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LETTER

Modeling marine surface microplastic transport to assess optimal removal locations

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Abstract

Marine plastic pollution is an ever-increasing problem that demands immediate mitigation and reduction plans. Here, a model based on satellite-tracked buoy observations and scaled to a large data set of observations on microplastic from surface trawls was used to simulate the transport of plastics floating on the ocean surface from 2015 to 2025, with the goal to assess the optimal marine microplastic removal locations for two scenarios: removing the most surface microplastic and reducing the impact on ecosystems, using plankton growth as a proxy. The simulations show that the optimal removal locations are primarily located off the coast of China and in the Indonesian Archipelago for both scenarios. Our estimates show that 31% of the modeled microplastic mass can be removed by 2025 using 29 plastic collectors operating at a 45% capture efficiency from these locations, compared to only 17% when the 29 plastic collectors are moored in the North Pacific garbage patch, between Hawaii and California. The overlap of ocean surface microplastics and phytoplankton growth can be reduced by 46% at our proposed locations, while sinks in the North Pacific can only reduce the overlap by 14%. These results are an indication that oceanic plastic removal might be more effective in removing a greater microplastic mass and in reducing potential harm to marine life when closer to shore than inside the plastic accumulation zones in the centers of the gyres.

1. Introduction

Oceanic plastic pollution is a widespread problem that has heavily-documented environmental, ecological, and economical impacts (Gregory 2009, Thompson *et al* 2009). Plastic impacts range from the microscopic, as zooplankton ingest microplastics (Cole *et al* 2013), to the macroscopic, as ships could be damaged (APEC 2009). With the cumulative plastic ocean input expected to continue increasing in the coming decades (Jambeck *et al* 2015), these problems will only be exacerbated. Although larger plastics break down from several weathering processes (Eriksen *et al* 2014), they remain in the environment, with estimated lifespans of 'hundreds to thousands of years' (Barnes *et al* 2009).

While the marine plastic problem will never be solved unless we stop plastic input altogether, we can potentially reduce harm by removing marine plastic that is already in the ocean. *The Ocean Cleanup* is one proposed method to remove surface plastic, utilizing floating collection devices and the ocean currents to gather debris. *The Ocean Cleanup* focuses on placing plastic collectors ('sinks') in the regions of largest surface plastic mass in the so-called garbage patch in the North Pacific gyre, with the goal to most efficiently remove a significant amount of ocean plastic (Slat *et al* 2014, p 107). The question we address here, however, is whether the North Pacific garbage patch is the most effective location of these sinks. Since the centers of the subtropical gyres are oligotrophic and hence relatively devoid of animal life (van Sebille 2015, Wilcox *et al* 2015), placing sinks within these regions may not be the optimal strategy to reduce the impact of oceanic plastic.

Here, we investigate where in the ocean marine microplastic can most effectively be removed. We explicitly do not address engineering challenges associated with the design of the sinks, but assume that

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deploying, maintaining, and removing effective plastic collection devices is logistically and economically feasible. However, we hypothesize that removing floating microplastic from the ocean can be done more efficiently from near the coastline than from within the North Pacific garbage patch, as it is not the amount of microplastic but rather the flux of microplastics that determines the amount of plastic that can be removed in a given period. Furthermore, by placing the sinks close to the sources of pollution, the microplastic is removed before it can pass through areas of high ecosystem impact, thereby reducing harm.

To verify this hypothesis, we placed 29 sinks (the number proposed by *The Ocean Cleanup*) in an oceanographic model (van Sebille *et al* 2012, van Sebille 2014) and computed the amount of microplastic removed and reduction in the overlap with regions of phytoplankton growth by varying the sink locations. We then mapped the optimal locations for the two scenarios to identify regions of peak benefit—locations where the sinks might be placed to address both scenarios.

