The long-term legacy of plastic mass production

Sönke Hohn[1,*], E. Acevedos-Trejos[1], J. F. Abrams[2,3], J. Fulgencio de Moura[1], R. Spranz[4] & Agostino Merico[1,5]

[1]Leibniz Centre for Tropical Marine Research (ZMT), Fahrenheitstraße 6,28359 Bremen, Germany

[2]Global Systems Institute and Institute of Data Science and Artificial Intelligence, University of Exeter, Exeter, EX4 4PY, United Kingdom

[3]Leibniz Institute for Zoo and Wildlife Research (IZW), Alfred-Kowalke-Straße 17, 10315 Berlin, Germany

[4]Making Oceans Plastic Free e.V., Basler Landstr. 41a, 79111 Freiburg, Germany

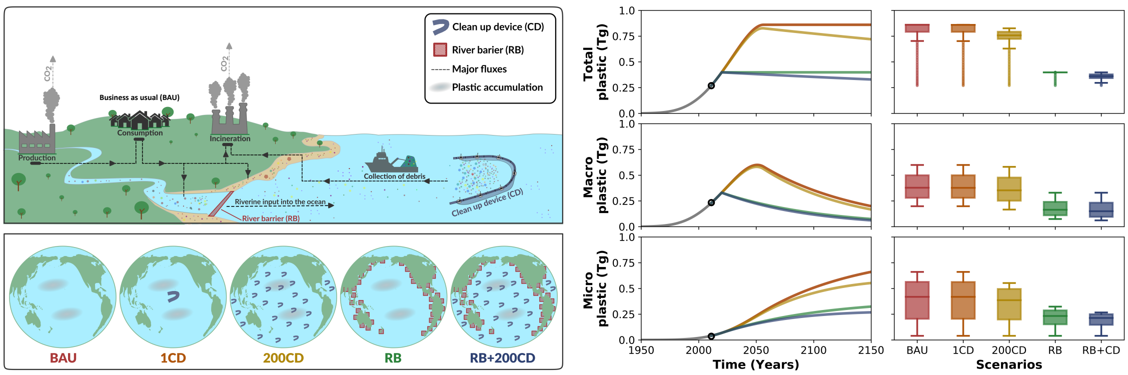
[5]Department of Physics and Earth Sciences, Jacobs University Bremen, Campus Ring 1, 28759 Bremen, Germany

*To whom correspondence should be addressed; E-mail: soenke.hohn@leibniz-zmt.de.

Highlights

- The long-term consequences of global plastic production are still unknown
- We examine the effectiveness of ocean cleanup devices and river barriers
- Collection in both rivers and seas can reduce plastic pollution significantly
- Plastic production and incineration are relevant contributions to CO_2 emissions
- Long-term solutions should combine emission reduction and collection reinforcement

Graphical abstract



Abstract

Mismanaged plastic waste is transported via rivers or city drains into the ocean where it accumulates in coastal sediments, ocean gyres and the deep ocean. Plastic harms marine biota and may ultimately return to humans via the food chain. Private initiatives proposing to collect plastic from the sea and rivers have gained widespread attention, especially in the media. However, few of these methods are proven concepts and it remains unclear how effective they are. Here we estimate the amount of plastic in the global surface ocean to assess the long-term legacy of plastic mass production, calculate the time required to clean up the oceans with river barriers and clean up devices, and explore the fate of collected plastic waste. We find that the projected impact of both single and multiple clean up devices is very modest. A significant reduction of plastic debris in the ocean can be only achieved with collection at rivers or with a combination of river barriers and clean up devices. We also show that the incineration and production of plastic has a significant long-term effect on the global atmospheric carbon budget. We conclude that a combination of reduced plastic emissions and reinforced collection is the only way to rid the ocean of plastic waste.

Keywords

Plastic pollution, Marine debris, Litter, Clean up devices, Waste management, Mathematical model, Future scenarios

1. Introduction

Plastic waste has become globally pervasive (Andrady, 2011; Cressey, 2016; Doyle, Watson, & Bowlin, 2011; Eriksen et al., 2013; Cózar et al, 2014; Barnes, Galgani, Thompson, & Barlaz, 2009; Law, 2017; Law, 2010; van Sebille et al, 2015; Worn, Lotze, Jubinville, Wilcox, & Jambeck, 2017). In 2015, mismanaged plastic was estimated at 6.3 Pg, 79% of which ended up in landfills or was released to the natural environment (Geyer, Jambeck, & Law, 2017). The accumulation of plastic waste in the environment (Worm, 2015) has become increasingly hazardous (Rochman, 2013) and global policy actions have been invoked to reduce the effects of plastic pollution (Xanthos & Walker, 2017; Löhr et al, 2017; Vince & Hardesty, 2017; Tessnow-von Wysocki, & Le Billon, 2019). Although the implications of plastic waste on Earth system processes are not fully determined, the irreversible and ubiquitous nature of this form of pollution represents an additional threat to planetary boundaries (Rockström et al, 2009; Steffen et al, 2015; Villarrubia-Gómez, Cornell, & Fabres, 2018).

Annually, 5 to 13 Tg of plastic invade the oceans from land (Jambeck et al, 2015; Boucher & Friot, 2017). Marine plastic debris are found in coastal areas all around the globe (Jambeck & Jonson, 2015), in sedimentary environments of fjords, estuaries, shallow coastal areas, continental shelves (Harris, 2020), and even in the deepest part of the ocean (Chiba et al, 2018). The positively buoyant plastic polymers, however, accumulate in the surface waters of large ocean gyres as a result of global ocean circulation (van Sebille et al, 2015). Approximately 5.25 trillion plastic particles, weighing about 269,000 Mg, float on the ocean surface (Eriksen et al, 2014) with concentrations of up to 580,000 plastic fragments per square kilometer (Barnes, Galgani, Thompson, & Barlaz, 2009). The riverine transport of plastic debris into the ocean (Zhao, Zhu, & Wang, 2014; Lebreton et al., 2017) is directly related to the production, rapid disposal, often after single use, and mismanagement of plastic waste at a global scale (Jambeck et al, 2015). Given the future projections of plastic production and the lack of effective disposal strategies, the amount of plastic waste in the natural environment is expected to double by 2050 (Geyer, Jambeck, & Law, 2017).

Oceanic plastic debris is recognized as a major threat for global marine ecosystems with expected negative consequences for marine wildlife and also for human health (Barnes, Galgani, Thompson, & Barlaz, 2009; Talsness, Andrade, Kuriyama, Taylor & vom Saal, 2009; Jiang, 2018; Tavares et al., 2020). The impacts of marine plastic pollutants on the marine biota include physical injury linked to entanglement, as well as physiological, biochemical and behavioral impairments due to the ingestion of plastics and the harmful chemicals they contain (Besseling, Wegner, Foekema, Van Den Heuvel-Greve, & Koelmans, 2013; de Sá, Oliveira, Ribeiro, Rocha, & Futter, 2018; Chen et al., 2018). Small pieces of plastics have been found in the gastrointestinal tract of more than 2200 different marine species, from zooplankton to apex predators (de Sá, Oliveira, Ribeiro, Rocha, & Futter, 2018; Galloway, Cole, & Lewis, 2017; Wright, Thompson & Galloway, 2013; Jepsen & Bruyn, 2019, Tekman et al. 2020). The impact of plastic pollution is not limited to the individual level, but also has wide-reaching consequences at the population and community levels (Lamb et al., 2018). The fact that microplastics release harmful chemicals (e.g. phthalates, polybrominated diphenyl ethers - PBDEs, bisphenol A) (Engler, 2012; Lee, Shim, & Kwon, 2014; Rochman, Hoh, Kurobe, & Teh, 2013) exacerbates the problems.

