig. 1). For example, plastic items can enable greenhouse gas (GHG) savings where their lightweight properties release lower $CO_2$ emissions during transport, relative to other materials such as glass, wooden or metal items (Andrady and Neal, 2009; Stefanini et al., 2020). The extraction phase of fossil fuels contributes to GHG emissions through indirect emissions such as methane leakage, land clearance for extraction infrastructure, and the subsequent transport of the fuels to refineries (Hamilton et al., 2019). The extraction and transportation of natural gas for plastic production is estimated to emit 12.5 – 13.5 million Mt $CO_2$e in the United States alone (Hamilton et al. 2019).

## 1.2 Plastic disposal, mis-managed waste and degradation

Life Cycle Assessments are increasingly used to evaluate environmental and economic impacts of various plastic waste management systems (Bernardo et al., 2016). One such assessment found that the EOL section accounts for 9 % of total GHG emissions of the entire life cycle of plastic (Zheng and Suh, 2019). The EOL section, is commonly comprised of recycling, landfill and incineration, which vary in the amount of GHG emissions produced. For example, the comparison between incineration or landfill in terms of emissions depends on the efficiency of incineration and if it is carried out with or without energy recovery in comparison with current energy grid portfolios (Eriksson and Finnveden, 2009). Whilst recycling is considered more sustainable, it also faces a number of challenges such as large energy requirements, costliness and can result in low-quality plastics (Al-Salem et al., 2009; Denison, 1996; Rahimi and Garciá, 2017; Shen and Worrell, 2014). When using 100 % renewable energy throughout the process, recycling of plastics could allow for a 77 % reduction in GHG emissions from that of virgin plastic production (Zheng and Suh, 2019). Out of the three main disposal options, plastic waste incineration is generally considered to have the largest climate impact (Eriksson and Finnveden, 2009). In 2015, US emissions from plastic incineration was 5.9 million Mt of $CO_2$ and these are expected to increase to 91 million Mt by 2050 (Hamilton et al., 2019).

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

Degradation of plastic can be further retarded if plastic reaches deeper marine environments due to lower temperatures, oxygen and UV-B levels (Andrady, 2011). During degradation, both virgin and aged plastic continue to emit direct and indirect GHGs indefinitely, with the most common plastics emitting methane and ethylene (Royer et al., 2018). Polyethylene, accounting for 36 % of all plastic types (Geyer et al., 2017), is the most prolific emitter of methane and ethylene out of a number of plastics tested. Due to its relatively weaker structure and exposed hydrocarbon branches, low density polyethylene (LDPE) produced more GHGs than plastics with a more compact structure (e.g HDPE) (Royer et al., 2018). While plastics release GHGs in most environments, this rate of release can vary. For example, LDPE releases ~76 times the amount of ethylene while incubated in air compared to water (Royer et al., 2018). As plastic degrades into smaller pieces and increases with greater surface-to-volume and edge length-to-volume ratios, GHG production will accelerate (Royer et al., 2018).

## 1.3 Bio-based plastics

Increased awareness of mismanaged waste and its impact on the environment has led to a growing interest in creating a circular economy for plastics and the use of alternatives to fossil fuels as raw materials (Berriman, 2020; Nielsen et al., 2020). One of these pathways has been the emergence of bio-based plastics as a more sustainable alternative to fossil fuel-based plastics. In 2019, the contribution of bio-based plastics to global plastic production was ~ 1 %, yet this is expected to increase (European Bioplastics, 2019). Bio-based plastics are made from renewable plant feedstocks and offer lower GHG emissions in their overall life cycle compared to conventional plastics (Fig. 2) (Zheng and Suh 2019). However, this is highly dependent on their raw materials, composition, EOL management and crucially, the carbon storage potential lost from their associated land use change (Hottle et al., 2013; Kakadellis and Rosetto, 2021; Piemonte and Gironi, 2011; Zheng and Suh, 2019). Spierling et al. (2018) calculated a potential saving of 241 to 316 million Mt $CO_2e$ annually by substituting 65.8 % of all conventional plastics with bio-based plastics.

