Model exploration of microplastic effects on zooplankton grazing reveal potential impacts on the global carbon cycle

Camille Richon, Thomas Gorgues, Matthew Cole, Ika Paul-Pont, Christophe Maes, Alessandro Tagliabue, Charlotte Laufkötter

To cite this version:

Camille Richon, Thomas Gorgues, Matthew Cole, Ika Paul-Pont, Christophe Maes, et al.. Model exploration of microplastic effects on zooplankton grazing reveal potential impacts on the global carbon cycle. Environmental Research Letters, 2024, 19 (7), pp.074031. 10.1088/1748-9326/ad5195 . hal-04628031

HAL Id: hal-04628031
https://hal.univ-brest.fr/hal-04628031v1

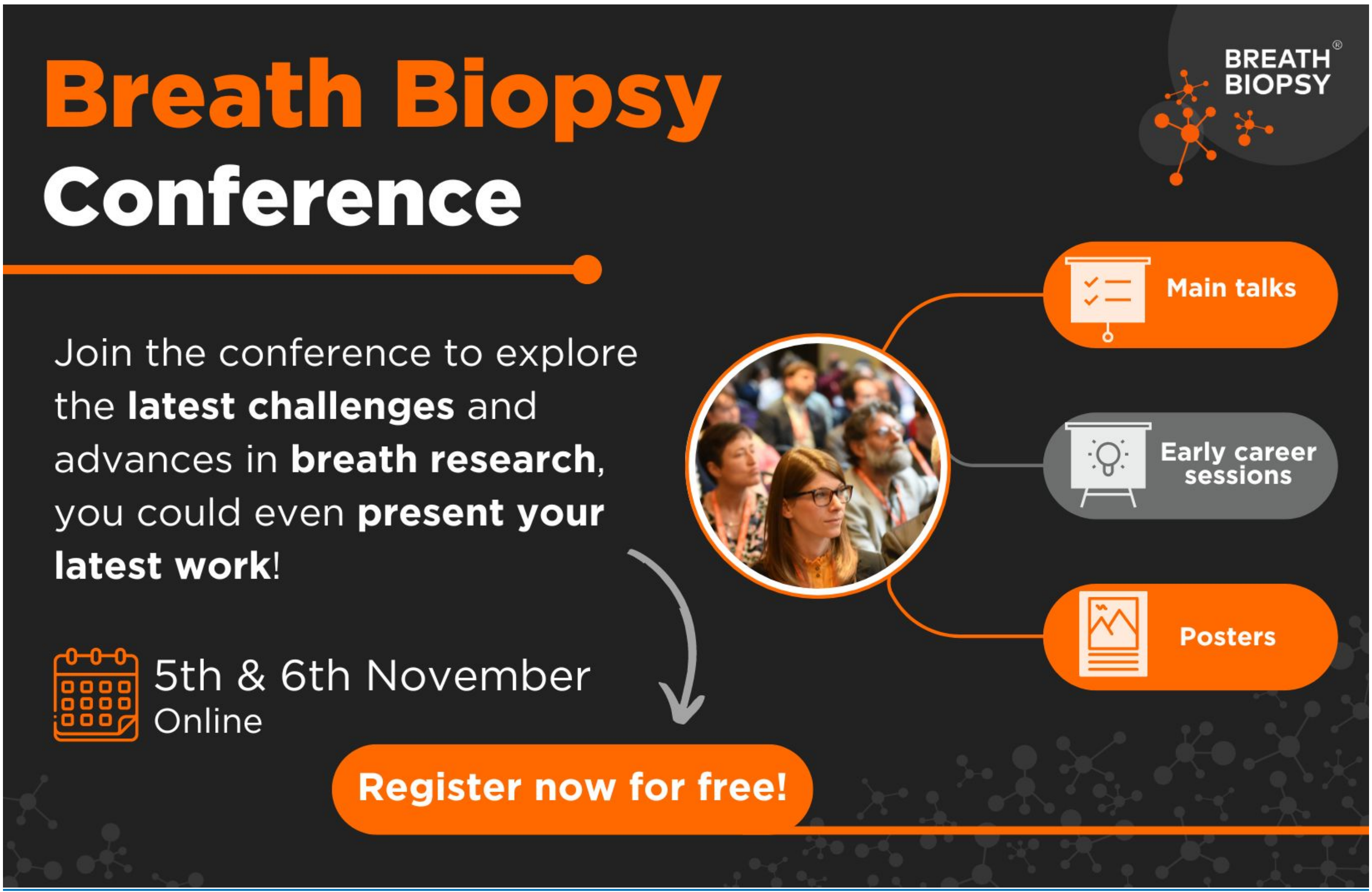
Submitted on 28 Jun 2024

ENVIRONMENTAL RESEARCH
LETTERS

LETTER • **OPEN ACCESS**

Model exploration of microplastic effects on zooplankton grazing reveal potential impacts on the global carbon cycle

To cite this article: Camille Richon *et al* 2024 *Environ. Res. Lett.* **19** 074031



IOP Publishing Environ. Res. Lett. 19 (2024) 074031 https://doi.org/10.1088/1748-9326/ad5195

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
12 September 2023

REVISED
22 May 2024

ACCEPTED FOR PUBLICATION
29 May 2024

PUBLISHED
17 June 2024

LETTER

Model exploration of microplastic effects on zooplankton grazing reveal potential impacts on the global carbon cycle

Camille Richon[1,7,*], **Thomas Gorgues**[1], **Matthew Cole**[2], **Ika Paul-Pont**[3], **Christophe Maes**[1], **Alessandro Tagliabue**[4] and **Charlotte Laufkötter**[5,6]

[1] Laboratoire d'Océanographie Physique et Spatiale, CNRS/IFREMER/IRD/UBO, Institut Universitaire Européen de la Mer, Plouzané, France
[2] Marine Ecology and Biodiversity Group, Plymouth Marine Laboratory, Plymouth PL1 3DH, United Kingdom
[3] Laboratoire des Sciences de l'Environnement Marin, CNRS/IFREMER/IRD/UBO, Institut Universitaire Européen de la Mer, Plouzané, France
[4] Department of Earth Ocean and Ecological Sciences, School of Environmental Sciences, University of Liverpool, Liverpool, United Kingdom
[5] Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland
[6] Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[7] Laboratoire d'Océanographie et du Climat: Expérimentations et Approches Numériques, Institut Pierre-Simon Laplace (LOCEAN-IPSL), Sorbonne Université, CNRS, IRD, MNHN, 75005 Paris, France
[*] Author to whom any correspondence should be addressed.

E-mail: camille.richon@univ-brest.fr

Keywords: microplastics, zooplankton, modeling, carbon cycle, ocean, grazing

Abstract

Amongst the increasing number of anthropogenic stress factors threatening ocean equilibrium, microplastics (MP; <5 mm) have emerged as particularly worrisome. *In situ* observations have shown that MP accumulate in large areas at the surface ocean where it may threaten the functioning marine species. In particular, experimental evidence has shown that the grazing rates of several zooplankton species may be significantly altered by MP. These direct impacts on zooplankton may alter nutrient and carbon cycling. However, how these laboratory results may translate into impacts on the global ocean is yet unknown. Here, we use a global coupled physical-biogeochemical model including MP (NEMO/PISCES-PLASTIC) to investigate the impacts of MP exposure on zooplankton grazing rates. Drawing from experimental results, we use varying water contamination impact thresholds to explore the biogeochemical consequences of MP impacts on short (10 years) and long timescales (100 years). Our simulations show that the geographical extent of MP impacts on zooplankton remains restricted to about 10% of the global ocean surface, even after 100 years of constant MP contamination. However, in the most contaminated regions (e.g. the sub-tropical gyres), [MP] has surged from a few $\mathrm{mg\,m^{-3}}$ to $>50\ \mathrm{mg\,m^{-3}}$. Despite their oligotrophic nature and limited contribution to the overall ocean carbon cycle, MP impacts on zooplankton grazing could disrupt carbon cycling in these highly contaminated regions (up to 50% reduction in yearly primary production, carbon export fluxes and organic matter remineralisation after 100 years). Our research suggests that persistent MP pollution in the ocean could diminish primary production by 4%. In spite of the large sensitivity of our results to the water contamination impact threshold, we suggest MP impacts on zooplankton grazing may cause an annual loss of 1 $\mathrm{Gt\,yr^{-1}}$ of exported carbon after 100 years, if MP inputs remain constant globally.

1. Introduction

Zooplankton play a crucial role in ocean ecosystems, both ecologically and biogeochemically. Zooplankton form the base of the marine food web, serving as a primary food source for many invertebrates, fish, birds and mammal species (Bertram *et al* 2001, Macias *et al* 2014). They also play an important role in controlling phytoplankton populations, thereby regulating primary productivity (Steinberg and Landry 2017, Ratnarajah *et al* 2023). Biogeochemically, zooplankton are also involved in the cycling of key macro and micronutrients (Boyd *et al* 2015, Rafter *et al* 2017, Richon *et al* 2020, Richon and Tagliabue 2021), and play a vital role in the export of particulate organic matter from the surface ocean to the deep sea, thereby influencing the global carbon cycle (Longhurst and Harrison 1988, Cavan *et al* 2015, Turner 2015, Hansen and Visser 2016). Since the onset of the Anthropocene (Zalasiewicz *et al* 2015), the number and magnitude of anthropogenic stressors on marine ecosystems has rapidly increased (Heinze *et al* 2021). Such stressors include rapid changes in water temperature, acidification, and the introduction of new pollutants such as microplastics (MP; <5 mm), pharmaceuticals, or endocrine disrupters (Lloyd-Smith and Immig 2018, Richon *et al* 2024).

Amongst all anthropogenic stressors threatening marine ecosystems, MP constitute a family of emerging contaminants of particular interest due to their abundance, ubiquity, persistence and wide diversity in terms of size, morphology and chemical composition (Rochman *et al* 2019, Richon *et al* 2023). MP are found in all ocean regions and their global fluxes to the ocean have been increasing since the onset of their global production and increased usage in the 1950s (Auta *et al* 2017, Crawford and Quinn 2017). Observational and modeling work has highlighted regions like gyres and coastal areas close to major sources (lands and rivers) as accumulation zones of MP (Eriksen *et al* 2014, van Sebille *et al* 2015, 2020, Onink *et al* 2021, Richon *et al* 2022). In such regions, MP mass may already exceed that of plankton (Moore *et al* 2002, Collignon *et al* 2014), which poses significant risks for zooplankton populations fitness and the overall food web contamination (Setälä *et al* 2014, Richon *et al* 2022). Over the past decades, the rapid increase in environmental contamination caused by MP and their associated chemical additives has contributed to the crossing of the planetary boundary for novel entities (Persson *et al* 2022). In this context, understanding the impacts of emerging contaminants such as MP in environmentally relevant conditions is instrumental to design and inform the necessary remediation policies. Global ocean models coupling physics and biogeochemistry are useful tools in such endeavors (Alekseenko *et al* 2018, Richon *et al* 2022, Kvale *et al* 2023).

A breadth of experimental and observational works have demonstrated that zooplankton may ingest MP (Desforges *et al* 2015, Bessa *et al* 2019, Cau *et al* 2019, Hossain *et al* 2020, Gurjar *et al* 2021, Johnston *et al* 2023), with impacts ranging from impaired feeding, reproduction, motility and growth to increased mortality (Lee *et al* 2013, Jeong *et al* 2016, 2017, Yu *et al* 2020). In particular, significant MP impacts on zooplankton grazing rates have been observed since the 1980s (Ayukai 1987). Experimental studies conducted on various species demonstrated that MP may decrease grazing by 25%–80% (Cole *et al* 2015, Coppock *et al* 2019, Yu *et al* 2020). Grazing is a key function for zooplankton, driving the amount of food ingested, nutrient recycling and fecal pellet production (Atkinson *et al* 2012, Richon *et al* 2020). Moreover, grazing rates describe the predatory behaviour of zooplankton and trophic interactions with its microbial prey (Lampert *et al* 1986, Franks 2001, Sterner 2009, Karakuş *et al* 2022). Thus, disturbance of zooplankton grazing rates upon MP exposure may modify the equilibrium between planktonic species as well as the biogeochemical cycles of carbon and nutrients (McManamay *et al* 2011, Atkinson *et al* 2012). Therefore, quantifying MP impacts on grazing rates at the global scale is essential to understand their ecosystem impacts. The use of modeling tools can help bridge the gaps in our understanding of such impacts.