The scale of the plastic problem calls for urgent mitigation strategies. Common interventions include national and subnational legislative measures, such as bans, taxes, and levies on single use plastics (Xanthos & Walker, 2017; Schnurr et al. 2018), and environmental education to avoid mismanagement and illegal disposal of plastic material at water bodies (Schnurr et al. 2018, Goodman et al. 2020). Private initiatives by NGOs and corporations can also have a positive effect on reducing single-use plastics (Schnurr et al. 2018), removing plastics from the environment or preventing them from reaching the ocean. The latter two mitigation strategies are promoted by initiatives such as the Ocean Cleanup project (https://theoceancleanup.com), which has the ambitious aim to clean 90% of the ocean plastic pollution by developing methods to remove plastic from oceans and rivers. These methods include the deployment of cost-effective cleaning devices in the great pacific garbage patch and 1000 autonomous interceptors in rivers, which are responsible for 80% of the global plastic pollution (https://theoceancleanup.com). However, it is unclear to what extent these cleaning and removal measures will be sufficient to abate the plastic problem.

Here, we use a mathematical model of the global surface ocean in combination with future projections of global plastic production and waste management (Geyer, Jambeck, & Law, 2017) to simulate plastic discard and accumulation in the past, present and future. Mathematical models are relevant tools to systematically test our understanding about a system (Levy and Currie, 2015) and were used to explore some of the unknowns of plastic pollution in the ocean (e.g. Lebreton et al. 2019). We use our proposed model (see Materials and Methods) to explore different management scenarios to mitigate ocean plastic pollution and quantify the CO_2 emissions from burning the collected plastic waste. From an Earth System perspective, we finally discuss the uncertainties related to our understanding of the marine plastic problem.

2. Materials and Methods

2.1 Model description

The accumulation of buoyant plastic in the global surface ocean is calculated using a set of two differential equations for the total amounts of macroplastic (P_M) and microplastic (P_m). We do not calculate the accumulation of nanoplastics (plastic particles of less than 1 micron) because their amount in the ocean has not been quantified (Koelmans, Besseling, & Shim, 2015). Part of the uncertainty about nanoplastic concentration in the ocean arises from the difficulties to discern such small particles in the field with environmental abundances below detection limits and inconsistent exposure conditions and methodologies (da Costa et al., 2016).

$$\frac{d}{dt}P_M = P_d \cdot f_{ocean} - F_M \cdot P_M - N_{CUP} \cdot \frac{\psi \cdot L_{CUP}}{A_{ocean}} \cdot P_M \quad [1]$$

$$\frac{d}{dt}P_m = F_M \cdot P_M - N_{CUP} \cdot \frac{\psi \cdot L_{CUP}}{A_{ocean}} \cdot P_m \quad [2]$$

The source of macroplastic to the ocean surface is calculated as the buoyant fraction (f_{ocean}) of mismanaged plastic discard (P_d) that is washed into the ocean via rivers (Lebreton et al., 2017; Hurley, Woodward, & Rothwell, 2018). Fragmentation (F_M) of macroplastic (P_M) due to exposure to UV-light and wave action (Barnes, Galgani, Thompson, & Barlaz, 2009) decreases the macroplastic pool and increases microplastic (P_m). Note that we do not simulate the ingestion of plastic by marine organisms (de Sá, Oliveira, Ribeiro, Rocha, & Futter, 2018; Galloway, Cole, & Lewis, 2017; Wright, Thompson, & Galloway, 2013; Jepsen, & Bruyn, 2019) because this flux and associated excretion of plastic are not known (Bergmann, Gutow, & Klages, 2015; Frydkjær et al, 2017; Ory, Gallardo, Lenz, & Thiel, 2018). The amount of plastic that sinks due to biofouling (Fazey, & Ryan, 2016; Kaiser, Kowalski, Waniek, 2017) is also not known and this flux is therefore not modeled explicitly. However, the quantification of plastic in ocean surface waters (Eriksen et al., 2014) covers only the relative fraction of plastics that remained positively buoyant over 61 years. The simulation of the net accumulation of surface plastics, therefore, implicitly excludes plastic waste that never reaches the ocean, plastics with a higher density that are immediately lost to the ocean interior, or plastics that were removed from the surface between 1950 and 2011 due to biofouling. All those potential sinks are thus implicitly accounted for as the model considers only the relative fraction of plastic waste that contributes to the net accumulation of surface plastic.

2.2 Forcing data and initialization

The annual plastic discard on land (P_d) is obtained from projections of future plastic emissions (Geyer, Jambeck, & Law, 2017). Since plastic production started in the early 1950s, we initialized the model with zero plastic content in the year 1950. A global quantification of the total plastic content of the global surface ocean reported an amount of 268,940 Mg of total plastic floating in the surface ocean of which 233,400 Mg are macroplastic and 35,540 Mg represent the size class termed microplastic (Eriksen et al., 2014). These numbers are used to constrain the parameter values of the model and provide a conservative estimate of ocean surface plastic pollution, but we expect this number to increase as new information becomes available. The value of the relative fraction of plastic waste that reaches the ocean and accumulates in the surface ocean, f_M, is chosen to match the accumulation of total plastic from 1950 to 2011. The value of the fragmentation rate of the bigger macroplastic into the smaller size class of microplastic, F_M, is then adjusted to match the relative fractions of macro- and microplastic according to the observations (Eriksen et al., 2014).

2.3 Plastic collection

We introduce the effect of planned ocean clean up devices into the model as additional sinks for both macro- and microplastic. The plastic removal depends on the number of devices deployed (N_{CUP}), the length of the devices (L_{CUP}), the flow speed that brings plastic debris to the devices (ψ), and the amount of macro- and microplastic at the ocean surface. We test various scenarios to mitigate plastic pollution starting in the year 2020 by either switching on the collection via clean up devices, turning off riverine input of plastic, or doing both.

One ocean cleanup device has a length of 600 m and is deployed in an area that allows an average flow speed of 14 cm s^{-1} (https://theoceancleanup.com) leading to a total clearance of 2,649 km^2 per year per device. Given a total surface area of the global ocean (A_{ocean}) of approximately $361 \cdot 10^6$ km^2, this yields a relative fraction of 0.07% of the global surface ocean that can be cleared by one device per year. Admittedly, the model assumes that the ocean surface plastic is homogeneously distributed across the global surface ocean. The model may therefore underestimate the efficiency of the ocean cleanup devices. However, the model accounts for the magnitude of the global ocean and therefore accounts for the limits of a small number of individual devices to clear the whole surface ocean.

