Plastics in the deep sea – a global estimate of the ocean floor reservoir

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Running head: The ocean floor reservoir of plastic pollution

Significance Statement

Novelty and Significant Advancement in Science: Researchers are trying to solve the problem of the missing plastic. To solve the puzzle, global estimates are needed for major plastic reservoirs – e.g., surface waters, bottom. Here, we provide one of the first global estimates of plastic on the ocean floor and predict its global distribution, thereby providing another piece of the puzzle of the missing plastic. Our methods are not purely theoretical; our model synthesizes and incorporates empirical data allowing for more reliable and insightful predictions. Overall, we show that plastic clusters around continental shelves, closer to human populations. Moreover, the size of our reservoir suggests that plastic on the ocean floor is not increasing at the same pace as plastic production. Our finding challenges the prevailing estimate of how much plastic enters the ocean annually. Finally, our study shows numerous gaps in sampling effort and we discuss how researchers can fill these gaps to improve future models.

Breadth of interest of science and appropriateness of L&O: Our research will be of interest to the multidisciplinary audience of L&O, including oceanographers who are interested in the global distribution of plastics, biogeochemists and earth scientists who are interested in how plastics are changing the composition of the Earth, ecologists and conservationists who are interested in how plastics are affecting benthic organisms and ecosystems, and policymakers who are working on global environmental issues such as this one.

Author Contribution Statement

Xia Zhu: conceptualization (lead); data curation (lead); formal analysis (lead); methodology (lead); project administration (lead); visualization (lead); witing – original draft preparation (lead); writing – review & editing (equal). **Chelsea Rochman:** formal analysis (supporting); methodology (supporting); resources (lead); supervision (equal); writing – review & editing (equal). **Britta Denise Hardesty:** formal analysis (supporting); methodology (supporting); resources (lead); supervision (equal); writing – review & editing (equal). **Chris Wilcox:** formal analysis (supporting); methodology (supporting); resources (lead); supervision (equal); writing – review & editing (equal).

Abstract

The exponential increase in plastic production coupled with variable global waste management system efficiencies has resulted in large amounts of plastic waste entering the ocean every year. Although we know millions of tonnes of plastic have entered the oceans, we do not yet understand the patterns of its accumulation across space nor the drivers of these patterns. The deep ocean is expected to be a resting place, or reservoir, for plastic pollution. Here, we conducted a rigorous, systematic review of previously published datasets to synthesize our understanding of macroplastic pollution (> 5 mm) on the ocean floor. Using extracted data, we built predictive additive models to estimate the amount and distribution of plastic on the ocean floor. We built two models: one using data from remote operated vehicles (ROVs) and another using data from bottom trawls. Using the model built with ROV data, which was better-constrained, we estimate that 3 to 11 million metric tonnes (MMT) of plastic pollution resides on

the ocean floor as of 2020. This is of similar magnitude to annual inputs from land and one to two orders of magnitude greater than what is predicted to be floating on the ocean surface. To improve future estimates and our understanding of global patterns, we provide recommendations for ocean floor monitoring of plastic pollution.

Introduction

The production of plastic has increased exponentially over time, such that by 2050 we are predicted to have generated a total of 26,000 million metric tonnes (MMT) of virgin resin[1]. Approximately half of this plastic is projected to become waste[1]. Plastic waste that escapes management systems or is shed from plastic during use (e.g., tire wear particles) enter the environment as emissions of plastic pollution[2–4] and cycle through environmental reservoirs much like carbon and nitrogen[5,6]. Millions of tonnes of plastic pollution, estimated at 4 - 23 MMT per year[7,8], enter the ocean as part of the Global Plastic Cycle[5,9].

Fate of plastic pollution is poorly understood

Physical forcing via wind[10–13] and currents[14,15], biological forcing via the movement of marine life, and the incorporation of plastic into organic particles (e.g., marine snow and fecal material) [16–19] transport plastic pollution throughout the ocean. The amount and spatial distribution of plastic pollution in all major marine reservoirs, including the ocean surface, ocean column, ocean floor, marine sediments, coastlines, and marine animals have not yet been quantified[5,20]. Although there are estimates of the amount of plastic floating on the surface of the global ocean[14,21,22], global estimates for the other reservoirs are lacking. Moreover, due to a lack of broad-scale empirical data across reservoirs, including the ocean's surface, models to date are poorly constrained[23]. The risks that plastic pollution may pose to marine life[24,25] is motivation for better understanding the spatial extent of plastic pollution to inform the exposure landscape for organisms more holistically.