In this article, we explore the impacts of MP on global ocean biogeochemistry through alteration of zooplankton grazing rates with an environmental contamination threshold for MP impacts. To this end, we used a global model representing the environmentally relevant 3D distribution of MP and biogeochemical tracers (Richon *et al* 2022) to simulate impacts on zooplankton grazing rates. With the results from our idealized simulations, we first investigate the changes in MP surface distribution over 100 years. Then, we explore how various environmental contamination thresholds modulate MP impacts on the global surface plankton biomass and carbon cycle. Finally, we discuss the implications of our results for global ocean ecosystems and future MP studies.

2. Methods

2.1. The NEMO/PISCES-PLASTIC model

Ocean circulation is based on the NEMO model (Madec 2008). Similarly to Richon *et al* (2019, 2020, 2022), we used a climatological year for physical forcing with 5 day resolution. The model horizontal resolution is 2°, and includes 31 z-levels of variable thickness (10 m at the surface to over 500 m at the bottom).

This physical model is coupled one-way with the biogeochemical model PISCES-PLASTIC (Richon *et al* 2022), developed from the biogeochemical model PISCES (Aumont *et al* 2015). In PISCES the 3D distribution and biogeochemical transformations of 6 nutrients (PO_4, NO_3, NH_4, Si, $CaCO_3$ and Fe) are represented. The biomass and production of two phytoplankton functional types (nanophytoplankton and diatoms) and two zooplankton size classes (micro and mesozooplankton) are represented. Microzooplankton represent small organisms preying on phytoplankton and small particulate matter. Mesozooplankton represent larger organisms, such as copepods, preying on both phytoplankton groups, small and large particulate matter, and microzooplankton (see Aumont *et al* 2015, for details and prey preference). Finally, organic matter is represented under the dissolved, small and large particulate forms (see Aumont *et al* 2015, for a full description and equations of PISCES). In PISCES, zooplankton metabolism and interactions with other microbial species is represented through three main functions: respiration, grazing and nutrient recycling (see also Richon *et al* 2020).

Recent developments to PISCES allowed representing the 3D distribution of MP of 3 density categories with fixed physical properties (i.e. vertical velocity, Richon *et al* 2022). No explicit size distribution of MP were used. Floating, neutral and sinking MP are simulated with fixed vertical velocities of -64, 0 and $+90$ m d^{-1}, respectively (negative indicates MP movement towards the surface). In this model, rivers are the only source of MP and deliver about 1.4 Mt yr^{-1} with seasonal variability (input fluxes are taken from Lebreton *et al* 2017).

2.2. Simulating microplastic effects on zooplankton grazing

Microplastic impacts on zooplankton grazing rate were demonstrated in laboratory experiments that used MP/food ratio from 0.1 to >0.5 (Cole *et al* 2015, Coppock *et al* 2019, Yu *et al* 2020). Yet, the community response, which depends on the types and concentration of MP as well as the community structure, is poorly known (e.g. Malinowski *et al* 2023, Yin *et al* 2024). As a first approach and without prior information regarding the shape of the relationship between water contamination and zooplankton grazing rates, we simulated MP impacts using a threshold for the MP contamination level (equation (1)) that triggers a zooplankton grazing rate decrease by 50%. This set up allows representing the strong MP impacts observed experimentally while considering that these impacts are negligible at low environmental contamination levels (as demonstrated by Ayukai 1987). Sensitivity tests using five contrasted contamination threshold (0.01, 0.1, 0.3, 0.5 and 0.9) as well as another value for the decrease of the zooplankton grazing rate (25%) have also been performed.

In our modeling experiments, environmental contamination is represented as the MP/food mass ratio in the water. When the level of environmental contamination surpasses a designated threshold (α), MP impacts occur and zooplankton grazing rates decrease (see Hämer *et al* 2014, Cole *et al* 2015, Ogonowski *et al* 2016, Coppock *et al* 2019, and equations (1), (2)).

Total zooplankton grazing rates (Tot. Grazing) are affected by MP according to equation (1):

$$\text{If}\,\frac{[\text{MP}]}{[\text{food}_j]} > \alpha :$$

$$\text{Tot. Grazing} = \left(\sum_j \text{grazing}_j \times 0.5\right). \tag{1}$$

With grazing$_j$ the grazing rates of zooplankton j (j = microzooplankton or mesozooplankton), [MP] microplastic mass concentration in the water and $food_j$ the available prey for zooplankton j defined as:

$$\text{food}_j = \sum_i P_i \times p_i^j. \tag{2}$$

With P_i the biomass of prey i and p_i^j the preference of zooplankton j for prey i (see Aumont *et al* 2015, for p_i^j values).

In equation (1), α represents the threshold environmental contamination level beyond which MP impacts are simulated. This threshold modulates the geographical extent of MP impacts (see appendix A1 for a sensitivity test on MP impacts geographical extent). Crossing the environmental contamination threshold (MP/food $> \alpha$) can occur for two reasons, high [MP] or low prey availability. The latter favors MP ingestion through increased encounter rates between MP and zooplankton (Cheng *et al* 2020, Richon *et al* 2022).

In these experiments, no impacts of zooplankton grazing on MP concentrations or vertical dynamics were considered. Furthermore, no retention of MP in zooplankton was considered because most experimental studies report rapid egestion (within minutes, see Ogonowski *et al* 2016, Yu *et al* 2020), which is quicker than the model's time step (5 h).

2.3. Simulations

Initial biogeochemical and MP conditions are taken from Richon *et al* (2022), which represent the MP concentration at present time (see figure 1 in Richon *et al* 2022, for a comparison of modelled MP concentration with *in situ* measurements). MP impacts on zooplankton grazing were simulated globally over a 100 year period during which constant contamination of the surface ocean by MP was assumed, using the fluxes from Lebreton *et al* (2017).

Despite their importance to marine food webs and biogeochemical cycling, relatively few studies have considered the impact of microplastics on microzooplankton (e.g. Cole *et al* 2015, Coppock *et al* 2019). Here, we conducted the simulations with similar MP impacts on micro and mesozooplankton since no experimental evidence of different impacts exist between these two specific groups. In appendix A.1.3, we analyse the impacts of MP on micro and mesozooplankton separately (simulations MICRO and MESO).

After an initial perturbation, most biogeochemical tracers reach quasi-equilibrium (i.e. only the trend from the added MP remains) within 3–8 years in the surface layer (0–100 m, where 90% of the modeled plankton biomass is found). In the following sections, we report the impacts of MP contamination at short and long timescales, corresponding to years 10 and 100 of our simulations, respectively. Our results account for all types of MP (floating, neutral, and sinking) and are presented as surface (0–100 m) averages.

In our reference simulation (EXP), α is set to an average value of 0.5 for both micro and mesozooplankton, which is coherent with the ratio of MP/food used in Coppock *et al* (2019) to demonstrate alteration of zooplankton grazing rates. Additional simulations were performed considering various MP/food impact thresholds ($\alpha = 0.01$, 0.1, 0.3, 0.5 and 0.9). The results from these simulations are analysed in appendix A.1. All results were compared with a control simulation (CTL) in which ocean contamination by MP did not impact zooplankton grazing.

Finally, in all our simulations, MP impacts lead to 50% decrease in zooplankton grazing rates (as observed in Cole *et al* 2015, Coppock *et al* 2019). In order to explore the consequences of potential lower MP impacts, we performed an additional sensitivity test (simulation 'LOW_IMP') where MP impacts lead to 25% decrease in zooplankton grazing rates (which corresponds to the lower boundary of MP impacts, Yu *et al* 2020).

3. Results and discussion

3.1. Short and long term MP distribution and simulated impacts

3.1.1. Simulated microplastic distribution at the ocean surface

In the initial state of our EXP simulation (α = 0.5, figure 1(a)), 10 Mkm^2 (<3% of the global ocean surface) is susceptible to MP impacts. On short timescales (after 10 years), MP surface distribution remained similar to the initial distribution (figure 1(b)). MP concentration increased by a few mg m^{-3} in the most contaminated areas (subtropical gyres and coastal regions close to major sources). An exception was the Indian Ocean, likely due to eastward MP transport south of Australia (Maes *et al* 2018). The South Pacific sub-tropical gyre (30–40° S) is the only region where [MP] strongly increased on short timescales (by 0.4–1 mgMP m^{-3}, figures 1(a) and (b)). On longer timescales (after 100 years), [MP] strongly increased in all sub-tropical gyres (figure 1(c)) so that MP surface accumulation zones expanded. In these regions, [MP] reached over 50 mg m^{-3} and even >100 mg m^{-3} in the North Pacific. After 100 years, about 10% of the global surface ocean is directly impacted by MP, based on our water contamination impacts threshold (α = 0.5, see contours on figure 1(c) and table A1). Our sensitivity analysis demonstrates that the extent of impacted areas is overall weakly sensitive to the environmental contamination threshold, with the fraction of the global surface ocean potentially impacted by MP varying between 7% and 25% after 100 years of MP contamination. Only in the case of extremely low environmental contamination impacts threshold (α = 0.01, which is currently not backed by observations), MP impacts may expand to over 75% of the surface ocean (see appendix A.1, table A1). The low sensitivity of the spatial extent of MP impacts to α can be attributed to the steep [MP] gradient in the gyres.

Our model assumes that MP inputs remain constant over a 100 year period. However, this conservative approach may underestimate the true impacts of MP, as projections indicate that MP riverine inputs are likely to increase in the future, thus implying an increase in MP concentrations in all ocean regions (Lebreton and Andrady 2019, Borrelle *et al* 2020, Sonke *et al* 2022). Thus, long-term MP impacts could occur in larger areas than our simulations highlight. Additionally, our model does not account for any MP sinks, such as coastal areas and beaches (Onink *et al* 2021), and thus may overestimate MP impacts in such areas. Moreover, our model does not consider variations in MP sinking rates due to interactions with zooplankton or other environmental factors (e.g. biofouling, fragmentation, Kaandorp *et al* 2021, Lobelle *et al* 2021, Onink *et al* 2022). The impacts of such changes on MP surface residence times and impacts on zooplankton are yet difficult to anticipate.

3.1.2. Short and long term impacts on zooplankton grazing

Zooplankton grazing rates at the surface ocean are linked to global primary production, with higher grazing occurring in productive regions (coastal and upwelling regions, figure 2(a) where food is abundant. In CTL, zooplankton grazing is stable over the simulation (figure 2(b)). In EXP, short-term MP impacts on zooplankton grazing occur in highly contaminated regions (figures 1 and 2(c)). The largest decrease in zooplankton grazing occurs along the coastal regions of Southeast Asia and India, where MP riverine fluxes are highest (>1 mg m^{-3} d^{-1}, figure 2(c), but a significant decrease also occurs in the North Pacific oligotrophic gyre. In these regions, MP/food is >α (i.e. 0.5 in EXP) and zooplankton grazing rates decrease by several mgC m^{-3} d^{-1} (see also figure A6).