As bio-based plastics are derived from biomass, land is needed to cultivate and grow the raw materials needed for manufacture. To satisfy the land requirement to replace plastics used for packaging globally, 61 million ha would be needed for planting bio-based plastic feedstock, an area larger than France (Brizga et al., 2020). The land required would also be damaging to biodiversity. Globally, land use change has been estimated to reduce the number of species by 13.6 %, with agriculture as a major driver (Newbold et al., 2015). A life cycle assessment that took land use change from biofuels into consideration through GHG emission equivalents, found total emissions to be comparable between plastic made from both sugarcane (biofuel) and crude oil (fossil fuel) (Liptow and Tillman, 2012). However, this is a rare example where bio-based and fossil-based plastic have been compared, with the global warming potential of land use change considered. Firmer guidelines on the methodologies used to conduct LSAs across these various plastic products are needed to allow for increased studies that can make stronger comparisons in sustainability and GHG contribution (Spierling et al., 2018).

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

Recent research shows biodegradable bio-based plastics stimulate microbial metabolism, which can release $CO_2$ into the water column from buried carbon (Sanz-Lázaro et al., 2021). While biodegradable plastics can mitigate issues related to persistence in the environment by biodegrading, this biodegradation should occur under controlled conditions in a compost setting to be able to reap the benefits of the compost produced. Alongside research on the impacts of traditional plastics, biodegradable plastics should continue to be evaluated for their impact on our waste management systems and impact on the environment.

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

## 2. Climate change impacts plastic pollution

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

Climate change is already causing increased extreme weather events (Coumou and Rahmstorf, 2012; IPCC, 2021, 2019), including tropical storms, which can disperse mis-managed waste between terrestrial, freshwater and marine environments (Lo et al., 2020; Wang et al., 2019). After a typhoon in Sanggou Bay, China, the abundance of microplastics increased within seawater and sediments by as much as 40 % (Wang et al., 2019). Further inputs of terrestrial plastic into aquatic environments is likely increased by stronger winds, more frequent rain events and sea level rise may release plastics trapped in coastal sediments and increase the risk of flooding (Galgani et al., 2015; Van Sebille et al., 2020; Welden and Lusher, 2017). Roebroek et al. (2021) demonstrated that flooding of global rivers has the potential to further worsen riverine plastic pollution, with flood risk areas often becoming sites with high plastic mobilisation during flooding events. Increased rainfall, associated with monsoons, is estimated to increase estimated monthly river plastic inputs into the ocean. Napper et al. (2021) estimated the microplastic concentration entering the Bay of Bengal from the Ganges at approximately 1 billion microplastics per day during the pre-monsoon season and 3 billion post-monsoon season.

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

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

Although more pronounced in plastics studies, early climate studies often manipulated stressors beyond anticipated projections, which help identify worst-case scenario impacts, but are of limited relevance for understanding proximate and foreseeable climate impacts (Wernberg et al., 2012). Plastic studies are commonly conducting experiments and showing lethal effects in organisms subjected to much higher concentrations of microplastics than how they presently occur in natural environments (Burns and Boxall, 2018).

### 3.1 Marine species and ecosystems are presently vulnerable to both crises

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

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

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

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

Polar regions, considered a relatively pristine environment with a highly sensitive ecosystem, now have substantial microplastics accumulated in sea ice and sediments and are being consumed by sea bird populations (Amélineau et al., 2016; Munari et al., 2017; Obbard et al., 2014). The presence of microplastic particles in these environments is an additional threat to the fragile, already climate-sensitive ecosystems containing organisms with low genetic differentiation, making them particularly vulnerable to environmental change (Rowlands et al., 2021). Additionally, microplastics could also decrease surface albedo of the snow and ice and accelerate melting, adding to another ramification of global warming (Evangeliou et al., 2020). There are also concerns for poorly known deep sea ecosystems that are increasingly recognised as sinks for plastic pollution (Woodall et al., 2014), with their key functions in carbon storage and nutrient cycling threatened by climate change (Sweetman et al., 2017). As with many of these remote and vulnerable environments, the combined impacts are not yet understood.

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

The effects of both global warming and microplastics may additively impact ocean primary production. Research surrounding the interactions of phytoplankton, marine microbes and marine plastic pollution is in its early stages, but suggests that plastic can disrupt biogeochemical cycles like the biological carbon pump, essential to maintaining the ocean's role as a carbon sink (Stoett and Vince, 2019). Sjollema et al. (2016) showed that microplastics disrupt microalgal (or phytoplankton) growth at very high concentrations of microplastics yet did not find significant impacts on photosynthetic rates. Other experiments show an interactive effect of temperature and $CO_2$ on the toxicity of nanoplastics to microalgae, with toxicity attenuated under simultaneous increases in $CO_2$ and temperature (Yang et al., 2020). A climate change driven decline in primary production has been projected under all emissions scenarios (Couespel et al., 2021). Primary consumers, such as zooplankton will be impacted by this reduction in phytoplankton, which directly relates to predicted reductions in fish biomass (Couespel et al., 2021). Gove et al. (2019) showed how coastal ocean surface convergence features known as bio-slicks  spatially concentrate phytoplankton and zooplankton, but also microplastics. Zooplankton included larval fish that ingest these non-nutritious prey-sized plastics, at a time when food is critical for their survival. The projected decrease in primary production because of climate change and ingestion of microplastics by higher trophic levels could therefore have significant additive impacts on the productivity of marine food webs and should be a focus of future research.