2.4 CO_2 emissions

The amount of plastic that is collected under the different cleanup scenarios is converted into CO_2 emissions using a conversion factor of 2.6 kg CO_2 per kg of plastic burned (Harding, Dennis, von Blottnitz, & Harrison, 2007). The emitted CO_2 is then accumulated in an atmospheric box in order to quantify the total expected impact of the incineration of collected ocean plastic. Additionally, the expected CO_2 emissions from the increasing plastic production and incineration on land are calculated according to the scenario of (Geyer, Jambeck, & Law, 2017) using a conversion of 0.35 kg CO_2 per kg of plastic produced and 2.6 kg CO_2 per kg of plastic burned (Harding, Dennis, von Blottnitz, & Harrison, 2007).

3. Results and Discussion

3.1 Accumulation of plastic

The discard rate of plastic waste is projected to reach zero in 2052 due to a rise in the recycling rate and the incineration of plastic waste on land (Geyer, Jambeck, & Law, 2017). Using this scenario and the projection of historic and future generation of plastic waste (Geyer, Jambeck, & Law, 2017), we estimate annual discard rates to simulate the accumulation of plastic waste in the surface waters of the open ocean. Our results suggest that plastic emissions will peak in the year 2029.

Since large-scale plastic production started in the early 1950s, we initialized our model with a plastic concentration in the surface ocean equal to zero in the year 1950. In 2011, the total amount of floating plastic in the surface ocean was quantified to be approximately 269,000 Mg (Eriksen et al., 2014). We used this estimate to quantify the relative fraction of generated plastic waste that reaches the ocean and remains floating in the surface waters (f_{ocean}). This fraction is around 6.8 ppm of the total plastic discarded. The relative fraction of mismanaged plastic entering the ocean interior may be much higher (Jambeck et al., 2015), but here we focus on the amount of plastic that reaches the ocean surface water and remains positively buoyant during the considered accumulation period of 61 years. This simulated net accumulation of plastic in the surface ocean implicitly includes losses of plastic particles sinking into the ocean interior as a consequence of biofouling (Fazey, & Ryan, 2016; Kowalski, Reichardt, & Waniek, 2016; Kaiser, Kowalski, & Waniek, 2017).

If we consider that plastic waste enters the ocean as macroplastic and that microplastic forms after fragmentation of bigger plastic particles (Barnes, Galgani, Thompson, & Barlaz, 2009; Koelmans, Kooi, Law, & van Sebille, 2017), we obtain a maximum possible fragmentation rate, F_M, of 1.14% a^{-1} that is consistent with the relative fractions of macro- and microplastic measured in the year 2011 (Eriksen et al., 2014). This fragmentation rate reflects a theoretical maximum because, in reality, a certain fraction of plastic enters the ocean as microplastic (Horton et al. 2017; Lebreton et al., 2017; Hurley, Woodward, & Rothwell, 2018) and the true fragmentation rate will, therefore, be lower than our estimate. However, the relative amount of microplastic with respect to total plastic release is highly variable between rivers (Lebreton et al., 2017) and this parameter is, therefore, associated to large uncertainties. Given also that the accumulated mass of macroplastic is almost one order of magnitude larger than that of microplastic (Eriksen et al., 2014), we omit the release of microplastic into the ocean and combine its uncertainty with the fragmentation of macroplastic to microplastic.

With these two parameters, f_{ocean} and F_M, we can simulate future scenarios of open ocean surface accumulation of both macro- and microplastic (Lebreton et al., 2018) using the projections of plastic waste generation and discard (Geyer, Jambeck, & Law, 2017). Our model predicts that total plastic waste will continue to accumulate in the surface ocean until 2052 and then remain steady at about 860,600 Mg (Fig. 2). According to this result, if no further action is taken to prevent plastic pollution (that is, if we follow the business as usual scenario, BAU), then the amount of plastic in the ocean will triple with respect to 2011, even if plastic discard is completely abandoned in 2052 and all plastic waste is burnt or recycled in the future (Geyer, Jambeck, & Law, 2017). The ongoing fragmentation of macroplastic to microplastic by UV light and wave action (Barnes, Galgani, Thompson, & Barlaz, 2009) will decrease macroplastic concentrations after plastic emissions cease in 2052 at the expense of increasing microplastic concentrations (Fig. 2). Note, however, that we do not consider further fragmentation of microplastic into nanoplastic (Koelmans, Kooi, Law, & van Sebille, 2017) because the global concentration of nanoplastic is not known (Koelmans, Besseling, & Shim, 2015) and thus the model cannot be constrained in this respect.

3.2 Ocean Cleanup and plastic collection

The projected future increase in ocean plastic emphasizes the need to actively counterbalance this form of pollution by removing plastic waste from the surface ocean. One initiative to collect surface plastic at a large scale is the Ocean Cleanup project, whose aim is to clean the Pacific garbage patch within the next 20 years. The method consists in deploying 600 m long floating barriers in the garbage patch. These barriers are designed to hold the floating plastic using a vertical screen and are able to catch plastic particles down to the size of about 1mm (https://theoceancleanup.com). The plastic is then collected by a vessel and transported to land for incineration or recycling. The speed with which ocean currents will transport plastics to the devices is estimated at around 14 cm s^{-1}, resulting in about 2700 km a^{-1}, or 7.3 ppm of the global surface ocean being cleared by one device annually. Assuming that the cleaning devices work without failure and assuming that 100% of the collected plastic can be removed from the ocean irrespective of its size, we quantify the impact of one Ocean Cleanup device on the total plastic accumulation in the global surface ocean (Fig. 2, 1CD). We find that the amount of surface plastic in the open ocean will only be reduced by 768 Mg with respect to the business as usual scenario (which is a reduction of 0.09% of total ocean surface plastic) by the year 2150. Note that the model assumes a homogeneous distribution of plastic debris throughout the global surface ocean.

Since the projected impact of a single clean up device is relatively low with respect to the amount of plastic present in the ocean, we analyze the potential impact of deploying 200 Cleanup devices in the year 2020, running without downtime until 2150. In this scenario, global floating plastic debris will be reduced by 44,900 Mg of plastic with 816,000 Mg of plastic remaining afloat at the ocean surface by 2150 (Fig. 2, 200CD). Given the costs associated with the production and maintenance of the proposed Cleanup devices, the relative impact or catch per unit effort (CPUE) is quite modest. Therefore, we explored the potential effect of surface barriers at river mouths as an alternative solution to reduce ocean plastic pollution. A complete halt of plastic emissions into the ocean by the year 2020 due to the implementation of effective barriers (scenario ES) could reduce the amount of ocean surface plastic by 462,000 Mg with respect to the business as usual scenario (Fig. 2, ES). This would leave around 398,000 Mg of plastic debris floating in the ocean. However, although river barriers are quite effective at preventing plastic from reaching the ocean, they are of no help with the plastic that already made its way into the ocean (Cózar et al, 2014; Eriksen et al., 2014; Eriksen et al., 2013; Law et al., 2010; Lebreton et al., 2018). Our model shows that only a combination of reduced emissions and active removal of floating plastic (Scenario ES+CD) can effectively mitigate the problem of plastic pollution (Fig. 2). The amount of plastic that can be collected in a given time period, however, depends on the concentration of plastic particles per unit volume and the speed of the water current. Therefore, the efficiency of any Cleanup device will decline as surface plastic concentrations reduce, thus increasing relative costs over time.