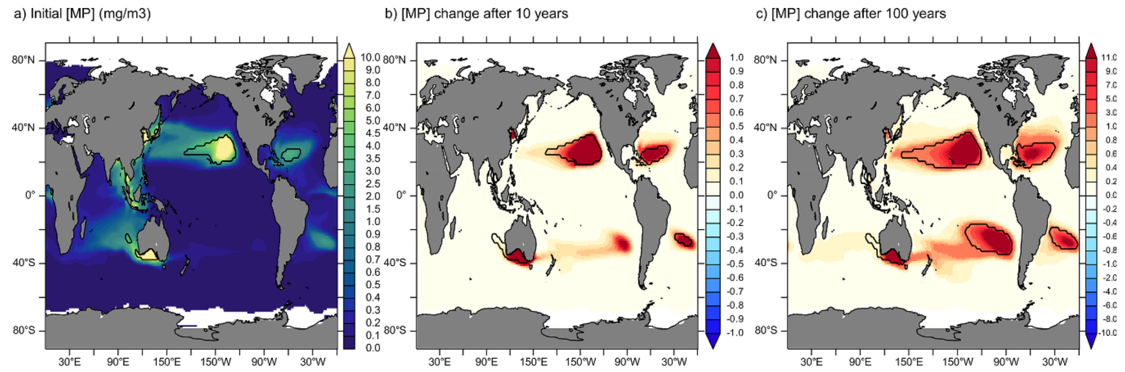


Figure 1. Maps of simulated microplastic concentration ([MP], in mgMP m^{-3}) in surface waters (0–100 average) at the start of the simulations (a), on year 10 of simulation (b) and year 100 (c). Contours represent the areas impacted by MP defined by the environmental contamination impact threshold (α, see Methods).

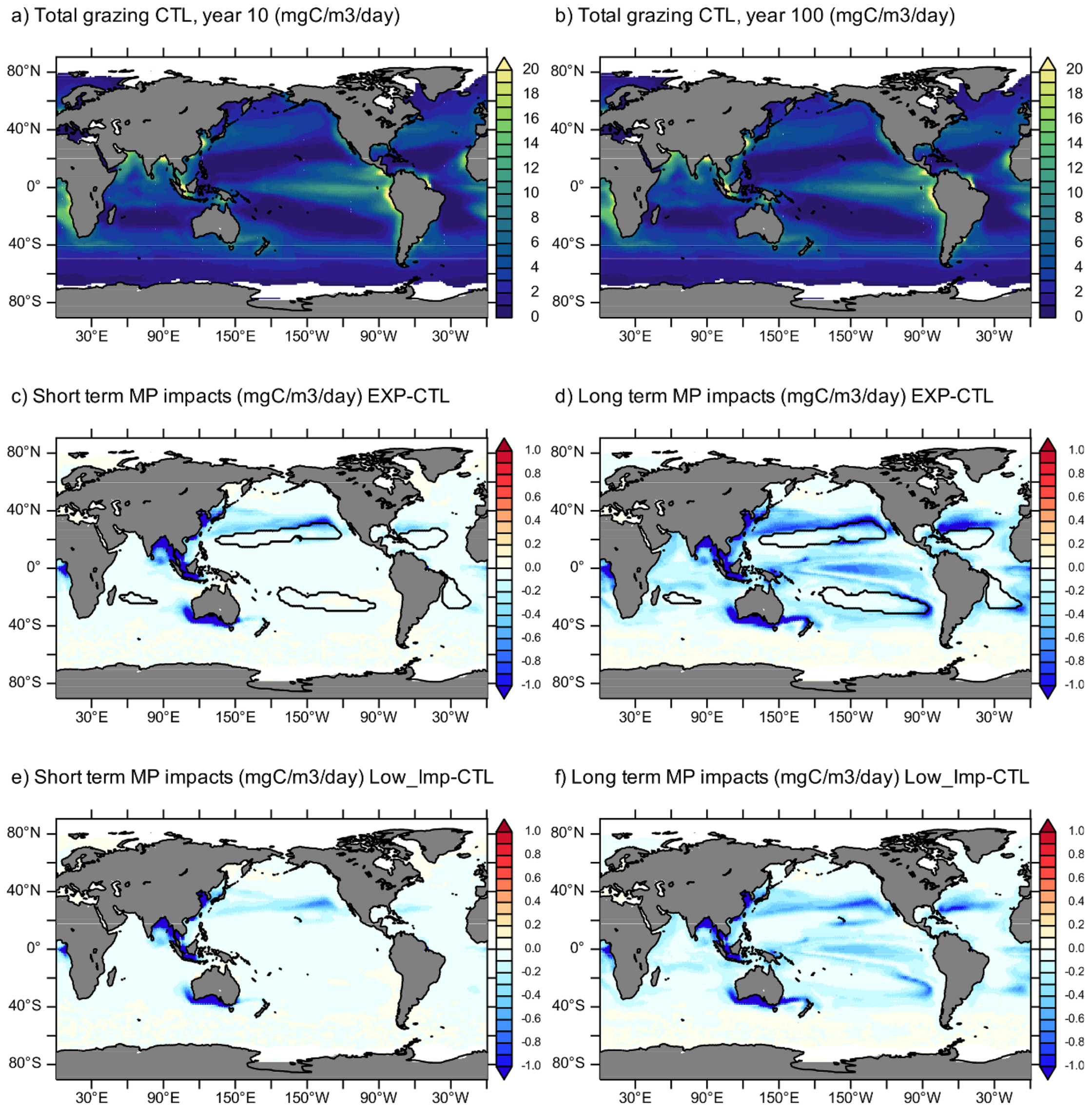


Figure 2. Maps of MP impacts on total zooplankton grazing (*Tot.Grazing*, equation (1)). Maps (a) and (b) represent zooplankton total grazing (microzooplankton + mesozooplankton grazing rates, averaged in 0–100 m) in the CTL simulation after 10 (a) and 100 years of simulation (b). Maps (c) and (d) show the absolute impacts of MP on total grazing (EXP-CTL) in 0–100 m. Maps (e) and (f) represent the absolute MP impacts on total grazing in the LOW_IMP sensitivity test (MP impacts limited to 25% decrease in grazing rate). Contours on maps (c) and (d) indicate oligotrophic regions *sensu* Longhurst *et al* (1995) (total daily primary production in the first 100 m<0.4 gC m^{-2} d^{-1}).

Over long timescales, MP impacts on zooplankton grazing spread over the inter-tropical zone (figure 2(d)). The largest decreases in zooplankton grazing occur around the gyres boundaries (>1 mgC m^{-3} d^{-1} in the North Pacific and Atlantic gyres, around 40° N and for the South Pacific gyre at 90° W, figure 2(d). In these regions, [MP] is high enough to directly impact zooplankton grazing rates. Additionally, we observe MP impacts outside these regions due to the transport of water masses containing less planktonic biomass. These non local impacts may decrease zooplankton grazing by up to 0.4 mgC m^{-3} d^{-1} (20%) even in regions where [MP] is low (e.g. in the Eastern Tropical Pacific figure 2(d). Moreover, our sensitivity test (appendix A.1) reveals that the location of MP impacts on zooplankton grazing has a limited sensitivity to αbecause of the stability of MP accumulation zones (i.e. the sub-tropical gyres concentrate high amounts of MP, figure A1). Thus, even in the case of high environmental contamination impacts threshold ($\alpha = 0.9$, the most conservative case), these highly contaminated ocean areas still experience MP impacts.

As expected, our sensitivity test simulating low MP impacts on zooplankton grazing rates (LOW_IMP, 25% decrease, figures 2(e) and (f)) yields a similar spatial extent of MP impacts than EXP. On short and long timescales, the same regions are affected by MP in EXP and in LOW_IMP, with the overall impacts on grazing being twice as low in LOW_IMP. Yet, the lower MP impacts on grazing lead to a limited decrease of only 0.5mgC m^{-3} d^{-1} at the northern bounday of the North Pacific sub-tropical gyre on short term and to -0.5–0.7mgC m^{-3} d^{-1} on long term (figures 2(e) and (f)). MP impacts are overall similar in EXP and LOW_IMP with regards to spatial distribution and the intensity of these impacts can be inferred from the imposed decrease in zooplankton grazing rates, thus we will focus the rest of the manuscript on the EXP simulation. All results from LOW_IMP can be found in appendix (figures A3 and A4) .

Finally, results from our MICRO and MESO sensitivity tests demonstrate that the MP impacts on total zooplankton grazing are mostly due to impacts on the microzooplankton size class, which constitutes most of the zooplankton biomass in our simulations (see appendix A.1.3).

Here, we evaluate direct impacts of MP contamination on zooplankton through decreased grazing rate. However, MP may have other impacts on ocean biogeochemistry and food-webs that are not currently represented in our model. For example, incorporation of buoyant MP particles in zooplankton faecal pellets significantly reduces their sinking velocity, thus increasing the likelihood of remineralisation of organic matter in the upper ocean (Long et al 2015, Cole et al 2016, Coppock et al 2019). Furthermore, MP may interfere with zooplankton physiology, including fecundity and development (Cole et al 2015, 2019). Such impacts could be exacerbated given MP can act as carriers of harmful contaminants and pathogens (Foulon et al 2016, Bowley et al 2021). As a result, the true impacts of MP contamination on ocean ecosystems may be greater than what we have estimated based solely on the effects of MP on zooplankton grazing rate.

3.2. MP impacts on planktonic functional groups

MP impacts on zooplankton grazing rates affect the balance between plankton species (figure 3). Reduced grazing rates due to MP contamination lead to decreased zooplankton growth and biomass. This has significant biogeochemical implications, as demonstrated by the simulated decrease in remineralization rates in figures 3(d) and (g). In our simulation, the decrease in remineralization rates is less than 1 mg m^{-3} d^{-1} in the oligotrophic gyres both on short and long timescales (figures 3(d) and (g)). Yet, this corresponds to halving yearly remineralization rates in extensive oceanic regions, as depicted in figure A7.

The consequences of decreased zooplankton biomass following MP impacts affect phytoplankton differently depending on the f-ratio at the surface ocean. The f-ratio represents the proportion of new to total primary production. Most MP impacts occur in regions with low f-ratio (i.e. the sub-tropical gyres where f-ratio <0.25, figures 3(e) and (h) where primary production strongly relies on recycled nutrients. In these regions, decreased zooplankton biomass leads to reduced nutrient recycling and remineralization, thus limiting nutrient availability for phytoplankton growth. Conversely, decreased zooplankton biomass in regions with high f-ratio lowers the predatory pressure on phytoplankton, with limited relative impacts on nutrient concentrations. In these regions (i.e. over 40° S and in the Eastern Tropical Pacific upwelling zone), the simulated MP impacts on zooplankton grazing rate trigger a limited increase in phytoplankton biomass (about 0.1 mgC m^{-3}, figure 3(h). This positive effect of MP on phytoplankton, triggered by decreased predation has been experimentally observed by Malinowski et al (2023).