### 3.2 Direct testing of the plastic pollution and climate change interaction

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

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

## 4. Integrated Approaches

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

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

By finding solutions to tackle climate change, we may also help in mitigating marine plastic pollution. For example, the conservation and restoration of blue carbon coastal habitats, including salt marshes and seagrass meadows that support high sediment accumulation rates and are also able to bury and trap plastics, whilst sequestering large amounts of carbon in their sediments (Martin et al., 2020). Mangroves are an example of a blue carbon habitat efficient in the burial and retention of plastic litter, where the plastic can remain undegraded for decades, and also act as a barrier against its dispersal into the marine environment (Martin et al., 2020, 2019). The removal of these vital coastal blue carbon habitats globally would equate to 1 Pg of $CO_2$ emissions annually (Duarte et al., 2013), whilst also potentially losing a natural mechanism containing the spread of plastic. Although recent evidence has shown marine debris can have detrimental ecological effects on these ecosystems (Giles et al., 2021), the burial of plastic prevents the spread of plastic to the wider ocean and the dynamics of this novel ecosystem service requires further investigation. Additionally, macroplastic can be ejected out of the sea via seagrass “neptune balls”, showing another example of how these coastal habitats could be key to benefitting both issues (Martin et al., 2019; Sanchez-Vidal et al., 2021).

Action on climate change has been compromised by uncertainty, aspects of human psychology (Ross et al., 2016), and the need for acts of good global citizenship versus national interest. Plastic pollution is unequivocally due to human actions, decisions and behaviour (Pahl et al., 2017), with few ‘plastics deniers’ that compare to ‘climate change deniers’. Marine litter is clearly visible in our coastal environments and seeing it can have a measurable negative effect on an individual's wellbeing (Wyles et al., 2016). People's commitment to tackle marine plastic pollution through beach cleans is associated with increased environmental awareness (Wyles et al., 2017). Therefore, engagement in such activities can be a gateway to the issue of climate change. Further, science-based solutions to marine conservation are often poorly documented, it is therefore important to highlight marine conservation successes to inspire public action and provide exemplars to conservation professionals and policy makers (Knowlton, 2021). There is considerable opportunity to build on the success in mobilising action on plastic pollution for subsequent action on the impacts of climate change in the ocean.