Plastic resting on the ocean floor

The ocean floor is predicted to be among the largest reservoirs of plastic pollution[20,23], and is suspected to be a long-term reservoir, or sink, due to the lack of removal processes acting upon it. This is further exacerbated by the extremely slow degradation rates of plastic in cold environments lacking in both oxygen and UV radiation[26]. The deep ocean consists of two major reservoirs of plastic pollution: the ocean floor[20,23], which consists of large plastic objects sitting on top of the floor, and bulk ocean sediment[27–29], which consists of smaller plastic particles mixed into the sediment.

Field surveys and sampling campaigns have quantified benthic plastic pollution from seas, estuaries, and deep ocean basins (e.g., [30–34]). Modelling studies have used empirical data to assess drivers of benthic debris accumulation regionally (e.g., [28,35–37]) and data simulations to predict vertical particle transport (e.g., [38,39]). Regional studies shed light on plastic accumulation in specific locations, and simulations of vertical transport allow extrapolation to predict benthic contamination. To date, we lack a holistic assessment of the global distribution and overall importance of the ocean floor as a global reservoir.

Here, we synthesize empirical data from the peer-reviewed literature to build a predictive model of the extent and spatial distribution of plastic pollution on the ocean floor at a global scale. We also consider the driving forces relevant to the transport and accumulation of plastic in the deep ocean, which informs source-reduction and environmental remediation efforts. Finally, based on our findings, we make specific suggestions for improving sampling and data collection to improve future predictions of the load of plastics in the global ocean.

Materials and Methods

Systematic review

The terms ("marine debris" OR "plastic debris" OR "microplastic") was included in a literature search query via "All Databases" in Web of Science to find peer reviewed publications that report abundances of plastic pollution in either the ocean floor or the sediment compartment of the deep ocean. We included papers published from September 1976 until January 1st, 2020. Inclusion criteria were used to select papers for the systematic review and meta-analysis (see details in **Figure 1**). Only studies that report abundances of plastic in marine settings that are underwater, or below zero meters with respect to sea level, were included in the analysis. As a result, we excluded studies conducted in intertidal environments (e.g., wetlands, mangroves), on beaches, and in any terrestrial or freshwater environments (e.g., lagoons, terrestrial parks, forests). A quality assurance search through LITTERBASE (https://litterbase.awi.de/) was conducted to identify any studies that our search may have missed. To synthesize what we know about plastics in the deep ocean and to retrieve data needed for our predictive modelling, we extracted geographic coordinates, area name, country (if applicable), sampling method, sample size, abundance of plastic pollution, plastic sizes, plastic types, year of sampling, sampling depth, sampling season, and ocean floor topographic feature from each of the included studies.

Meta-analysis – predicting global estimates

Although we present the state of the knowledge of plastic pollution in both the ocean floor and bulk sediment reservoirs, we only modelled the distribution of plastic on the ocean floor. Studies on plastic pollution in sediment were not included due to the inherent differences in plastic morphologies and sizes between the ocean floor and bulk sediment reservoirs, and because preliminary estimates of the size of the bulk sediment reservoir already exist[27,28]. Studies included in the meta-analysis were used to build a generalized additive model[40] (**Supplementary Information Table S1**). The chosen studies must have reported adequate quantitative information that enables the calculation of an abundance measure for plastic pollution on the ocean floor - specifically, they need to either provide a mass of plastic per area measurement, or a count of plastic per area measurement along with a physical description of the plastic items retrieved. We chose to only focus on studies that used remote operated vehicles (ROV) or trawling methodology because they are the most commonly deployed methods for sampling plastic pollution on the ocean floor.