3.3. MP impacts on the carbon cycle

MP impacts on zooplankton grazing trigger feedbacks that propagate across the entire ocean carbon (C) cycle (figure 4). On short timescales, most MP impacts occur in oligotrophic regions (figure 2) where C fluxes are low (figures 4 (a) and (b)). Similarly to the impacts on plankton biomass, short

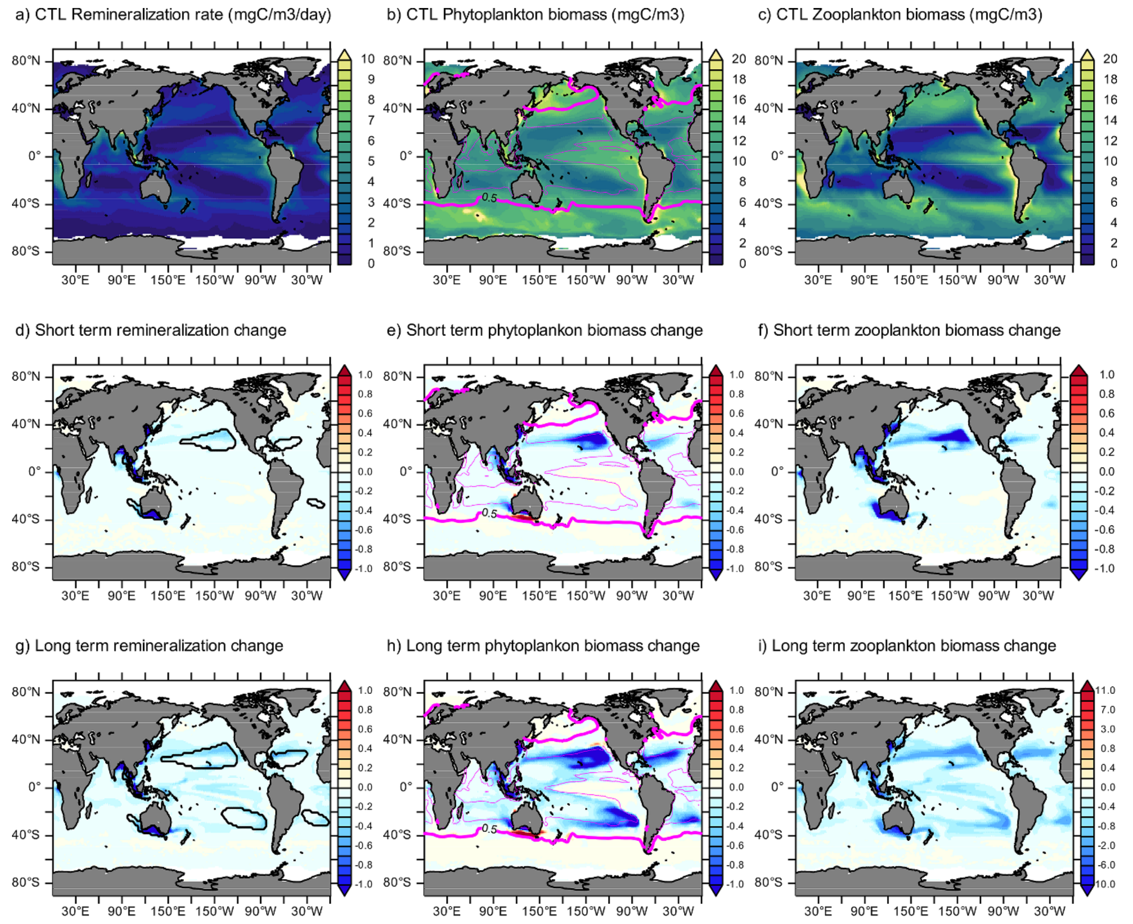


Figure 3. MP impacts on surface remineralization rates and plankton biomass. Top row (a)–(c) shows the surface remineralization rate (mgC m^{-3} d^{-1}) and biomasses of total phytoplankton and zooplankton (mgC m^{-3}) averaged over 0–100 m on year 10 of the CTL simulation. Middle row (c)–(e) shows absolute differences between EXP and CTL averaged over 0–100 m and over after 10 years of MP impacts. Bottom row (e)–(g) show the absolute differences between EXP and CTL averaged over 0–100 m and after 100 years of MP impacts. Black contours on maps (d) and (g) show the regions directly impacted by MP (MP/food $> \alpha$). Thin purple contours on maps (b), (e) and (h) show regions where the f-ratio is >0.25 and thick contours indicate where f-ratio >0.5.

term MP impacts on C fluxes are maximal in the MP accumulation zones of the Indian, Southeast Asian and South Australian coasts as well as on the North Pacific gyre (figures 4(c) and (d)). Decreased C export of about 3–5 mgC m^{-2} d^{-1} is observed on short timescales in the North Atlantic gyre and in the coastal region of Western Equatorial Africa (figure 4(f)). These negative impacts are the consequence of the low f-ratio in most MP accumulation zones (see figure 3). The negative feedback loop triggered by MP impacts on grazing rate leads to lower primary production. This general decrease in C cycling ultimately leads to decreased C export.

While short-term MP impacts on ocean C cycling are confined to regions with elevated [MP] (figures 4(c) and (d)), long-term effects may extend across most of the ocean at low and mid latitudes (figures 4(e) and (f)), leading to reduced primary production and C export by up to 50% in gyres and 10%–20% in the Equatorial region (figure A8). Conversely, there are negligible positive effects on C fluxes in mid to high latitudes (figures 4(e) and (f)), attributed to the high f-ratio in those regions, triggering a positive feedback loop with less grazing and increased primary production. Despite the rise in primary production and carbon export by less than 0.05 gC m^{-3} d^{-1} and 0.05 mgC m^{-2} d^{-1}, respectively, the annual surface carbon fluxes remain quasi-unaltered in these areas (see figure A8).

Our simulations provide a quantification of MP impacts on zooplankton-mediated C cycling at the surface ocean. Based on experimental estimates of acute MP impacts on zooplankton grazing, we demonstrate that short-term MP impacts on the global carbon budget are limited (−1.3% total primary production and −1.4% carbon export, figure 5). However, long-term MP impacts expand over most of the inter-tropical zone, leading to about −4% total primary production and carbon export globally (−2 GtC yr^{-1} for primary production

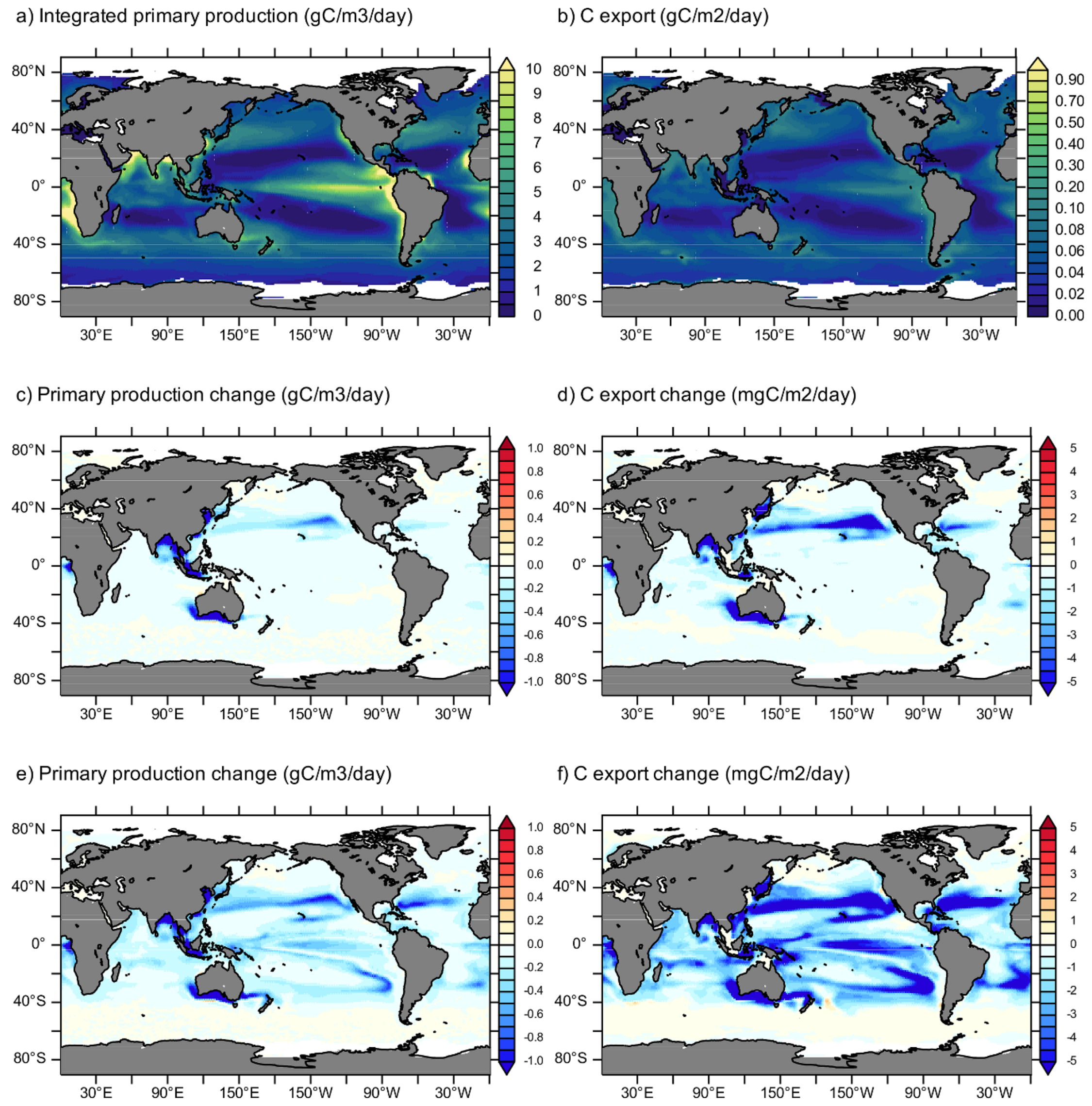
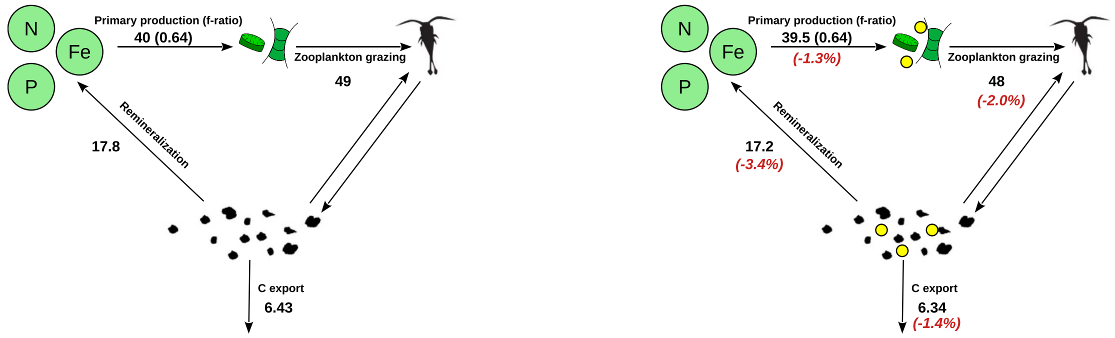


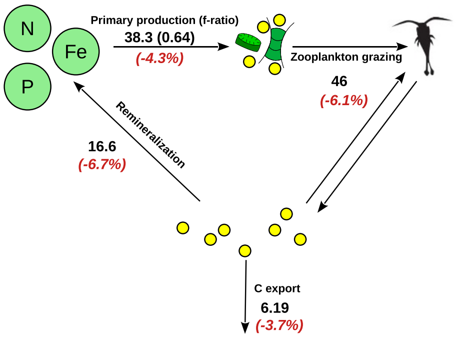
Figure 4. Maps MP impacts on C fluxes. Top row: averaged C fluxes in the first 100 m on year 10 of the CTL simulation. Middle row, absolute differences between EXP and CTL on short timescales (year 10, averaged in 0–100 m). Bottom row: absolute differences between EXP and CTL on long timescales (year 100, averaged in 0–100 m).

and 0.2 GtC yr^{-1} for C export). In our sensitivity tests, we used environmental contamination impacts thresholds from experimental work (ranging from $<$0.1 to $>$0.5, Cole *et al* 2015, Ogonowski *et al* 2016, Coppock *et al* 2019, Yu *et al* 2020). Such thresholds probably vary with ecosystem composition, MP type and environmental conditions. Overall, simulated MP impacts on the global C cycle show that, except in the case of an extremely low threshold ($\alpha = 0.01$), long term MP impacts on the zooplankton-mediated global surface carbon cycle are between 2.5 and 13.5% (figure A2). Our additional sensitivity test (LOW_IMP) also demonstrates that MP impacts on zooplankton-mediated surface C cycling at the global scale are overall robust to variations in impacts intensity (because most impacts occur in oligotrophic zones, see figure A2 for global fluxes values). Finally, we simulated MP impacts on zooplankton grazing only, but other types of impacts may occur (e.g. Cole *et al* 2016, measured significantly lower sinking speed of MP-laden fecal pellets). Future works should aim at quantifying the full range of MP impacts on zooplankton, in order to understand its net effects.