## Conclusion

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

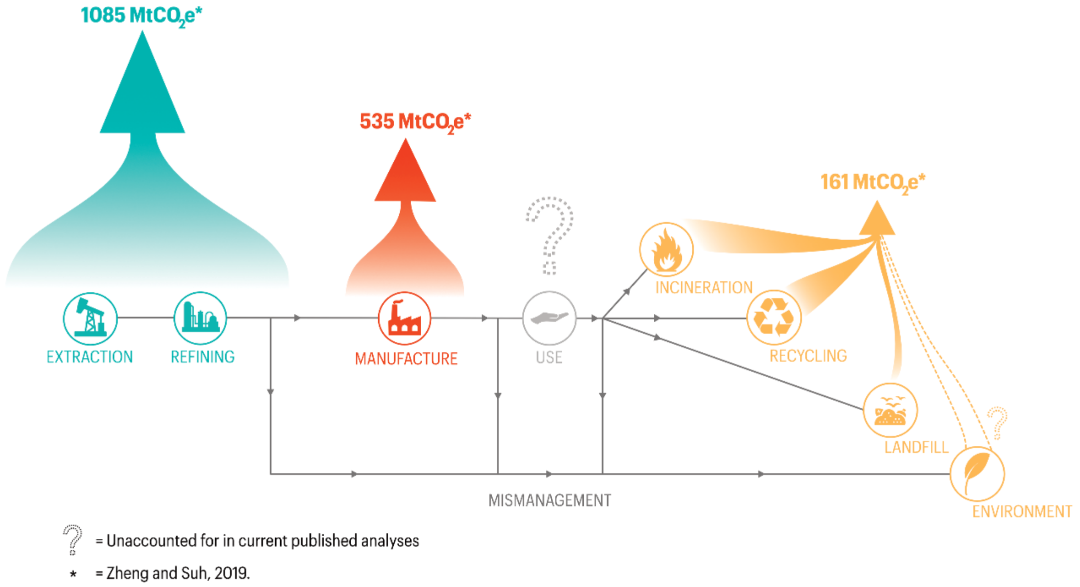

Fig. 1 The Plastic Lifecycle. Schematic representing the estimated amounts of greenhouse gases released in $CO_2$e at each stage of the plastic life cycle. The amount stored during use and released when plastic ends up in the natural environment is largely unknown. Data taken from Zheng and Suh (2019).

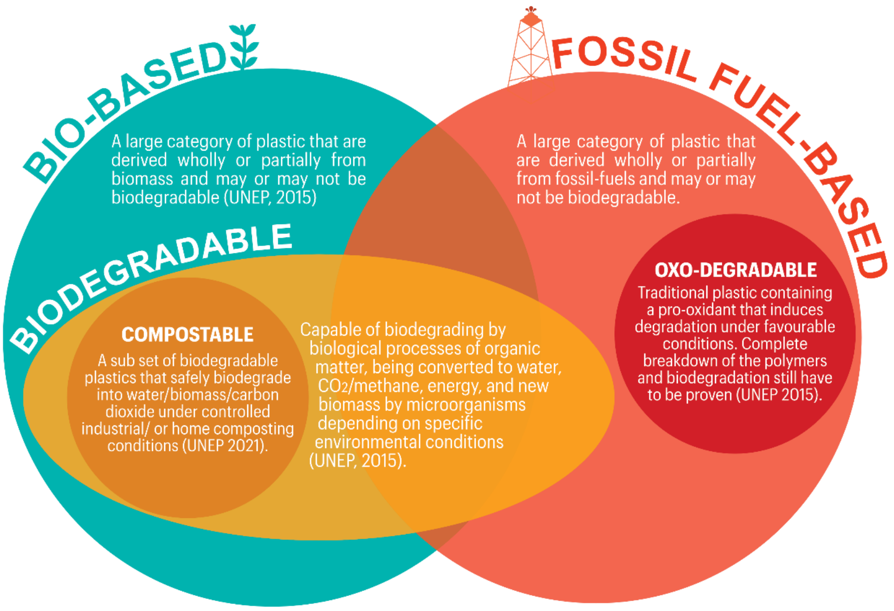

Fig. 2 Differences and biodegradability of different types of plastics. Here we show the differences between bio-based and fossil fuel-based plastics and where they overlap in terms of biodegradability.

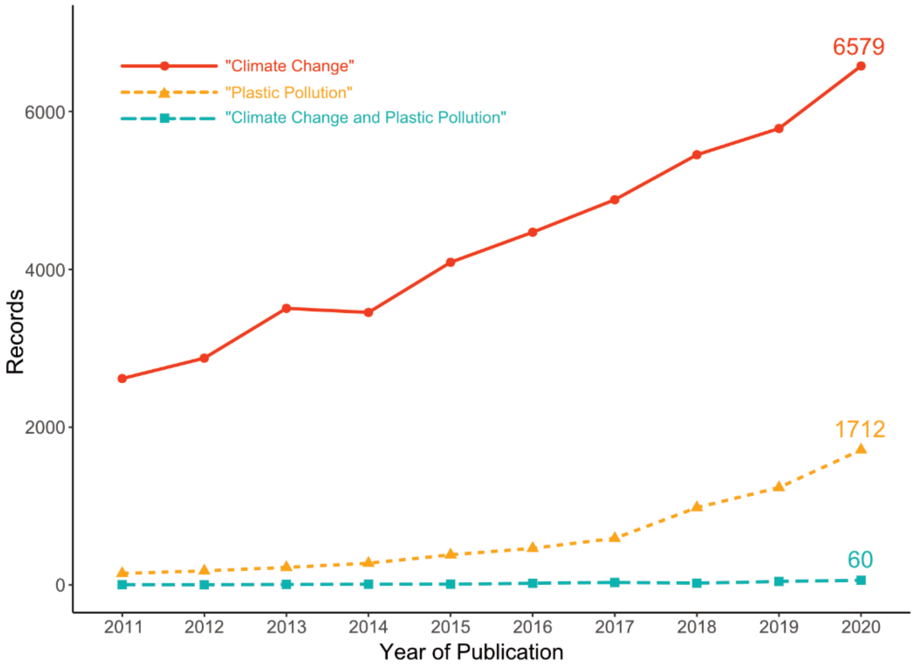

Fig. 3 Web of Science search results. The number of records published in the years 2011-2020 that address climate change in marine systems (top), marine plastic pollution (middle) and both plastic pollution and climate change in marine systems (bottom).