2. Methods

2.1. Tracer release

Observational drifter trajectories from the NOAA Global Drifter Program (Lumpkin 2003, Lumpkin *et al* 2012) were mapped onto a $1^\circ \times 1^\circ$ grid to create six transition matrices $\mathbf{P}_b$ representing the probabilities of moving from one cell to any other cell in a two-month period, which simulate the seasonal ocean circulation variability (van Sebille 2014). Each two-month iteration of time updated the probability of transport to any other cell (Froyland *et al* 2007, Dellnitz *et al* 2009, van Sebille 2014). We assumed plastic mass is conserved in the ocean by row normalizing all of the $\mathbf{P}_b$. The models were initialized with plastic tracer from coasts, following a procedure where the amount of plastic released in each country was related to the amount of mismanaged waste in a country (Jambeck *et al* 2015). Within each country the source amount released in each grid cell was proportional to the coastal population density (Lebreton *et al* 2012, van Sebille *et al* 2012). Coastal tracer was released every two months, following an exponential increase over time (Wilcox *et al* 2015) from 1965 to 2025, assuming pollution increases exponentially with production. The total tracer concentration in the year 2014 was then scaled per basin to best agree with a data set of more than 11 000 surface net trawls of 'small' (less than 20 cm in size) plastic counts and mass (van Sebille *et al* 2015). The model therefore simulates the mass flux of this microplastic.

2.2. Mass removal with sinks

To simulate the removal of mass for a given cell *c*, we multiplied the corresponding row in all six of the $\mathbf{P}_b$ matrices by (1–*captEff*) for the last 10 years of the simulation (from 2015 to 2025), where *captEff* represents the percentage of mass collected by a sink relative to the mass passing through cell *c* in a two-month span. *The Ocean Cleanup* team estimated that 29 sinks could remove 42% of the mass in the North Pacific Gyre (between 27–36° N and 130–149° W) over a decade (Slat *et al* 2014). With this data, the van Sebille (2014) model yields a *captEff* of 0.45, which was then used for all of the simulations. Note that our study should not be viewed as an endorsement of *The Ocean Cleanup* or its research—we merely use their sink number and *captEff* because this is, to our knowledge, the only study that has ever addressed these parameters. Furthermore, we expect that the main conclusions will stand for a broader range of *captEff* and we explicitly investigate the sensitivity of the number of sinks to the amount of microplastic captured.

2.3. Optimization for each scenario

Finding the optimal location of 29 sinks is a computationally hard problem. There are more than 30 000 different ocean grid cells in the model, so brute-force searching the entire phase space would mean computing sink system efficiency over $30\,000^{29} > 10^{129}$ scenarios. This is computationally unfeasible. Hence, searching needed to be done in an efficient way, to maximize the chance that we did find the global most optimal strategy for removing microplastic. For this, we realized that it is likely a good assumption to place sinks in regions where there is a large plastic mass flux. Even with this assumption, we ran each scenario for 1 week on a high-end iMac and could only test 500 sink arrangements. Given that there are over $30\,000^{29}$ scenarios without our assumption, and it took 1 week to run 500, it would have required more than 2.64×10^{125} years to obtain the globally optimal solution.

The oceans were partitioned into six basins: the North Pacific, South Pacific, North Atlantic, South Atlantic, Indian, and Mediterranean. For the microplastic mass removal scenario, the number of sinks in each basin at the start of the search was determined by multiplying the total number of sinks (29) by the percentage of mass in each region after 10 years without sinks. The initial sink locations within each basin were then determined by finding the coordinate with the maximum cumulative plastic mass flux after a decade (figure 1(a)).

In the ecosystem scenario, we created a map which assigned each $1^\circ \times 1^\circ$ cell a value corresponding to its net primary production (NPP, in mg Carbon per m^2 per day) based on satellite observations (Behrenfeld and Falkowski 1997; http://science.oregonstate.edu/ocean.productivity/index.php). This value can be used as an index of phytoplankton growth (Behrenfeld and Boss 2006), which in itself is a proxy of ecosystem size. It should be noted, while there is a very little information on how microplastic impacts phytoplankton growth, we have assumed here that the NPP-plastic overlap is a measure of generally negative