3.3 The fate of collected plastic

Even if the ocean plastic can be successfully collected, questions about the fate of this collected waste remain. Currently, most discarded plastics end up in landfills where they take hundreds of years to decompose while leaching toxins into soil and groundwater during the process (Thompson, Moore, Saal, & Swan, 2009; Teuten et al., 2009). There are possibly three options to remediate the problem: (1) recycling, (2) incineration, and (3) permanent burial. Much of the collected ocean plastic is very difficult to recycle (Bergmann, Gutow, & Klages, 2015; Moore, 2015) because of different types of plastics and the contamination by ocean sources. Marine plastics include many different compositions, qualities, sizes, shapes and colors, making the separation into pure streams for traditional recycling cost prohibitive (Bergmann, Gutow, & Klages, 2015; Moore, 2015). The difficulty associated with recycling ocean plastics, therefore, leaves incineration or permanent burial as the only cost-effective options.

Permanent burial belowground could return the polymers to their provenance (Tolinski, 2011). However, it is unclear how far toxins could potentially leach from these reservoirs into the soil and groundwater (Knight, 1983; Hahladakis et al, 2018) or, in cases where burial is close to the land-sea transition zone, sedimentary transport can potentially bring this plastic litter to marine environments (Harris, 2020). In addition, given the incomplete understanding on the fate of plastic (particularly smaller particles such as nano and microplastic) in terrestrial and freshwater environments (Horton et al. 2017, Rochman 2018) and its interconnected cycling between atmosphere, marine, freshwater, and terrestrial environments (Rochman & Hoellein 2020) it is imperative to look for more sustainable alternatives and rethink the way we produce, consume, and dispose plastic (Gallo et al. 2018).

Turning plastic waste into energy may appear to be an attractive option as many types of plastic burn hotter than wood or coal. However, the incineration of plastic for producing electricity has a 25% efficiency, which is much lower than the 55% efficiency of new gas-fired power stations (Eriksson, 2009). Furthermore, the burning of plastic releases CO_2 and other toxic chemicals, such as hydrochloric acid, sulfur dioxide, dioxins, furans and heavy metals, as well as small particulates (Verma, Vinoda, Papireddy, & Gowda, 2016; Katami, Yashura, Okuda, & Shibamoto, 2002; Thompson, Moore, Saal, & Swan, 2009), to the atmosphere. These emissions will further contribute to air pollution and the ongoing rise in global atmospheric CO_2.

To investigate the impact to the atmosphere we quantify the CO_2 emissions resulting from burning the collected plastic waste. We assume that 2.6 kg CO_2 will be emitted per kilogram of burnt plastic (Harding, Dennis, von Blottnitz, & Harrison, 2007). Plastic collection on any significant scale would be possible only under scenarios ES and ES+CD. Here, annual plastic collection would peak within the first 20 years of plastic collection and rapidly drop to near zero as the amount of plastic available for collection dwindles (Geyer, Jambeck, & Law, 2017). Accordingly, cumulative CO_2 emissions (Fig. 4) would rapidly rise in the first 30 years of ocean plastic collection and plateau at around 1.4 Gt CO_2, which will add to the atmosphere less than 1 ppmv of CO_2 (Fig. 4). In all scenarios, the annual emissions from burning ocean plastic remain below 50,000 t a^{-1} (Fig. 4), which is comparatively much lower than the 10 Gt a^{-1} CO_2 emitted by fossil fuel combustion (Le Quéré et al, 2018).

Additionally, global plastic production is expected to increase over the next 30 years totaling 26 Gt by 2050 (Geyer, Jambeck, & Law, 2017). Accounting for the expected CO_2 emissions from the increasing plastic production will add another 10 Gt CO_2 to the atmosphere, corresponding to 4.4 ppmv (Fig. 4). If terrestrial plastic waste is also incinerated, an additional 33 Gt CO_2, or 15.7 ppmv, will be added to the atmosphere by 2050 (Fig. 4C). The combined emissions from total plastic production and incineration will add around 20 ppmv to the Earth's atmosphere. Therefore, although the CO_2 emissions from the incineration of collected ocean plastic are negligible, the impact on atmospheric CO_2 of large-scale production is significant.

3.4 Alternative solutions to marine plastic pollution

Based on the best available information on marine plastic pollution to date, our results show that removing plastic from the ocean has negligible effects due to the sheer size of the ocean surface and the magnitude of the annual plastic emissions into the natural environment. The best strategy to mitigate marine plastic pollution is therefore to avoid plastic entering the ocean, e.g. via barriers at river mouths, or to avoid plastic entering the natural environment from landfills by improving waste management (Haward, 2018; Hoornweg, Bhada-Tata, & Kennedy, 2013; Hoornweg, Bhada-Tata, & Kennedy, 2015), by implementing extended producer responsibility strategies (Prata et al. 2019, Diggle & Walker, 2020), and by burning plastic waste on land (Geyer, Jambeck, & Law, 2017). However, since the combustion of plastic waste adds to atmospheric CO_2 pollution (Eriksson, 2009; Harding, Dennis, von Blottnitz, & Harrison, 2007; Knorr, Jiang, & Arneth, 2016), the ultimate and most sustainable strategy is to reduce production and use on a global scale (Hoornweg, Bhada-Tata, & Kennedy, 2013; Spranz, Schlüter, & Vollan, 2018) and avoid incineration.

Plastic pollution is a complex and global problem that cannot be easily solved by individual states (Worm, Lotze, Jubinville, Wilcox, & Jambeck, 2017; Xanthos, & Walker, 2017; Löhr et al, 2017; Vince, & Hardesty, 2017; Tessnow-von Wysocki, & Le Billon, 2019). Despite the magnitude of the problem, there are a number of tools that can be applied by governments, businesses, NGOs and other actors to reduce waste and, in particular, to prevent the use of single-use plastics (Vince, & Hardesty, 2018; Worm, Lotze, Jubinville, Wilcox, & Jambeck; Rochman, 2016; Rochman et al., 2013; Haward, 2018). For example, through the implementation of taxes, fees, and/or bans on single-use plastic (Schnurr et al 2018), several countries around the globe have managed to reduce their use, although follow-up measures of their effectiveness on waste reduction are still necessary (Xanthos, & Walker, 2017). In addition, improving waste management and recycling, and promoting a circular economy can help to reduce plastic production and thus reduce the amount of plastic waste that enters the ocean (Worm, Lotze, Jubinville, Wilcox, & Jambeck, 2017). Businesses can tap into the needs of consumer groups concerned with environmental values and consumption ethics, by providing ecologically sound products and sustainable lifestyle solutions using materials alternative to plastic (Worm, Lotze, Jubinville, Wilcox, & Jambeck, 2017). NGOs and other actors can raise awareness of the plastic pollution problem, support further innovations, and promote the existing solutions (Xanthos, & Walker, 2017; Spranz, Schlüter, & Vollan, 2018, Prata et al. 2019).