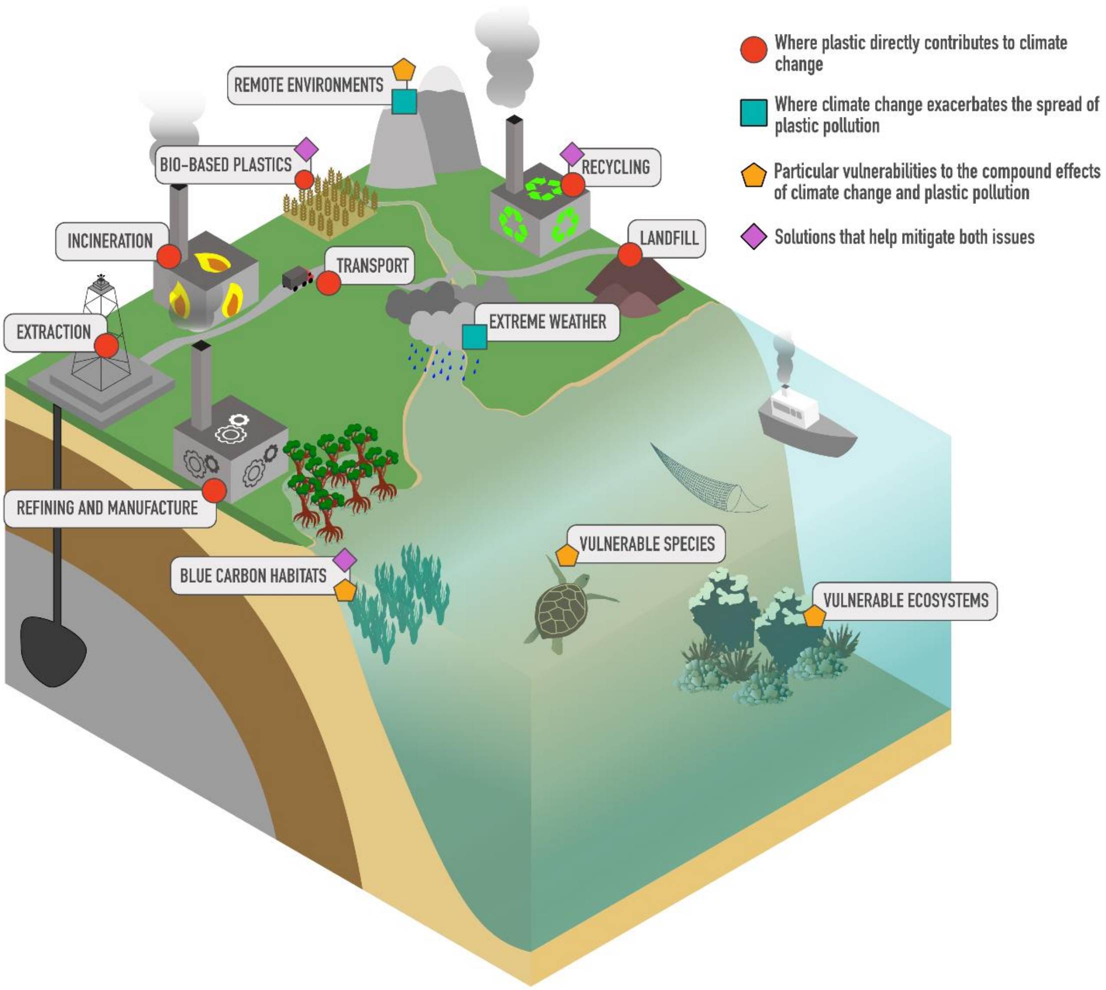

Fig. 4 Interactions between plastic and climate. A schematic illustrating points that we make throughout this article, whereby plastic will affect climate change through the contribution of GHGs and interact with the impacts of climate change in the natural environment. Coloured shapes indicate how each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

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## Supplementary Material

**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*") |