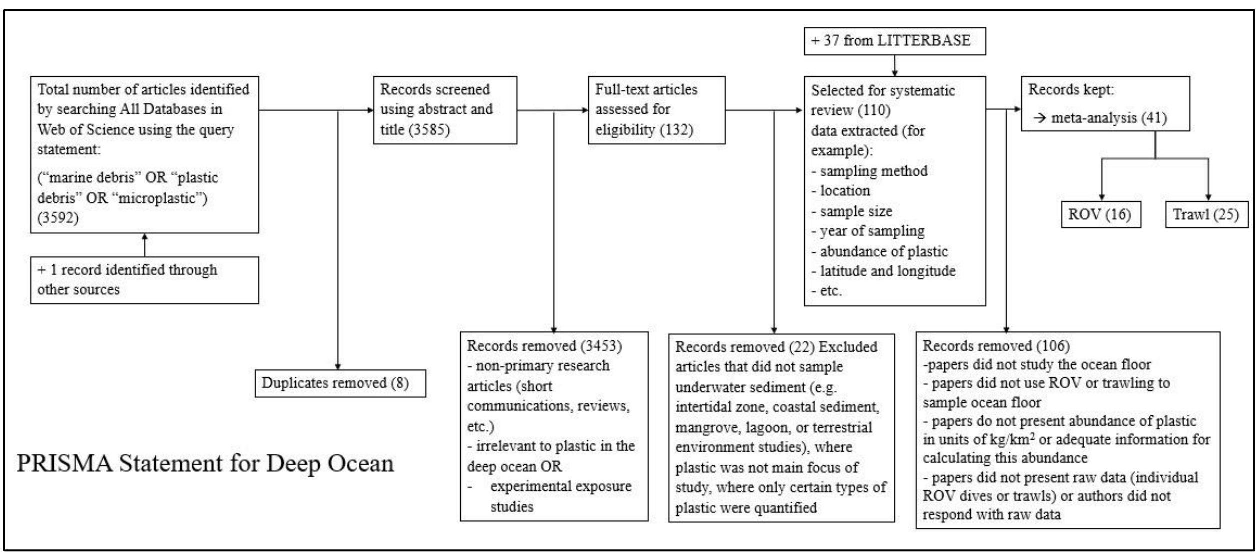

Figure 1. PRISMA statement showing how studies for the systematic review and meta-analysis were sequentially filtered. The numbers in parentheses represent the number of papers relevant to each step in the process.

Our literature search generated a total of 3592 studies. After filtering out articles using exclusion criteria at every step, and adding articles from LITTERBASE as a quality check, we were left with 41 studies (16 ROV and 25 Trawl studies) for the meta-analysis or modelling component of this paper (**Figure 1**).

We asked authors of the 41 studies chosen for the ocean floor meta-analysis (**Supplementary Information Table S1**) to provide raw data in the cases where raw data was not presented in their manuscript or corresponding Supplementary Materials (please see Acknowledgements section). Our meta-analysis originally consisted of all studies that contained quantitative abundances of plastic pollution (raw or average), but because we needed raw data to build our model via a Generalized Additive Model (GAM) approach, we only included studies where raw data was available or ultimately provided by the authors. Authors were asked to provide geographic coordinates and a mass of plastic per area measurement for each of the ROV dives or trawls (**Figure 2**). Where mass of plastic per area information was not provided, it was calculated (**Supplementary Information Text 1**).