The private Ocean Cleanup project has created a lot of awareness around plastic pollution. However, such initiatives and the way they are presented as effective solutions may create the misleading perception among the public that the problem is being solved and no further collective action is needed. Even if Ocean Cleanup could collect a considerable amount of plastic from the ocean, many waste management challenges would remain (Verma, Vinoda, Papireddy, & Gowda, 2016; Katami, Yashura, Okuda, & Shibamoto, 2002; Thompson, Moore, Saal, & Swan, 2009) and the majority of plastic pollution will remain untouched, within ecologically relevant time-scales, in deeper waters and ocean sediments (Goodman et al. 2020). We propose, therefore, that efforts should be focused on finding effective measures to reduce plastic use and production.

4. Author Contributions

SH and AM conceived the study. SH, EAT, and JFA ran the analyses. All authors contributed to interpret the results and write the manuscript.

5. Acknowledgements

EAT was funded by DFG (grant no. AC 331/1-1).

6. Competing Interests

The authors declare that they have no competing financial interests.

References

Andrady, A. L. (2011). Microplastics in the marine environment. Marine pollution bulletin, 62(8), 1596-1605.

Barnes, D. K., Galgani, F., Thompson, R. C., & Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 1985-1998.

Bergmann, M., Gutow, L., & Klages, M. (Eds.). (2015). Marine anthropogenic litter. Springer.

Besseling, E., Wegner, A., Foekema, E. M., Van Den Heuvel-Greve, M. J., & Koelmans, A. A. (2013). Effects of microplastic on fitness and PCB bioaccumulation by the lugworm Arenicola marina (L.). Environmental science & technology, 47(1), 593-600.

Boucher, J., & Friot, D. (2017). Primary microplastics in the oceans: a global evaluation of sources (pp. 2017-002). Gland, Switzerland: IUCN.

Chen, Q., Reisser, J., Cunsolo, S., Kwadijk, C., Kotterman, M., Proietti, M., Slat, B., Ferrari, F.F., Schwarz, A., Levivier, A. & Yin, D. (2018). Pollutants in plastics within the north Pacific subtropical gyre. Environmental science & technology, 52(2), 446-456.

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

Cózar, A., Echevarría, F., González-Gordillo, J.I., Irigoien, X., Úbeda, B., Hernández-León, S., Palma, Á.T., Navarro, S., García-de-Lomas, J., Ruiz, A. & Fernández-de-Puelles, M.L. (2014). Plastic debris in the open ocean. Proceedings of the National Academy of Sciences, 111(28), 10239-10244.

Cressey, D. (2016). The plastic ocean. Nature, 536(7616), 263-265.

da Costa, J. P., Santos, P. S., Duarte, A. C., & Rocha-Santos, T. (2016). (Nano) plastics in the environment–sources, fates and effects. Science of the Total Environment, 566, 15-26.

de Sá, L. C., Oliveira, M., Ribeiro, F., Rocha, T. L., & Futter, M. N. (2018). Studies of the effects of microplastics on aquatic organisms: what do we know and where should we focus our efforts in the future?. Science of the total environment, 645, 1029-1039.

Diggle, A., & Walker, T. R. (2020). Implementation of harmonized Extended Producer Responsibility strategies to incentivize recovery of single-use plastic packaging waste in Canada. Waste Management, 110, 20-23.

Doyle, M. J., Watson, W., Bowlin, N. M., & Sheavly, S. B. (2011). Plastic particles in coastal pelagic ecosystems of the Northeast Pacific ocean. Marine Environmental Research, 71(1), 41-52.

Engler, R. E. (2012). The complex interaction between marine debris and toxic chemicals in the ocean. Environmental science & technology, 46(22), 12302-12315.

Eriksen, M., Maximenko, N., Thiel, M., Cummins, A., Lattin, G., Wilson, S., Hafner, J., Zellers, A. & Rifman, S. (2013). Plastic pollution in the South Pacific subtropical gyre. Marine pollution bulletin, 68(1-2), 71-76.

Eriksen, M., Lebreton, L.C., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G. & 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(12), e111913.

Eriksson, O., & Finnveden, G. (2009). Plastic waste as a fuel-CO 2-neutral or not?. Energy & Environmental Science, 2(9), 907-914.

Fazey, F. M., & Ryan, P. G. (2016). Biofouling on buoyant marine plastics: An experimental study into the effect of size on surface longevity. Environmental Pollution, 210, 354-360.

Frydkjær, C. K., Iversen, N., & Roslev, P. (2017). Ingestion and egestion of microplastics by the cladoceran Daphnia magna: effects of regular and irregular shaped plastic and sorbed phenanthrene. *Bulletin of environmental contamination and toxicology*, *99*(6), 655-661.

Gallo, F., Fossi, C., Weber, R., Santillo, D., Sousa, J., Ingram, I., Nadal, A. & Romano, D. (2018). Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures. Environmental Sciences Europe, 30(1), 13.

Galloway, T. S., Cole, M., & Lewis, C. (2017). Interactions of microplastic debris throughout the marine ecosystem. Nature Ecology & Evolution, 1(5), 1-8.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science advances, 3(7), e1700782.

Goodman, A. J., Walker, T. R., Brown, C. J., Wilson, B. R., Gazzola, V., & Sameoto, J. A. (2020). Benthic marine debris in the Bay of Fundy, eastern Canada: Spatial distribution and categorization using seafloor video footage. Marine Pollution Bulletin, 150, 110722.

Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., & Purnell, P. (2018). An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. Journal of hazardous materials, 344, 179-199.

Harding, K. G., Dennis, J. S., Von Blottnitz, H., & Harrison, S. T. L. (2007). Environmental analysis of plastic production processes: comparing petroleum-based polypropylene and polyethylene with biologically-based poly-β-hydroxybutyric acid using life cycle analysis. Journal of biotechnology, 130(1), 57-66.

Harris, P. T. (2020). The fate of microplastic in marine sedimentary environments: A review and synthesis. Marine Pollution Bulletin, 158, 111398.

Haward, M. (2018). Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance. Nature communications, 9(1), 1-3.

Hoornweg, D., Bhada-Tata, P., & Kennedy, C. (2013). Environment: Waste production must peak this century. Nature News, 502(7473), 615.

Hoornweg, D., Bhada-Tata, P., & Kennedy, C. (2015). Peak waste: When is it likely to occur?. Journal of Industrial Ecology, 19(1), 117-128.

Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., & Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Science of the Total Environment, 586, 127-141.

Hurley, R., Woodward, J., & Rothwell, J. J. (2018). Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nature Geoscience, 11(4), 251-257.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R. & Law, K.L. (2015). Plastic waste inputs from land into the ocean. Science, 347(6223), 768-771.