While our findings are consistent with Kvale *et al* (2021) regarding the increase in C export in high f-ratio regions due to reduced zooplankton predatory pressure and subsequent primary production increase, our model, which includes macro and micronutrient biogeochemical cycles, projects a larger area of nutrient limitation (i.e. prone to a negative impact of MP on primary production through its effect on remineralization). Therefore, our model suggests more negative effects of MP



(a) CTL (b) Short term



(c) Long term

Figure 5. Schematics of MP impacts on the global carbon cycle in CTL (a) and EXP (short timescales, b, and long timescales, (c). Values in black are in GtC yr^{-1}, values in parenthesis are the relative impacts of MP.

on surface C cycling. Our results provide further evidence of potentially significant impacts of MP on surface ocean biogeochemical cycles, as previously demonstrated by Kvale *et al* (2021), and confirm the potential for long-term MP effects, as hypothesized by Kvale and Oschlies (2022), Richon *et al* (2023). Additionally, we emphasize the importance of surface ocean nutrient limitation regimes and recycling in regulating the response of primary production to MP-induced grazing rate changes.

3.4. Implications for ocean biogeochemistry and ecosystem functioning

Our simulations demonstrate that MP impacts on zooplankton grazing rates are spread in similar proportions throughout the simulated carbon cycle, thus leading to a local 50% decrease in annual C cycling rates (primary production, export and organic matter remineralization) in the most contaminated regions (figure A8). These regional effects may impact the surface ocean C cycling globally by decreasing primary production by 4% (range: 2.5%–13%) over 100 years. These impacts are similar in magnitude to those of climate change (global projection around −2% ± 8%, Tagliabue *et al* 2021) and may occur on the same timescales (see Kwiatkowski *et al* 2020, Tagliabue *et al* 2021, for global projections with the CMIP6 model ensembles). Despite large uncertainties in both climate change and MP impact projections, our findings indicate that MP could represent an equally significant threat to ocean biogeochemical cycles, albeit based on limited experimental data, with no data available for microzooplankton. The projected expansion of oligotrophic gyres (Bopp *et al* 2013), which are MP accumulation hotspots (Eriksen *et al* 2014, van Sebille *et al* 2015, Richon *et al* 2022), may lead to a geographical expansion of MP impacts. Finally, overlapping impacts between MP and other stressors, such as climate change or other contaminants, may amplify the overall impact of MP on ocean ecosystems (Richon *et al* 2024). In this context, ensemble simulations of all MP impacts on ocean biogeochemistry, mirroring the work made by the climate science community, is urgently needed. This collective endeavor is crucial to bridge knowledge gaps regarding the oceanic MP cycle and its global impacts on biogeochemistry and ecosystem functioning.

4. Summary and conclusions

We assessed the global-scale impacts of MP on zooplankton grazing rates over a 100 year period of constant MP contamination using model simulations. As expected, our results showed that MP impacts on zooplankton grazing rates are primarily localized in highly contaminated regions, such as coastal areas and sub-tropical oligotrophic gyres. Within these regions, MP can exert substantial influence on ocean biogeochemistry and food webs by altering the composition and functioning of planktonic communities. Our results indicate that MP contamination may substantially modify plankton biomass and zooplankton-mediated carbon fluxes in sub-tropical gyres and coastal regions near major MP sources. Although the spatial scope of MP impacts on zooplankton grazing rates is limited, their long-term effects on carbon cycling extend across a significant portion of the ocean surface. We estimate a global decrease in carbon export and primary production of approximately 4% after 100 years, assuming an average environmental contamination impacts threshold. Sensitivity analysis further revealed that the long-term global impact of MP on the surface ocean carbon fluxes could range from 2.5% to 17%. These global estimates reveal that MP impacts may be of similar magnitude than those of climate change. Although uncertainties in MP impacts on ocean ecosystems persist, our results underscore potential risks for oceanic food webs through trophic amplification of MP impacts (Chust *et al* 2014, Kwiatkowski *et al* 2018, Lotze *et al* 2019). We also highlight the need for a comprehensive evaluation of MP contamination levels and impacts on ocean biogeochemistry and food webs. This requires continued data acquisition and model developments. Our study provides new insights into the global-scale impacts of MP on ocean biogeochemistry and planktonic food webs. These findings have important implications for our understanding of the potential consequences of MP pollution on marine environments.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.10495604.

Acknowledgment

C R acknowledges support from the ISblue project, Interdisciplinary graduate school for the blue planet (ANR-17-EURE-0015) and co-funded by a grant from the French government under the program ‘Investissements d’Avenir’, and by a grant from the Regional Council of Brittany (SAD programme) and from the Institut des Sciences du Calcul et des Données (ISCD) of Sorbonne University (IDEX SUPER 11-IDEX-0004) through the support of the sponsored project-team FORMAL (From ObseRving to Modelling oceAn Life). C L acknowledges support from the Swiss National Science Foundation under Grants 174124 and 203448. M C acknowledges support from the Natural Environmental Research Council (UK) under Grants NE/V007351 and NE/V005413.

Appendix

A.1. Sensitivity tests

A.1.1. Exploring different geographical extent of MP impacts

As a complement to our EXP simulation, we conducted sensitivity tests in which we explored the model response under different values of α, representing varying degrees of environmental contamination threshold for impacts. We examined extreme scenarios with very low threshold, leading to large scale impacts ($\alpha = 0.01$) and very high threshold leading to spatially limited impacts ($\alpha = 0.9$), as well as intermediate cases.

In our simulations, the low initial [MP] in the surface ocean limits the spatial extent of MP impacts on zooplankton. The fraction of the surface ocean potentially impacted by MP varies between 4.9 and 50 Mkm^2, depending on the environmental contamination impact threshold (see table A1 and figure A1). Only a particularly low threshold ($\alpha = 0.01$) results in large fractions of the surface ocean affected by MP impacts (over 75% of the global ocean surface on long timescales).

Moreover, exploring the response of our model to various environmental contamination impact thresholds reveals that MP impacts on total grazing rates at the global scale have a limited sensitivity to α (figure A2). Strong variations of α (between 0.1 and 0.9) only result in long term variations of global grazing of 6 $\mathrm{GtC\,yr^{-1}}$ (figure A2). These results are due to the small changes in MP distributions, which concentrate in low productivity regions (i.e. the subtropical gyres, figure A1).

Overall, our sensitivity analysis demonstrates that, except in the case of an extremely low impact threshold, model results are weakly sensitive to α (figure A2). The extreme threshold case ($\alpha = 0.01$) allows estimating an upper boundary for global MP impacts on primary production and C export (-60% after 100 years of constant contamination). These sensitivity tests allow us to constrain the global-scale impacts of MP on zooplankton and the marine C cycle across the surface ocean. Thus, these results lend credibility to our modelling assessment of the global MP impacts on ocean biogeochemistry.

Table A1. Ocean areas impacted MP (Mkm^2) at the beginning of the simulations (initial), on short (year 10) and long term (year 100) depending on the environmental contamination impact threshold (α).

Environmental contamination impact threshold (α)	Area impacted (Mkm^2)		
	Initial	Short term	Long term
0.01	156	184	272
0.1	50	56	89
0.3	19	25	46
0.5	10	16	35
0.9	4.9	9.1	26

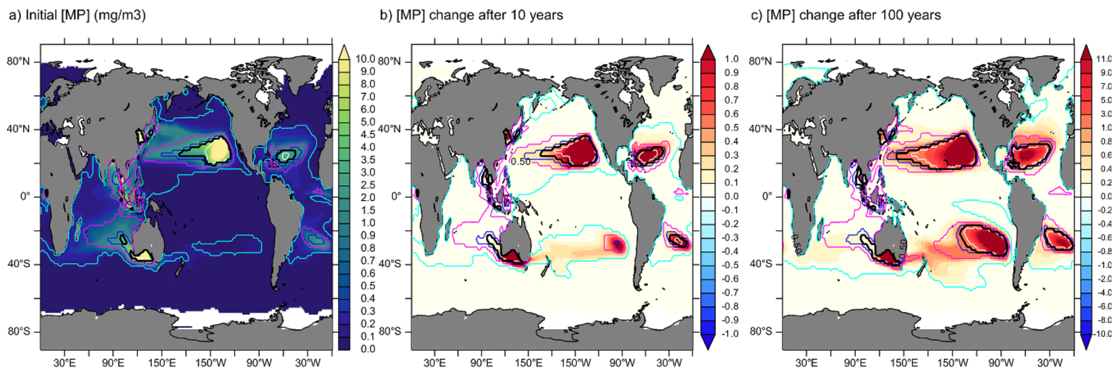


Figure A1. Maps of simulated microplastic concentration ([MP], in mgMP m^{-3}) in surface waters (0–100 average) at the start of the simulations (a), on year 10 of simulation (b) and year 100 (c). Contours represent the areas impacted by MP (defined by the threshold α, see Methods). Cyan: $\alpha = 0.01$, purple: $\alpha = 0.1$, blue: $\alpha = 0.3$, black: $\alpha = 0.5$, white: $\alpha = 0.9$.

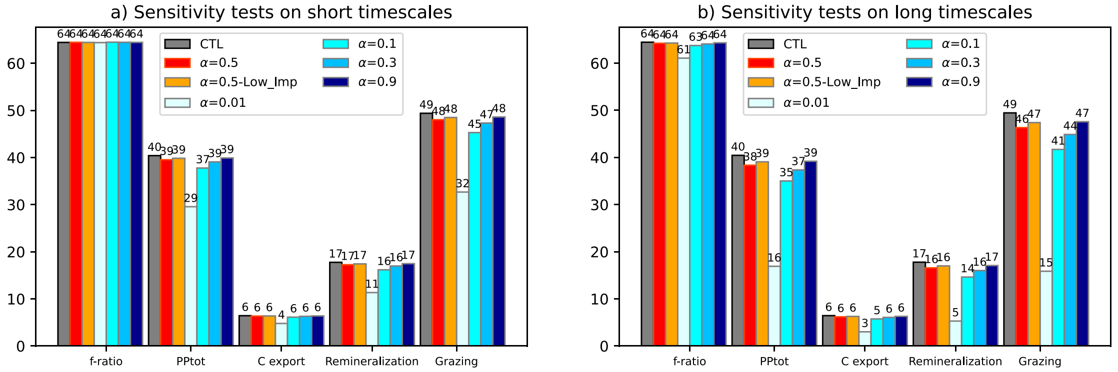


Figure A2. Sensitivity of the modeled global C cycle to the environmental contamination impact threshold (α). Bars represent the annual C fluxes (in GtC yr^{-1}) in different simulations with varying α. Red and orange bars correspond respectively to the EXP and LOW_IMP simulations.