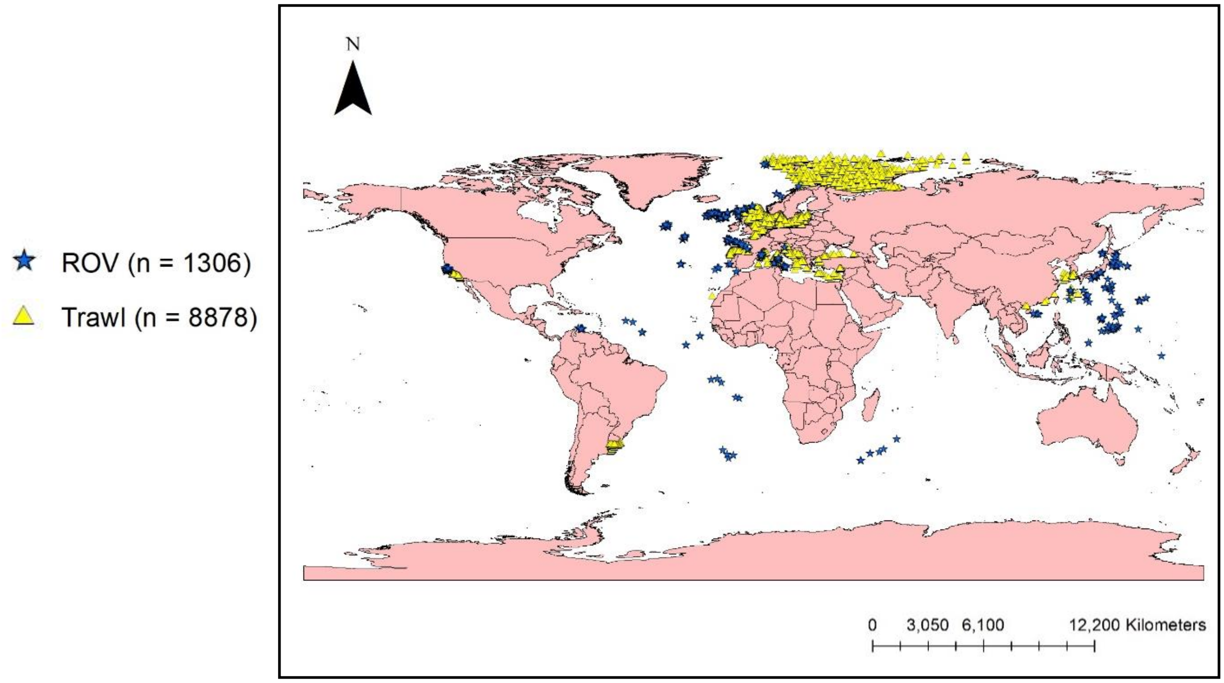

Figure 2. Raw ROV (n = 1306) and trawl (n = 8878) samples used to train their respective models from surveys taking place 1988-2018 and 1993-2017, respectively.

We fitted two generalized additive models, one using masses of plastic pollution from ROV imagery and the other using trawl samples, in RStudio using the *mgcv* package[41]. After evaluation, we found these two sampling methodologies to be too divergent to be combined and used to fit a single model. For both of our models, covariates were first checked for collinearity. The parent models are fit to their respective data using the *Tweedie* distribution[42]. The *dredge* function in the *MuMIn* package was used to search through all possible permutation of covariates and select the model with the most parsimonious fit to the data, measured using Akaike's Information Criterion (AIC) score[40,43]. The AIC score uses a model's maximum likelihood estimation as a relative measure of goodness-of-fit, and penalizes for complexity. The model with the lowest AIC score was considered the best model, and any model that is within two points of the best model is considered equivalent as it falls within the 95% confidence interval around the best model. More details on the modelling process can be found in the supplementary text (**Supplementary Information Text 2**).

The covariates we included in the GAMs were depth, slope, shipping intensity, fishing effort, distance to shore, and distance-weighted population. Area sampled and median year were control variables for the ROV model, while area sampled, median year, and net mesh acted as control variables for the model built using trawl samples. Covariates were standardized by subtracting the average from each value and dividing by the standard deviation. The covariates were chosen based on their consideration in previous studies or their suspected influence on the mass and/or distribution of plastic pollution on the ocean floor (please see supplementary text for more information, **Supplementary Information Text 2**).

Both models were used to predict the mass of plastic (in kg/km^2) for every 1^o x 1^o grid cell of the ocean floor. The total mass of plastic (kg) in each grid cell was determined by multiplying the predicted mass/area from our fitted models by the total area of the grid cell (km^2). The ocean floor reservoir was estimated by summing the masses of plastic pollution predicted by a model across all ocean floor grid cells.

Results

Summary of sampling effort in the deep ocean

For both the ocean floor and bulk ocean sediment, plastic pollution sampling efforts are concentrated in coastal marine environments (**Figures 2, 3a**, **Supplementary Information Figure S1a**). These sampling campaigns have not been decomposed into individual raw points. For macroplastics on the ocean floor, 73 out of 95 (77%) independent sampling campaigns took place in coastal marine environments including inland and coastal seas, bay-estuary systems, bights, reef habitats, continental shelves, and canyons (**Figure 3a**). The Atlantic and Pacific Oceans were the ocean basins with the highest number of sampling campaigns overall (**Figure 3a**). For microplastics embedded within bulk ocean sediment, 42 out of 50 (84%) independent sampling efforts took place in coastal marine environments (**Figure S1a**). The Arctic Ocean had the most sampling campaigns across all ocean basins. Plastic pollution sampling efforts on the ocean floor are dominated by ROV and trawl sampling; in fact, 80 of 96 studies (83%) used ROV or trawling to sample the ocean floor (**Figure 3b**, **Supplementary Information Figure S1b**). For bulk ocean sediment, just over half (51%) of all sampling campaigns deployed the grab sampling technique to sample microplastic pollution embedded within deep ocean sediment.