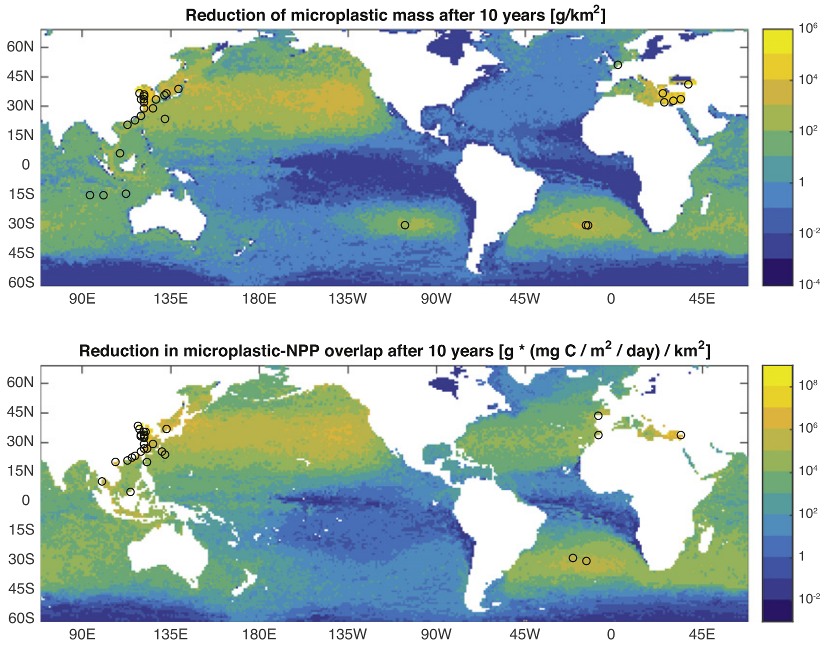

Figure 1. The set of 29 optimal sink locations for (a) the mass scenario where the objective is to remove the most microplastic and (b) the ecosystem scenario where the objective is to reduce the overlap between microplastic and plankton growth. In both cases, the vast majority of sinks are located close to coastlines, particularly in Asia. The locations were plotted on top of maps of the reduction by the sinks in (a) microplastic mass and (b) microplastic-NPP overlap in each grid cell after 10 years, compared to the case without any sinks.

impact on marine life. We then made a plastic-NPP overlap map by multiplying the microplastic mass in each cell by its corresponding NPP. A process similar to that above for the mass scenario was followed to identify the initial placement of sinks to minimize the overlap with NPP, so that the total number of sinks was multiplied by the percentage of the plastic-NPP overlap in each basin after 10 years without sinks. The initial sink locations within each basin were determined by finding the coordinates with the maximum cumulative overlap flux after a decade (figure 1(b)). Note that, in this ecosystem scenario, there is no initial sink in the South Pacific. This is likely due to a low microplastic mass relative to the other basins, as well as a small NPP-plastic overlap.

To find the optimal locations for each scenario, each sink was randomly moved from its initial location to another ocean coordinate within a $30^\circ \times 30^\circ$ grid. The optimal location for each sink was then determined from their new initialized location by moving to the optimal cell in a $5^\circ \times 5^\circ$ range. The sink continued to move in new $5^\circ \times 5^\circ$ regions until it could no longer optimize the global plastic removed or plastic-NPP overlap (depending on the scenario being investigated). This entire process was repeated 500 times (a number that was still computationally feasible, see above) to obtain a close-to-optimal sink arrangement for the two scenarios.

Note that, while we cannot be certain that our locations are indeed the most optimal, because the phase space is so enormous, we can make definite statements on how our locations compare to placing the sinks in the North Pacific garbage patch, as we can also compute the mass removed and the change in the plastic-plankton overlap if the 29 sinks were deployed between Hawaii and California.

3. Results

The majority of the optimal sink locations for each scenario (16 for plastic removal, 21 for reducing ecosystem harm) were in the North Pacific (figure 1), which is due to the massive plastic input sources in East Asia (Jambeck *et al* 2015). Furthermore, for both of the scenarios only a small fraction of the best sinks locations were in the centers of the gyres. This is an indication that while there is a larger microplastic mass in the gyres at any time, the mass flux is greater closer to coastlines. Both scenarios placed 2 sinks in the South Atlantic gyre, which is likely because there is no major single source of plastic pollution on the East coast of South America or the West coast of Africa.

Based on the model results, we found a set of locations that can remove 31% of the total microplastic mass by 2025 for the plastic removal scenario (figure 2(a), blue line) and another set that can reduce the plastic-NPP overlap by 46% by 2025 (figure 2(b), blue line). These placements are more effective than placing all 29 sinks in the North Pacific garbage patch, which can only remove 17% of the global plastic and reduce the overlap by 14% (figure 2, orange lines). The uncertainty in these estimates, based on the mapping procedure in van Sebille *et al* (2015), is 13% of the simulated estimate.