A.1.2. Evaluating zooplankton sensitivity to MP impacts

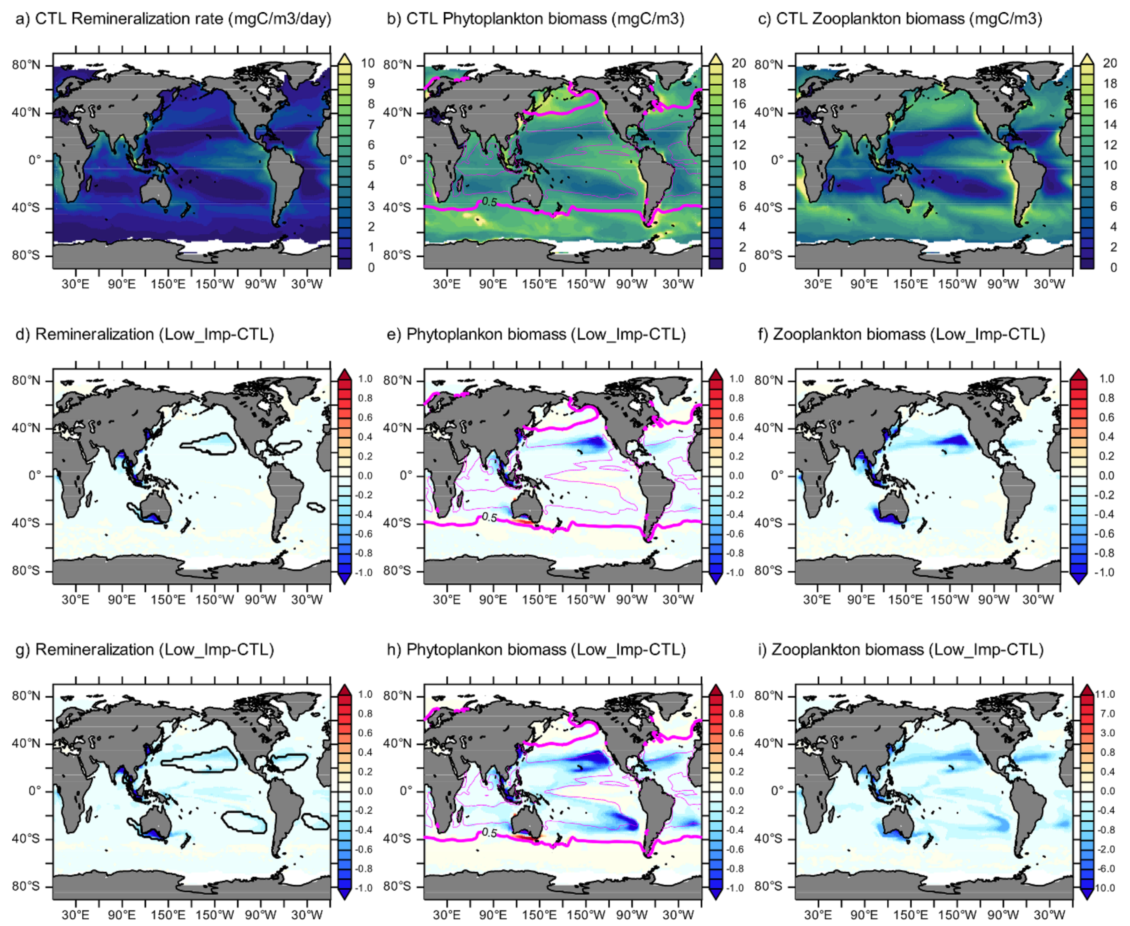


Figure A3. MP impacts on surface remineralization rates and plankton biomass. Top row (a)–(c) shows the surface remineralization rate (mgC m^{-3} d^{-1}) and biomasses of total phytoplankton and zooplankton (mgC m^{-3}) averaged over 0–100 m on year 10 of the CTL simulation. Middle row (c)–(e) shows absolute differences between LOW_IMP and CTL averaged over 0–100 m and over after 10 years of MP impacts. Bottom row (e)–(g) show the absolute differences between LOW_IMP and CTL averaged over 0–100 m and after 100 years of MP impacts. Black contours on maps (d) and (g) show the regions directly impacted by MP (MP/food $> \alpha$). Thin purple contours on maps (b), (e) and (h) show regions where the f-ratio is >0.25 and thick contours indicate where f-ratio >0.5.

A.1.3. Contrasting MP impacts on micro and mesozooplankton

In the surface ocean, micro and mesozooplankton fill different niches. On the one hand, microzooplankton are smaller species with faster growth rates that dominate in low nutrient regions (they constitute up to 90% of the zooplankton biomass in the oligotrophic gyres). On the other hand, mesozooplankton are larger organisms with slower metabolism that constitute the apex predators in PISCES and tend to dominate plankton biomass in more productive regions and in high latitudes (Aumont *et al* 2015, Richon *et al* 2020).

To evaluate the respective impacts of MP on microzooplankton and mesozooplankton (and the subsequent changes in ocean biogeochemistry), two additional simulations were performed: ‘MICRO’ and ‘MESO’. In MICRO, microplastics only affect microzooplankton grazing rates, while mesozooplankton grazing rates remain unchanged. Conversely, only mesozooplankton grazing rates are affected by MP in the MESO simulation (see figure A5).

Figure A5 highlights that microzooplankton contributes to the majority of total zooplankton grazing in the surface ocean. Indeed, in the MICRO simulation, the global MP impacts on total grazing are similar to those presented in figure 2(f) of the main manuscript. Conversely, if MP exclusively affects mesozooplankton, the overall response of zooplankton is minimal due to the relatively small contribution of mesozooplankton to total zooplankton biomass in our model. These additional simulations demonstrate that the response of microzooplankton to MP, given its dominance over zooplankton biomass, predominantly influences the ecosystem response in our model, despite being the least studied.

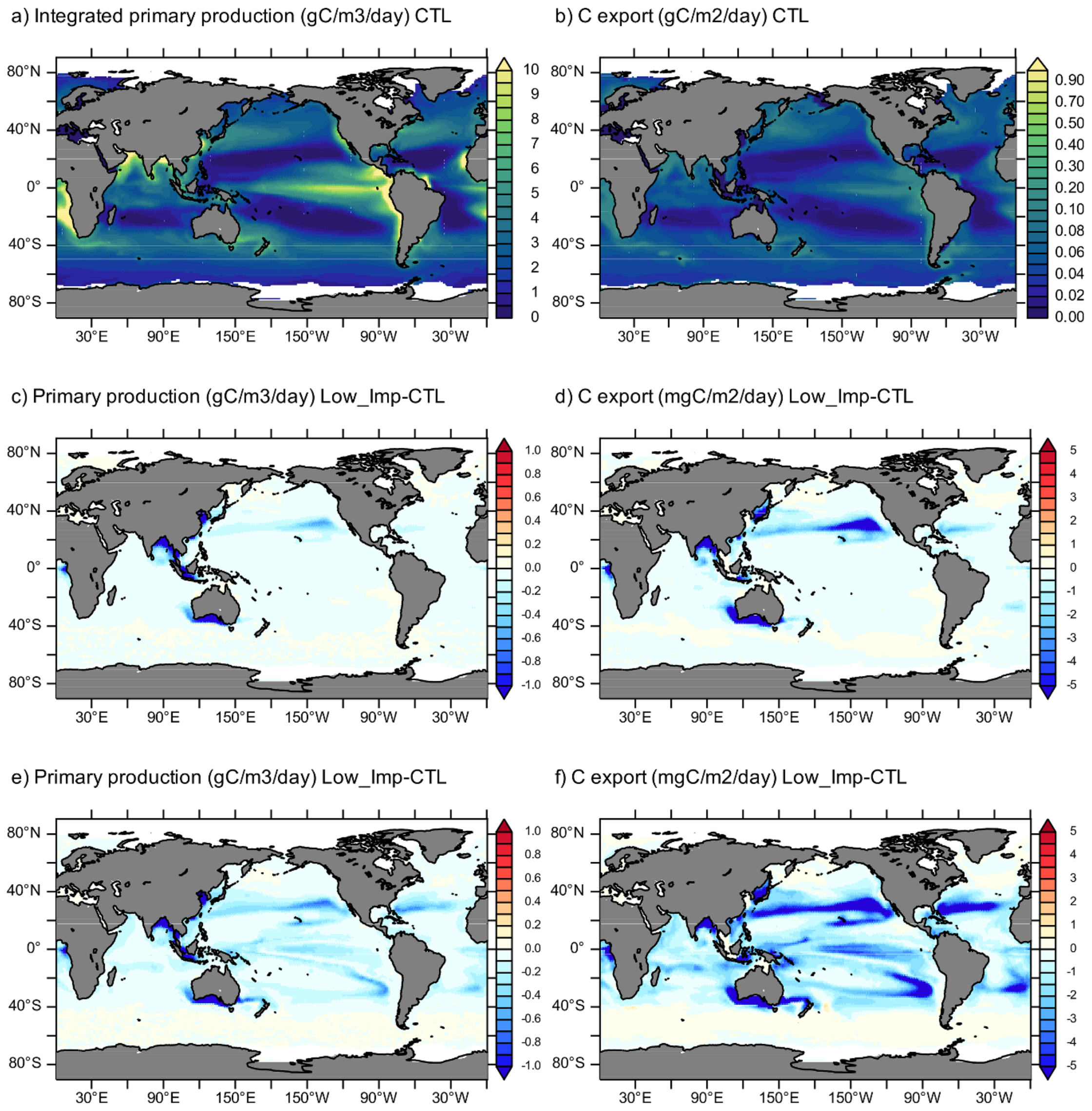


Figure A4. Maps MP impacts on C fluxes. Top row: averaged C fluxes in the first 100 m on year 10 of the CTL simulation. Middle row, absolute differences between LOW_IMP and CTL on short timescales (year 10, averaged in 0–100 m). Bottom row: absolute differences between LOW_IMP and CTL on long timescales (year 100, averaged in 0–100 m).

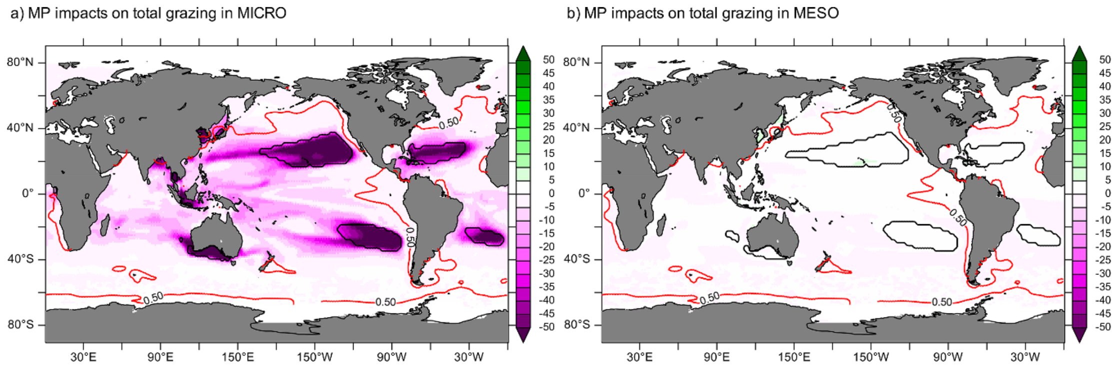


Figure A5. Long term MP impacts (i.e. after 100 years, in %) on total zooplankton grazing (i.e. microzooplankton + mesozooplankton grazing) in the MICRO (a) and MESO (b) simulations. Black contours represent the areas impacted by microplastic (defined by the threshold $\alpha = 0.5$, see Methods) and red contours indicate the regions where mesozooplankton dominates zooplankton biomass.