Jambeck, J. R., & Johnsen, K. (2015). Citizen-based litter and marine debris data collection and mapping. Computing in Science & Engineering, 17(4), 20-26.

Jepsen, E. M., & de Bruyn, P. N. (2019). Pinniped entanglement in oceanic plastic pollution: A global review. Marine pollution bulletin, 145, 295-305.

Jiang, X. (2018). Toxic food. Nature Sustainability, 1(1), 12-12.

Kaiser, D., Kowalski, N., & Waniek, J. J. (2017). Effects of biofouling on the sinking behavior of microplastics. Environmental Research Letters, 12(12), 124003.

Katami, T., Yasuhara, A., Okuda, T., & Shibamoto, T. (2002). Formation of PCDDs, PCDFs, and coplanar PCBs from polyvinyl chloride during combustion in an incinerator. Environmental science & technology, 36(6), 1320-1324.

Knight, M. J. (1983). Effect of soil erosion on the long-term stability of FUSRAP near-surface waste-burial sites (No. ANL/EIS-18). Argonne National Lab., IL (USA).

Knorr, W., Jiang, L., & Arneth, A. (2016). Climate, CO2 and human population impacts on global wildfire emissions. Biogeosciences, 13(1).

Koelmans, A.A., Besseling, E., & Shim, W.J. (2015). Nanoplastics in the aquatic environment: critical review, in: In M. Bergmann, L. Gutow & M. Klages (Eds.), Marine anthropogenic litter (pp. 325-340). Berlin: Springer

Koelmans, A. A., Kooi, M., Law, K. L., & Van Sebille, E. (2017). All is not lost: deriving a top-down mass budget of plastic at sea. Environmental Research Letters, 12(11), 114028.

Kowalski, N., Reichardt, A. M., & Waniek, J. J. (2016). Sinking rates of microplastics and potential implications of their alteration by physical, biological, and chemical factors. Marine pollution bulletin, 109(1), 310-319.

Lamb, J. B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., True, J.D., Kelly, L.A., Ahmad, A., Jompa, J. & Harvell, C.D. (2018). Plastic waste associated with disease on coral reefs. Science, 359(6374), 460-462.

Law, K. L., Morét-Ferguson, S., Maximenko, N. A., Proskurowski, G., Peacock, E. E., Hafner, J., & Reddy, C. M. (2010). Plastic accumulation in the North Atlantic subtropical gyre. Science, 329(5996), 1185-1188.

Law, K. L. (2017). Plastics in the marine environment. Annual review of marine science, 9, 205-229.

Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P.A., Korsbakken, J.I., Peters, G.P., Canadell, J.G. & Arneth, A. (2018). Global carbon budget 2018. Earth System Science Data 10, 2141–2194.

Lebreton, L. C., Van Der Zwet, J., Damsteeg, J. W., Slat, B., Andrady, A., & Reisser, J. (2017). River plastic emissions to the world's oceans. Nature communications, 8, 15611.

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., Hajbane, S., Cunsolo, S., Schwarz, A., Levivier, A. & Noble, K. (2018). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Scientific reports, 8(1), 1-15.

Lebreton, L., Egger, M., & Slat, B. (2019). A global mass budget for positively buoyant macroplastic debris in the ocean. Scientific reports, 9(1), 1-10.

Lee, H., Shim, W. J., & Kwon, J. H. (2014). Sorption capacity of plastic debris for hydrophobic organic chemicals. Science of the Total Environment, 470, 1545-1552.

Levy, A. & Currie, A. (2015). Model organisms are not (theoretical) models. Br. J. Philos. Sci., 66, 327–348

Löhr, A., Savelli, H., Beunen, R., Kalz, M., Ragas, A., & Van Belleghem, F. (2017). Solutions for global marine litter pollution. Current opinion in environmental sustainability, 28, 90-99.

Moore, C. J. (2015). How much plastic is in the ocean? You tell me. Marine pollution bulletin, 92(1-2), 1-3.

Ory, N. C., Gallardo, C., Lenz, M., & Thiel, M. (2018). Capture, swallowing, and egestion of microplastics by a planktivorous juvenile fish. Environmental Pollution, 240, 566-573.

Prata, J. C., Silva, A. L. P., Da Costa, J. P., Mouneyrac, C., Walker, T. R., Duarte, A. C., & Rocha-Santos, T. (2019). Solutions and integrated strategies for the control and mitigation of plastic and microplastic pollution. International journal of environmental research and public health, 16(13), 2411.

Rochman, C. M., Browne, M.A., Halpern, B.S., Hentschel, B.T., Hoh, E., Karapanagioti, H.K., Rios-Mendoza, L.M., Takada, H., Teh, S. & Thompson, R.C. (2013a). Classify plastic waste as hazardous. Nature, 494(7436), 169-171.

Rochman, C. M., Hoh, E., Kurobe, T., & Teh, S. J. (2013b). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Scientific reports, 3, 3263.Rochman, C. M. (2016). Strategies for reducing ocean plastic debris should be diverse and guided by science. Environmental Research Letters, 11(4), 041001.

Rochman, C. M. (2018). Microplastics research—from sink to source. Science, 360(6384), 28-29.

Rochman, C. M., & Hoellein, T. (2020). The global odyssey of plastic pollution. Science, 368(6496), 1184-1185.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J. & Nykvist, B. (2009). Planetary boundaries: exploring the safe operating space for humanity. Ecology and society, 14(2).

Schnurr, R. E., Alboiu, V., Chaudhary, M., Corbett, R.A., Quanz, M.E., Sankar, K., Srain, H.S., Thavarajah, V., Xanthos, D. & Walker, T.R. (2018). Reducing marine pollution from single-use plastics (SUPs): A review. Marine pollution bulletin, 137, 157-171.

Spranz, R., Schlüter, A., & Vollan, B. (2018). Morals, money or the master: The adoption of eco-friendly reusable bags. Marine Policy, 96, 270-277.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A. & Folke, C. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223), 1259855.

Talsness, C. E., Andrade, A. J., Kuriyama, S. N., Taylor, J. A., & Vom Saal, F. S. (2009). Components of plastic: experimental studies in animals and relevance for human health. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 2079-2096.

Tavares, D. C., Moura, J. F., Acevedo-Trejos, E., Crawford, R., Makhado, N., Lavers, J., Witteveen, M., Ryan, P., & Merico, A. (2020) Confidence intervals and sample size for estimating the prevalence of plastic debris in seabird nests. Environmental Pollution 263(A), 114394.

Tekman, M. B., Wekerle, C., Lorenz, C., Primpke, S., Hasemann, C., Gerdts, G., & Bergmann, M. (2020). Tying up Loose Ends of Microplastic Pollution in the Arctic: Distribution from the Sea Surface through the Water Column to Deep-Sea Sediments at the HAUSGARTEN Observatory. Environmental Science & Technology, 54(7), 4079-4090.