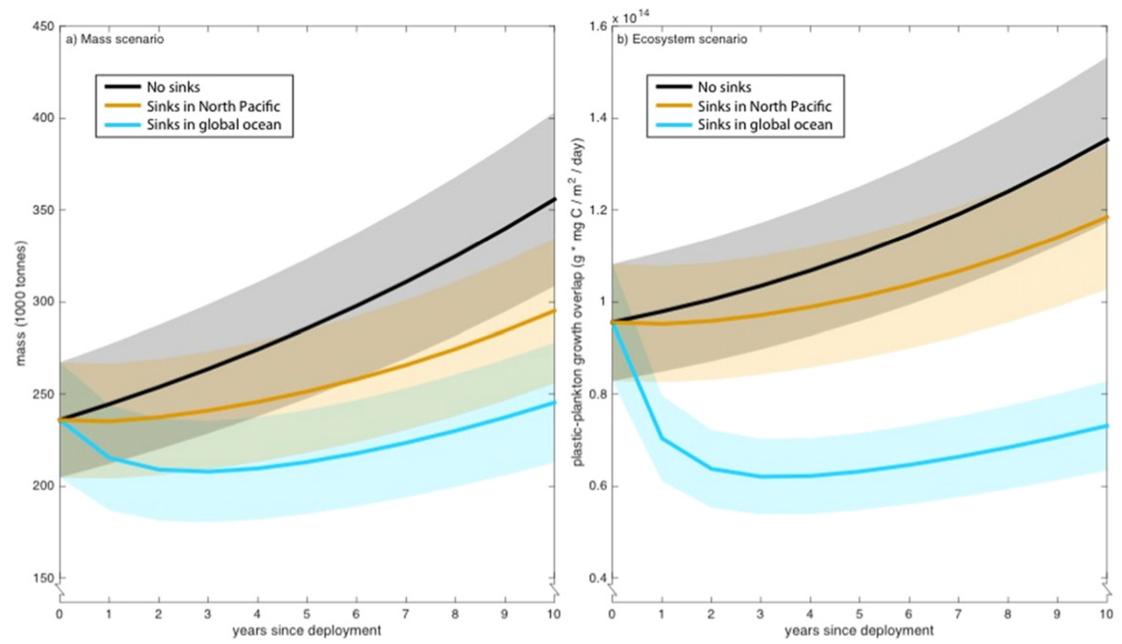

Figure 2. Time series of (a) the total mass of marine microplastic at the surface of the ocean without sinks (black line), with sinks in the North Pacific (yellow line), and with sinks near coastlines (blue line); (b) the overlap between surface marine microplastics and plankton growth without sinks (black), with sinks in the North Pacific (yellow), and with sinks near coastlines (blue). In the ecosystem scenario, a greater overlap (higher values) means more potential harm to marine life as related to phytoplankton growth. The shaded areas represent the 1 standard deviation confidence interval due to both the standardization and the regression based off of the errors from van Sebille *et al* (2015).

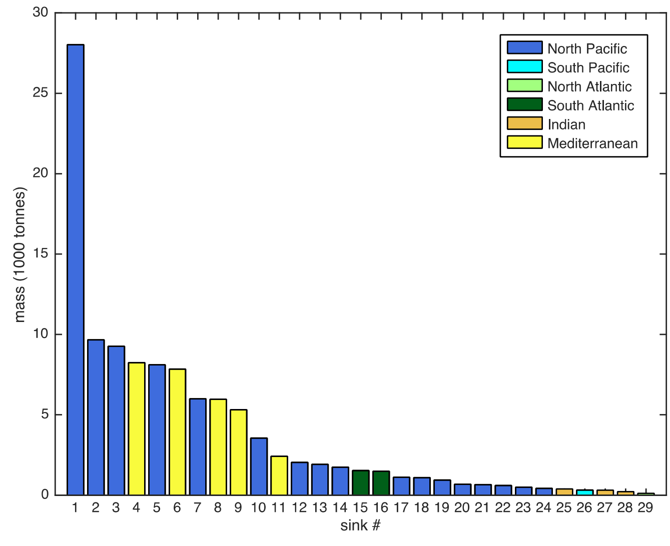

Figure 3. Bar graph showing the total amount of surface microplastic removed (in thousand tonnes) by each sink after 10 years for the maximum reduction in microplastic mass scenario. The sinks are arranged from most effective to least, and colored according to the basin. Since the color of sink 29 is too difficult to see on the graph, it is noted here that its location is in the North Atlantic.