A.2. Relative impacts of MP on surface biogeochemistry on short and long timescales

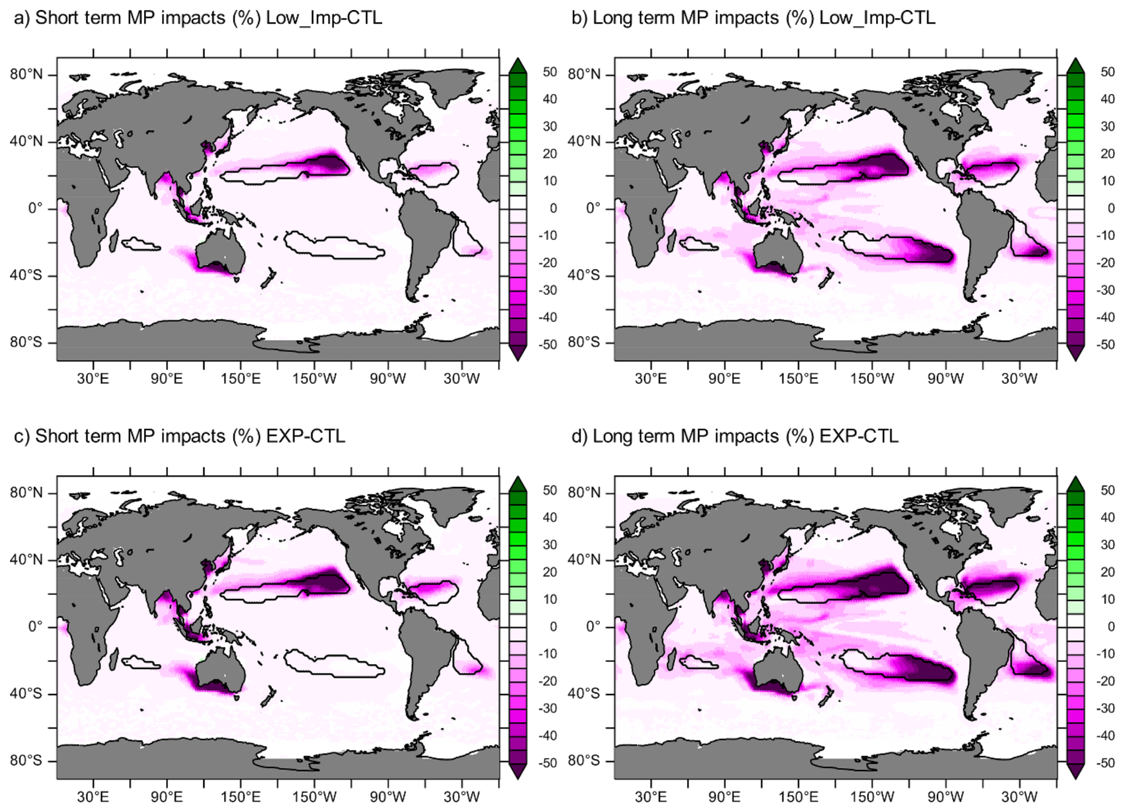


Figure A6. Maps of simulated relative MP impacts on surface total zooplankton grazing rates. Maps (a) and (b), represent MP impacts in the LOW_IMP simulation. Maps (c) and (d) represent EXP. Contours represent the oligotrophic regions.

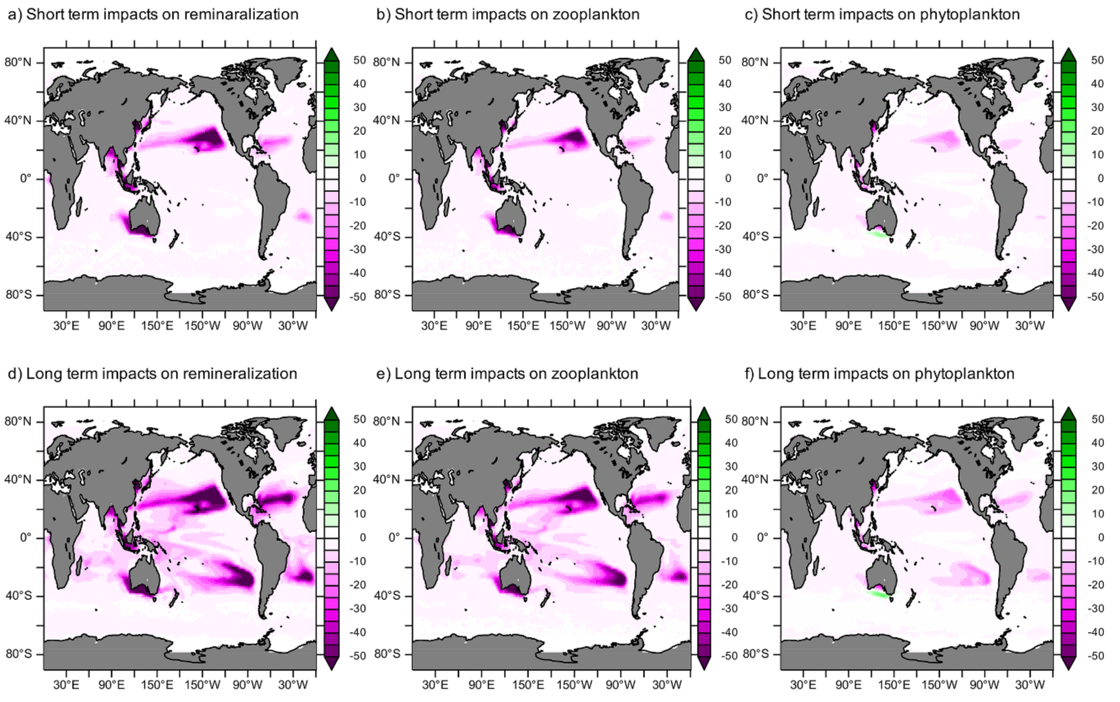


Figure A7. Maps of simulated relative MP impacts on surface remineralization (a), (d) and plankton biomasses (0–100 m averages). Maps (a)–(c) represent short term impacts (year 10) and maps (d)–(f) represent long term impacts (year 100).

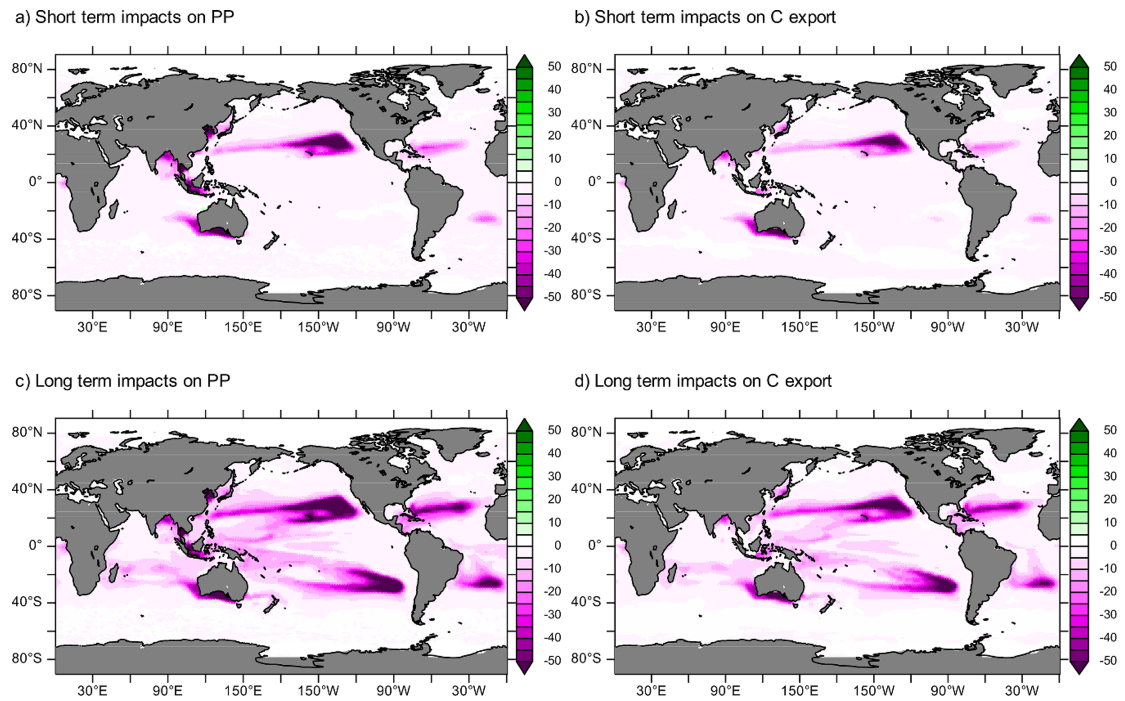


Figure A8. Maps of simulated relative MP impacts on surface C cycling (averaged over 0–100 m). Top row represents the short term impacts ((a), (b), year 10 of simulation), bottom row represents long term impacts ((c), (d), year 100 of simulation).

ORCID iDs

Camille Richon https://orcid.org/0000-0001-7097-7173
Christophe Maes https://orcid.org/0000-0001-6532-7141

References

Alekseenko E, Thouvenin B, Tronczyński J, Carlotti F, Garreau P, Tixier C and Baklouti M 2018 Modeling of PCB trophic transfer in the Gulf of Lions; 3D coupled model application *Mar. Pollut. Bull.* **128** 140–55

Atkinson A, Schmidt K, Fielding S, Kawaguchi S and Geissler P A 2012 Variable food absorption by Antarctic krill: relationships between diet, egestion rate and the composition and sinking rates of their fecal pellets *Deep Sea Res.* II **59-60** 147–58

Aumont O, Ethé C, Tagliabue A, Bopp L and Gehlen M 2015 PISCES-v2: an ocean biogeochemical model for carbon and ecosystem studies *Geosci. Model Dev.* **8** 2465–513

Auta H S, Emenike C U and Fauziah S H 2017 Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects and potential solutions *Environ. Int.* **102** 165–76

Ayukai T 1987 Discriminate feeding of the calanoid copepod A cartia clausi in mixtures of phytoplankton and inert particles *Mar. Biol.* **94** 579–87

Bertram D F, Mackas D L and McKinnell S M 2001 The seasonal cycle revisited: interannual variation and ecosystem consequences *Prog. Oceanogr.* **49** 283–307

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

Bopp L *et al* 2013 Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models *Biogeosciences* **10** 6225–45

Borrelle S B *et al* 2020 Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution *Science* **369** 1515–8

Bowley J, Baker-Austin C, Porter A, Hartnell R and Lewis C 2021 Oceanic Hitchhikers – Assessing Pathogen Risks from Marine Microplastic *Trends Microbiol.* **29** 107–16

Boyd P W, Strzepek R F, Ellwood M J, Hutchins D A, Nodder S D, Twining B S and Wilhelm S W 2015 Why are biotic iron pools uniform across high- and low-iron pelagic ecosystems? *Glob. Biogeochem. Cycles* **29** 1028–43

Cau A, Avio C G, Dessì C, Follesa M C, Moccia D, Regoli F and Pusceddu A 2019 Microplastics in the crustaceans *Nephrops norvegicus* and *Aristeus antennatus*: flagship species for deep-sea environments? *Environ. Pollut.* **255** 113107

Cavan E L, Le Moigne F a C, Poulton A J, Tarling G A, Ward P, Daniels C J, Fragoso G M and Sanders R J 2015 Attenuation of particulate organic carbon flux in the Scotia Sea, Southern Ocean, is controlled by zooplankton fecal pellets *Geophys. Res. Lett.* **42** 821–30

Cheng Y, Wang J, Yi X, Li L, Liu X and Ru S 2020 Low microalgae availability increases the ingestion rates and potential effects of microplastics on marine copepod *Pseudodiaptomus annandalei Mar. Pollut. Bull.* **152** 110919

Chust G *et al* 2014 Biomass changes and trophic amplification of plankton in a warmer ocean *Glob. Change Biol.* **20** 2124–39

Cole M, Coppock R, Lindeque P K, Altin D, Reed S, Pond D W, Sørensen L, Galloway T S and Booth A M 2019 Effects of nylon microplastic on feeding, lipid accumulation and moulting in a coldwater copepod *Environ. Sci. Technol.* **53** 7075–82

Cole M, Lindeque P, Fileman E, Halsband C and Galloway T S 2015 The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod calanus helgolandicus *Environ. Sci. Technol.* **49** 1130–7

Cole M, Lindeque P K, Fileman E, Clark J, Lewis C, Halsband C and Galloway T S 2016 Microplastics alter the properties and sinking rates of zooplankton faecal pellets *Environ. Sci. Technol.* **50** 3239–46

Collignon A, Hecq J-H, Galgani F, Collard F and Goffart A 2014 Annual variation in neustonic micro- and meso-plastic particles and zooplankton in the Bay of Calvi (Mediterranean–Corsica) *Mar. Pollut. Bull.* **79** 293–8