Tessnow-von Wysocki, I., & Le Billon, P. (2019). Plastics at sea: Treaty design for a global solution to marine plastic pollution. Environmental Science & Policy, 100, 94-104.

Teuten, E. L., Saquing, J.M., Knappe, D.R., Barlaz, M.A., Jonsson, S., Björn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R. & Ochi, D. (2009). Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 2027-2045.

Thompson, R. C., Swan, S. H., Moore, C. J. & vom Saal, F. S. (2009). Our plastic agePhil. Trans. R. Soc. B3641973–1976

Tolinski, M. (2011). Plastics and sustainability: towards a peaceful coexistence between bio-based and fossil fuel-based plastics. John Wiley & Sons.

Van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., Van Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F. & Law, K.L., (2015). A global inventory of small floating plastic debris. Environmental Research Letters, 10(12), 124006.

Verma, R., Vinoda, K. S., Papireddy, M., & Gowda, A. N. S. (2016). Toxic pollutants from plastic waste-a review. Procedia Environmental Sciences, 35, 701-708.

Villarrubia-Gómez, P., Cornell, S. E., & Fabres, J. (2018). Marine plastic pollution as a planetary boundary threat–The drifting piece in the sustainability puzzle. Marine Policy, 96, 213-220.

Vince, J., & Hardesty, B. D. (2017). Plastic pollution challenges in marine and coastal environments: from local to global governance. Restoration ecology, 25(1), 123-128.

Vince, J., & Hardesty, B. D. (2018). Governance solutions to the tragedy of the commons that marine plastics have become. Frontiers in Marine Science, 5, 214.

Worm, B., Lotze, H. K., Jubinville, I., Wilcox, C., & Jambeck, J. (2017). Plastic as a persistent marine pollutant. Annual Review of Environment and Resources, 42, 1-26.

Worm, B. (2015). Silent spring in the ocean. Proceedings of the National Academy of Sciences, 112(38), 11752-11753.

Wright, S. L., Thompson, R. C., & Galloway, T. S. (2013). The physical impacts of microplastics on marine organisms: a review. Environmental pollution, 178, 483-492.

Xanthos, D., & Walker, T. R. (2017). International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review. Marine pollution bulletin, 118(1-2), 17-26.

Zhao, S., Zhu, L., Wang, T., & Li, D. (2014). Suspended microplastics in the surface water of the Yangtze Estuary System, China: first observations on occurrence, distribution. Marine pollution bulletin, 86(1-2), 562-568.

Figures

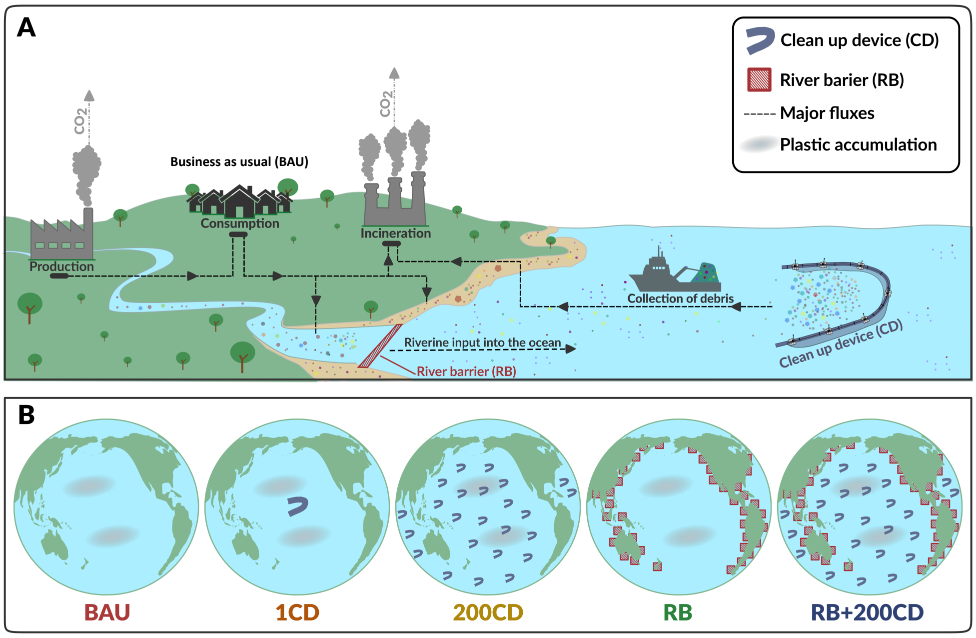


Figure 1: a) Processes related to oceanic plastic pollution. Plastic is produced from crude oil. After use, plastic is discarded, recycled, incinerated, or transferred to landfills. Transport via rivers leads to the accumulation of plastic waste in the ocean. Plastic debris in the ocean surface can be collected with floating devices whereas the plastic that makes it to the ocean interior is ultimately lost. Collected ocean plastic can be either recycled or incinerated, i.e. thermally recycled, a process that releases CO_2 to the atmosphere. b) We quantified the amount of plastic in the ocean over time according to different scenarios. The business as usual scenario (BAU), according to which plastic waste enters the ocean via rivers and accumulates in the surface ocean. This scenario assumes no removal of ocean plastic and no reduction of plastic emissions into the ocean besides the predicted enhancement of future plastic recycling (11). We explore four plastic removal scenarios: a scenario comprising one cleanup device (1CD), assumed to become operational in the year 2020; a scenario comprising 200 cleanup devices (200CD), assumed to become operational simultaneously in 2020; a scenario in which riverine plastic emissions into the ocean are assumed to cease in 2020 due to river barriers (RB) that collect plastic debris before it enters the ocean; and a combination of cleanup devices and river barriers (RB+CD) that also become operational in 2020.