Locally, the sinks remove most plastic very near the coastlines, as can be seen in the shading in figure 1. The largest amount of plastic removed per grid cell is around East Asia and in the Eastern Mediterranean. There is also a large reduction of plastic in the North Pacific accumulation zone due to the coastal plastic collectors.

The mass removed by each sink over the 10 year span can be calculated (figure 3). The first 10 sinks in the plastic scenario collect 83% (92 thousand tonnes) of the total plastic removed. These sinks are more effective than the other 19 because they are closer to regions of large input of plastic and collect the plastic before it can reach the other sinks.

It is unfortunately not possible to determine where captured plastic would have turned up at the end of a decade if a sink did not collect it. This is relevant because each 1° × 1° cell was assigned a NPP value that was multiplied by the collected mass. We cannot determine how much the plastic-NPP overlap changed after plastic was removed by a sink since the plastic would have likely reached a different cell with a different NPP value by the end of the simulation. This means we cannot measure the change in overlap due to each sink as we did for the mass scenario in figure 3.

4. Discussion and conclusions

The main purpose of this analysis was to show that hypothetical sinks that remove plastic drifting on the surface of the ocean may be more effective in removing microplastic and reducing ecosystem harm when placed close to shore than in the North Pacific garbage patch. Such sinks (in the form of plastic capturing devices) would be particularly effective close to very large sources of marine microplastics.

The model has a few underlying assumptions that might bear on our results. Unlike the Maximenko model (Maximenko *et al* 2012) and Lebreton model (Lebreton *et al* 2012), the van Sebille model assumes that plastics do not wash ashore. The model furthermore does not include the loss of surface plastics from sinking or animal ingestion. It is also assumed that the effects of climate change on global ocean circulation is negligibly small, and that currents are stationary in time except for the seasonal cycle. We finally assumed the sinks operated at a field efficiency of 45% irrespective of where they were placed in the ocean, compromising the assumption that sinks are designed to capture microplastic since plastic input near coasts is likely not in the form of microplastics. However, we do not think that these assumptions affect our main findings. The no-loss assumptions, for example, would actually overestimate the efficiency of sinks in the open ocean, as the microplastic mass in the centers of the gyres is relatively large in the model compared to closer to the coastline. In that sense, our results are an underestimation of the improvement of efficiency when sinks are placed near the coastlines.

Our research could be expanded further by adding more detail to the simulations. For example, the plankton scenario could be expanded to other animals (i.e. birds, fish, turtles, etc). Many adverse effects of plastic ingestion by animals have been found, but we do not know the extent of them. Rochman *et al* (2013), for example, shows the adverse effects experienced by fish. This expanded scenario could not be accomplished because the necessary data is not available for more than a few species. Similarly, a profit optimization scenario could be created that incorporates the monetary costs to ecosystems and damaged ships, as well as transportation and production costs of the sinks. While we would like to include this scenario, there are simply so many unknown costs to include (total ship damage costs, re-sell value of processed plastics, etc) that it is too difficult to evaluate. There are also associated environmental costs with extracting plastic closer to shore, where the plastic has less time to absorb toxic pollutants like PCBs and DDTs (Mato *et al* 2001).

This study reveals that the regions where best to place any hypothetical plastic capturing devices do not vary significantly between the two scenarios, so that they can both remove a large portion of global ocean microplastics while reducing microplastic impact on ecosystems, especially in East Asia. However, even though the 29 sinks can remove 31% of surface microplastic, the total mass of microplastic on the ocean surface in our model will still increase by 4% by 2025. To further address this problem, we must minimize the plastic input into the ocean, whether it be through reducing our dependence on plastic, increasing fines for littering, or engineering new plastics that degrade faster in the ocean.

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