Coppock R L, Galloway T S, Cole M, Fileman E S, Queirós A M and Lindeque P K 2019 Microplastics alter feeding selectivity and faecal density in the copepod, Calanus helgolandicus *Sci. Total Environ.* **687** 780–9

Crawford C B and Quinn B 2017 The contemporary history of plastics *Microplastic Pollutants* (Elsevier) pp 19–37

Desforges J-P W, Galbraith M and Ross P S 2015 Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean *Arch. Environ. Contam. Toxicol.* **69** 320–30

Eriksen M, Lebreton L C M, Carson H S, Thiel M, Moore C J, Borerro J C, Galgani F, Ryan P G and Reisser J 2014 Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea *PLoS One* **9** e111913

Foulon V, Le Roux F, Lambert C, Huvet A, Soudant P and Paul-Pont I 2016 Colonization of polystyrene microparticles by vibrio crassostreae: light and electron microscopic investigation *Environ. Sci. Technol.* **50** 10988–96

Franks P J S 2001 Phytoplankton blooms in a fluctuating environment: the roles of plankton response time scales and grazing *J. Plankton Res.* **23** 1433–41

Gurjar U R, Xavier M, Nayak B B, Ramteke K, Deshmukhe G, Jaiswar A K and Shukla S P 2021 Microplastics in shrimps: a study from the trawling grounds of north eastern part of Arabian Sea *Environ. Sci. Pollut. Res.* **28** 48494–504

Hansen A N and Visser A W 2016 Carbon export by vertically migrating zooplankton: an optimal behavior model *Limnol. Oceanogr.* **61** 701–10

Heinze C *et al* 2021 The quiet crossing of ocean tipping points *Proc. Natl Acad. Sci.* **118** e2008478118

Hossain M S, Rahman M S, Uddin M N, Sharifuzzaman S M, Chowdhury S R, Sarker S and Nawaz Chowdhury M S 2020 Microplastic contamination in Penaeid shrimp from the Northern Bay of Bengal *Chemosphere* **238** 124688

Hämer J, Gutow L, Köhler A and Saborowski R 2014 Fate of microplastics in the marine isopod *Idotea emarginata Environ. Sci. Technol.* **48** 13451–8

Jeong C-B *et al* 2017 Adverse effects of microplastics and oxidative stress-induced MAPK/Nrf2 pathway-mediated defense mechanisms in the marine copepod Paracyclopina nana *Sci. Rep.* **7** 41323

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 and 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** 8849–57

Johnston L W, Bergami E, Rowlands E and Manno C 2023 Organic or junk food? Microplastic contamination in Antarctic krill and salps *R. Soc. Open Sci.* **10** 221421

Kaandorp M L A, Dijkstra H A and Sebille E v 2021 Modelling size distributions of marine plastics under the influence of continuous cascading fragmentation *Environ. Res. Lett.* **16** 054075

Karakuş O, Völker C, Iversen M, Hagen W and Hauck J 2022 The role of zooplankton grazing and nutrient recycling for global ocean biogeochemistry and phytoplankton phenology *J. Geophys. Res.: Biogeosci.* **127** e2022JG006798

Kvale K, Hunt C, James A and Koeve W 2023 Regionally disparate ecological responses to microplastic slowing of faecal pellets yields coherent carbon cycle response *Front. Mar. Sci.* **10** 1111838

Kvale K and Oschlies A 2022 Recovery from microplastic-induced marine deoxygenation may take centuries *Nat. Geosci.* **16** 1–3

Kvale K, Prowe A E F, Chien C-T, Landolfi A and Oschlies A 2021 Zooplankton grazing of microplastic can accelerate global loss of ocean oxygen *Nat. Commun.* **12** 2358

Kwiatkowski L, Aumont O and Bopp L 2018 Consistent trophic amplification of marine biomass declines under climate change *Glob. Change Biol.* **25** 218–29

Kwiatkowski L *et al* 2020 Twenty-first century ocean warming, acidification, deoxygenation and upper-ocean nutrient and primary production decline from CMIP6 model projections *Biogeosciences* **17** 3439–70

Lampert W, Fleckner W, Rai H and Taylor B E 1986 Phytoplankton control by grazing zooplankton: a study on the spring clear-water phase1 *Limnol. Oceanogr.* **31** 478–90

Lebreton L and Andrady A 2019 Future scenarios of global plastic waste generation and disposal *Palgrave Commun.* **5** 1–11

Lebreton L C M, van der Zwet J, Damsteeg J-W, Slat B, Andrady A and Reisser J 2017 River plastic emissions to the world's oceans *Nat. Commun.* **8** 15611

Lee K-W, Shim W J, Kwon O Y and Kang J-H 2013 Size-dependent effects of micro polystyrene particles in the marine copepod *Tigriopus japonicus Environ. Sci. Technol.* **47** 11278–83

Lloyd-Smith M and Immig J 2018 Guide sur les polluants océaniques *Menaces Toxiques Pour la Santé Humaine et la vie Marine* (IPEN) p 122

Lobelle D, Kooi M, Koelmans A A, Laufkötter C, Jongedijk C E, Kehl C and Sebille E V 2021 Global modeled sinking characteristics of biofouled microplastic *J. Geophys. Res. Oceans* **126** e2020JC017098

Long M, Moriceau B, Gallinari M, Lambert C, Huvet A, Raffray J and Soudant P 2015 Interactions between microplastics and phytoplankton aggregates: impact on their respective fates *Mar. Chem.* **175** 39–46

Longhurst A, Sathyendranath S, Platt T and Caverhill C 1995 An estimate of global primary production in the ocean from satellite radiometer data *J. Plankton Res.* **17** 1245–71

Longhurst A R and Harrison W G 1988 Vertical nitrogen flux from the oceanic photic zone by diel migrant zooplankton and nekton *Deep Sea Res.* A **35** 881–9

Lotze H K *et al* 2019 Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change *Proc. Natl Acad. Sci.* **116** 12907–12

Macias D, Garcia-Gorriz E, Piroddi C and Stips A 2014 Biogeochemical control of marine productivity in the Mediterranean Sea during the last 50 years *Glob. Biogeochem. Cycles* **28** 897–907

Madec G 2008 *NEMO Ocean Engine* (available at: http://nora.nerc.ac.uk/164324/)

Maes C, Grima N, Blanke B, Martinez E, Paviet-Salomon T and Huck T 2018 A surface "superconvergence" pathway connecting the South Indian Ocean to the subtropical South Pacific gyre *Geophys. Res. Lett.* **45** 1915–22

Malinowski C R, Searle C L, Schaber J and Höök T O 2023 Microplastics impact simple aquatic food web dynamics through reduced zooplankton feeding and potentially releasing algae from consumer control *Sci. Total Environ.* **904** 166691

McManamay R A, Webster J R, Valett H M and Dolloff C A 2011 Does diet influence consumer nutrient cycling? Macroinvertebrate and fish excretion in streams *J. North Am. Benthol. Soc.* **30** 84–102

Moore C J, Moore S L, Weisberg S B, Lattin G L and Zellers A F 2002 A comparison of neustonic plastic and zooplankton abundance in southern California's coastal waters *Mar. Pollut. Bull.* **44** 1035–8

Ogonowski M, Schür C, Jarsén Î and Gorokhova E 2016 The effects of natural and anthropogenic microparticles on individual fitness in *Daphnia magna PLoS One* **11** e0155063

Onink V, Jongedijk C, Hoffman M, Sebille E v and Laufkötter C 2021 Global simulations of marine plastic transport show plastic trapping in coastal zones *Environ. Res. Lett.* **16** 064053

Onink V, Kaandorp M L A, van Sebille E and Laufkötter C 2022 Influence of particle size and fragmentation on large-scale microplastic transport in the mediterranean sea *Environ. Sci. Technol.* **56** 15528–40

Persson L *et al* 2022 Outside the Safe Operating Space of the Planetary Boundary for Novel Entities *Environ. Sci. Technol.* **56** 1510–21

Rafter P, Sigman D and Mackey K 2017 Recycled iron fuels new production in the eastern equatorial Pacific Ocean *Nat. Commun.* **8** 1100

Ratnarajah L *et al* 2023 Monitoring and modelling marine zooplankton in a changing climate *Nat. Commun.* **14** 564

Richon C, Aumont O and Tagliabue A 2020 Prey stoichiometry drives iron recycling by zooplankton in the global ocean *Front. Mar. Sci.* **7** 451

Richon C, Dutay J-C, Bopp L, Vu B L, Orr J C, Somot S and Dulac F 2019 Biogeochemical response of the mediterranean sea to the transient SRES-A2 climate change scenario *Biogeosciences* **16** 135–65

Richon C, Gorgues T, Paul-Pont I and Maes C 2022 Zooplankton exposure to microplastics at global scale: influence of vertical distribution and seasonality *Front. Mar. Sci.* **9** 947309

Richon C, Kvale K, Lebreton L and Egger M 2023 Legacy oceanic plastic pollution must be addressed to mitigate possible long-term ecological impacts *Microplast. Nanoplast.* **3** 25

Richon C and Tagliabue A 2021 Biogeochemical feedbacks associated with the response of micronutrient recycling by zooplankton to climate change *Glob. Change Biol.* **27** 4758–70

Richon C, Wagner C, Sunderland E M, Ayata S-D and Tagliabue A 2024 A global biogeography analysis reveals vulnerability of surface marine zooplankton to anthropogenic stressors *One Earth* **7** 146–60

Rochman C M *et al* 2019 Rethinking microplastics as a diverse contaminant suite *Environ. Toxicol. Chem.* **38** 703–11

Setälä O, Fleming-Lehtinen V and Lehtiniemi M 2014 Ingestion and transfer of microplastics in the planktonic food web *Environ. Pollut.* **185** 77–83

Sonke J E, Koenig A M, Yakovenko N, Hagelskjær O, Margenat H, Hansson S V, De Vleeschouwer F, Magand O, Le Roux G and Thomas J L 2022 A mass budget and box model of global plastics cycling, degradation and dispersal in the land-ocean-atmosphere system *Microplast. Nanoplast.* **2** 28

Steinberg D K and Landry M R 2017 Zooplankton and the Ocean Carbon Cycle *Annu. Rev. Mar. Sci.* **9** 413–44

Sterner R W 2009 Role of zooplankton in aquatic ecosystems *Encyclopedia of Inland Waters* ed G E Likens (Academic) pp 678–88

Tagliabue A, Kwiatkowski L, Bopp L, Butenschön M, Cheung W, Lengaigne M and Vialard J 2021 Persistent uncertainties in Ocean net primary production climate change projections at regional scales raise challenges for assessing impacts on ecosystem services *Front. Clim.* **3** 15

Turner J T 2015 Zooplankton fecal pellets, marine snow, phytodetritus and the ocean's biological pump *Prog. Oceanogr.* **130** 205–48

van Sebille E *et al* 2020 The physical oceanography of the transport of floating marine debris *Environ. Res. Lett.* **15** 023003

van Sebille E, Wilcox C, Lebreton L, Maximenko N, Hardesty B D, Franeker J A V, Eriksen M, Siegel D, Galgani F and Law K L 2015 A global inventory of small floating plastic debris *Environ. Res. Lett.* **10** 124006

Yin J, Duan C, Zhou F, Gong L, Gunathilaka M D K L, Liu X, Liu D, Shen A and Pan Y 2024 Microplastics affect interspecific interactions between cladoceran species in the absence and presence of predators by triggering asymmetric individual responses *Water Res.* **248** 120877

Yu S-P, Cole M and Chan B K K 2020 Review: effects of microplastic on zooplankton survival and sublethal responses *Oceanography and Marine Biology* 1st edn, ed S J Hawkins, A L Allcock, A E Bates, A J Evans, L B Firth, C D McQuaid, B D Russell, I P Smith, S E Swearer and P A Todd (CRC Press) pp 359–408

Zalasiewicz J *et al* 2015 When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal *Quat. Int.* **383** 196–203