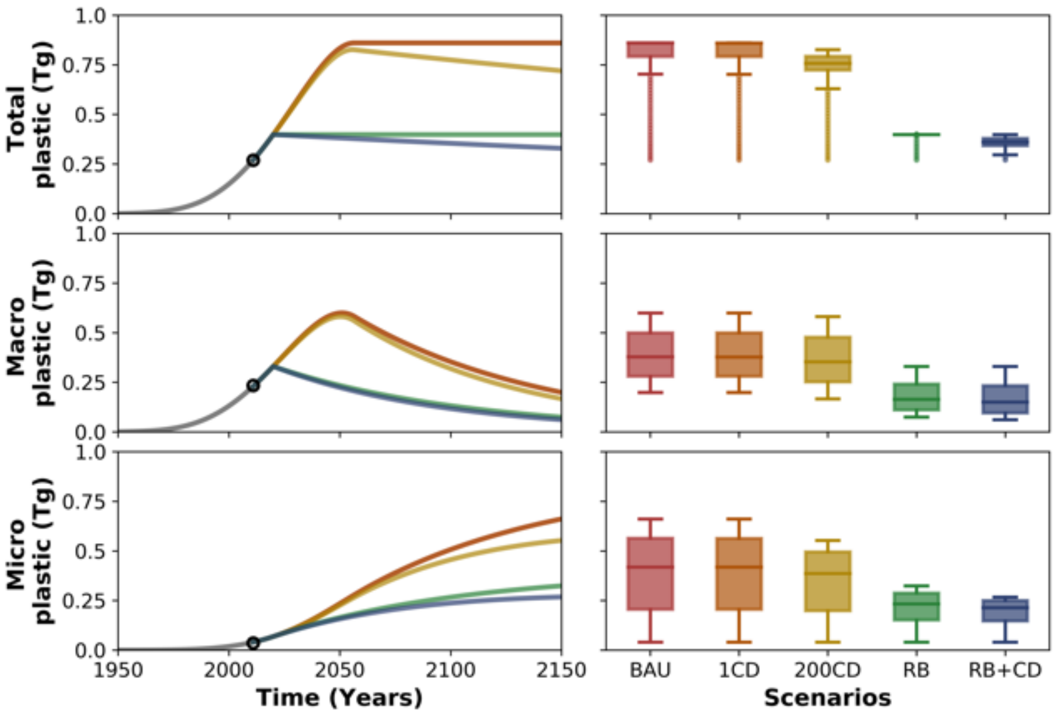


Figure 2: Projected plastic accumulation in the surface ocean according to different model scenarios. Business as usual (BAU, red), one clean up device (1CD, orange), 200 clean up devices (200CD, yellow), river barriers (RB, green), river barriers plus 200 clean up devices (RB+CD, blue). The diagrams on the left show the temporal development of surface concentrations of total plastic (upper), macroplastic (middle), and microplastic (lower panel). The model is calibrated with the observed amounts of surface plastic measured by (25) (open circles). The diagrams on the right show the total plastic accumulation according to each scenario and over the considered time period.

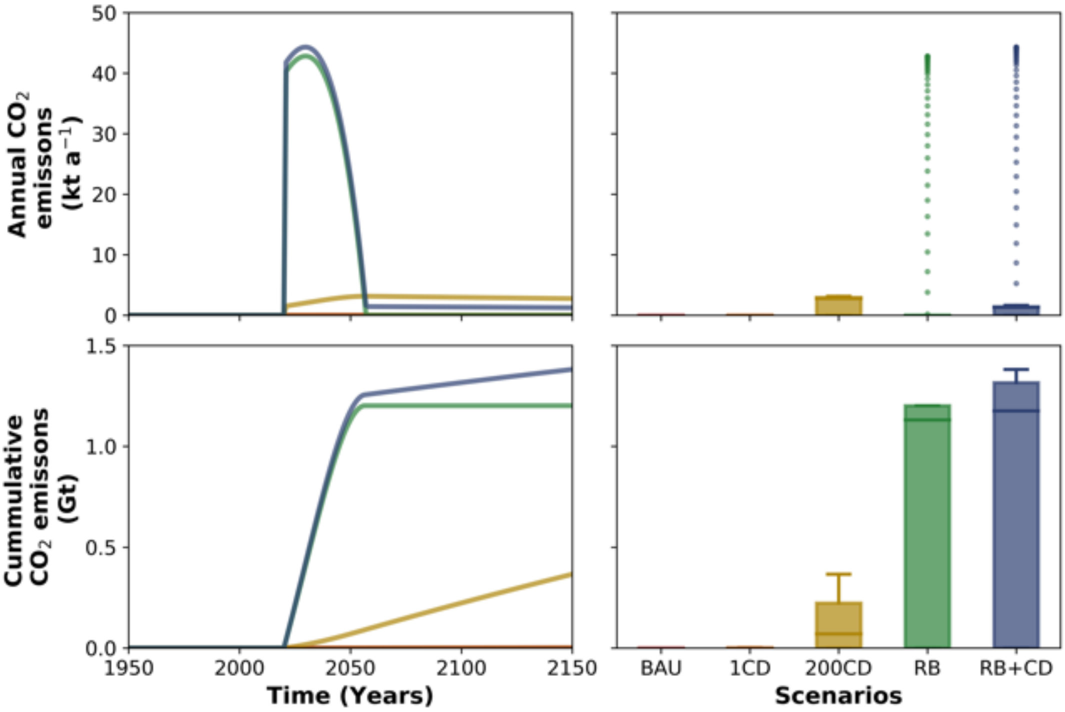


Figure 3: CO_2 emissions resulting from the incineration of plastic waste collected with different methods. BAU (red), no collection of ocean plastic; 1CD (orange), plastic collected by only one Cleanup device; 200CD (yellow), plastic collected by 200 Cleanup devices; RB (green), plastic collected with river barriers; RB+CD (blue), plastic collected with river barriers plus 200 Cleanup devices.

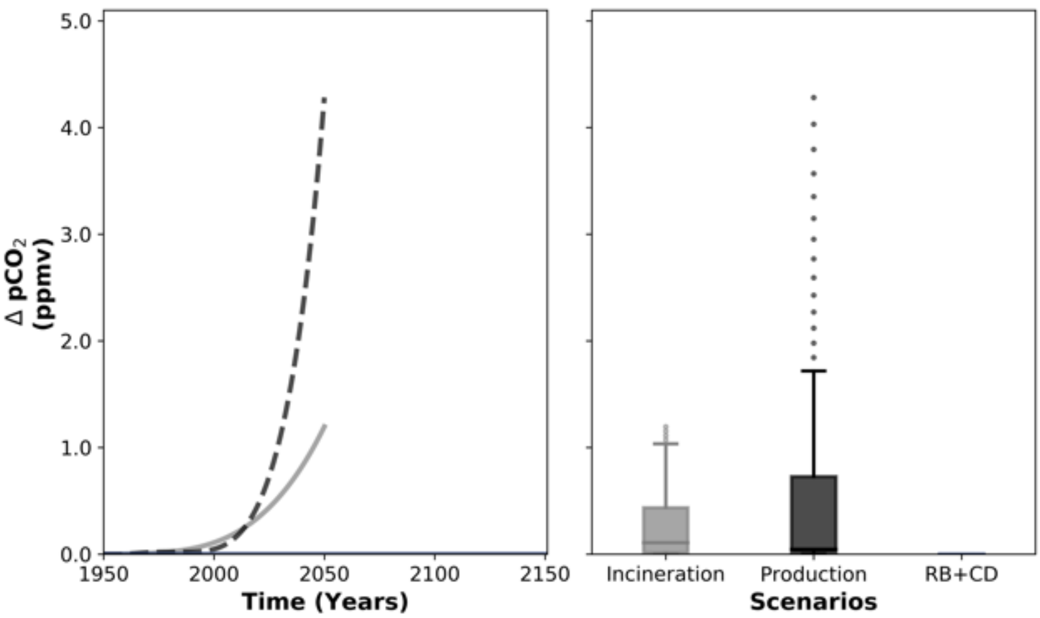


Figure 4: CO_2 emissions from producing and burning plastic on land. Incineration (grey), CO_2 emissions from incinerating plastic discarded on land; Production (black), CO_2 emissions from plastic production; RB+CD (blue), CO_2 emissions from burning plastic collected with river barriers plus 200 Cleanup devices (for comparison).