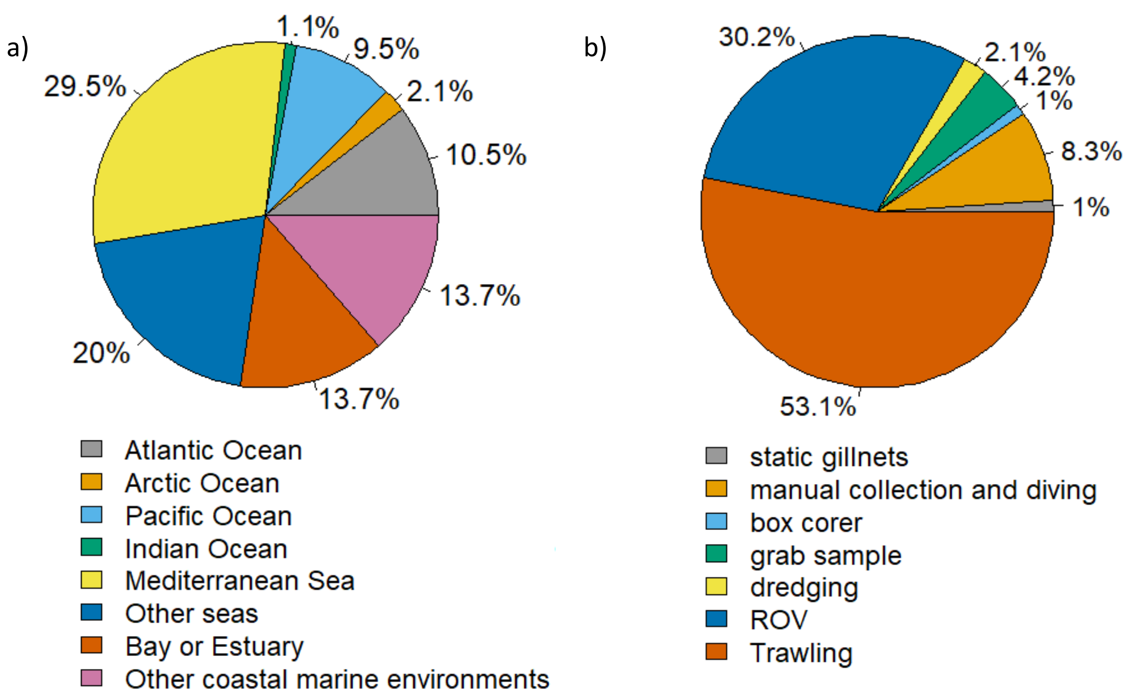

Figure 3. a) Sampling locations of plastic pollution on the ocean floor are displayed as percentage of total sampling campaigns conducted up until January 1, 2020. b) Sampling methodologies for large plastic objects on the ocean floor are also displayed as percentage of total sampling campaigns conducted globally up until January 1, 2020. Examples of other coastal

marine environments include gulfs, canyons, reefs, marine sanctuaries, harbours, bights, fjords, and coves.

Summary of ROV and Trawl models, and Derived Predictions

The best model built using ROV samples, henceforth referred to as the “ROV model”, explained 37.1% of the deviance in the mass of plastic pollution on the ocean floor and included area sampled, median year, depth, shipping intensity, fishing effort, and distance to shore (**Table 1**). All variables were significantly correlated with mass of plastic pollution except for area sampled ($p = 0.056$) and fishing effort ($p = 0.087$). The ROV model has a much lower AIC score than the null model, which is an indication that the ROV model has greater goodness-of-fit to the data than the null model (**Supplementary Information Table S2**). The best model built using trawl samples, henceforth referred to as the “Trawl model”, explained 21.8% of the variability in mass of plastic pollution on the ocean floor and included area sampled, median year, net mesh, depth, slope, shipping intensity, fishing effort, and distance to shore **(Table 1**). All variables in the Trawl model were significantly correlated with mass of plastic pollution found on the ocean floor. As with the ROV model, the Trawl model also has greater goodness-of-fit to the data than the null model, as indicated by its lower AIC score (**Supplementary Information Table S3**). Model diagnostics were performed for both models (**Supplementary Information Figure S2-S3).**

Population density was included as a smooth term and not as a parametric term. We fitted population by distance effect as a smooth term, which is a non-parametric approach using a set of approximating basis functions to build a complex functional relationship. Here, we used signal regression or a variable coefficient model, which allows coefficients to vary with different values of the covariate. The collective integration of the effect of distance on population over a given interval is represented by the p-value of the smooth, or the overall significance of the fit. For both the ROV and the Trawl model, distance-weighted population density was significantly correlated with plastic mass on the ocean floor (**Supplementary Information Figure S4**). For both models, the general trend is that large distant human populations have the largest impact on plastic densities at sampling locations. This finding may suggest a combination of limited mixing and settling out of material at short distances, as well as the importance of distant sources such as large cities that are delivering large amounts of inputs (**Supplementary Information Figure S4**).

Table 1. Summary of parametric variables in the best ROV and trawl models. Coefficients/effect estimates are directly comparable because covariates were standardized by subtracting their mean and dividing by the standard deviation.

ROV			
Variable	Coefficient/estimate	Standard Error	p-value
area sampled	0.11	0.055	0.056
median year	1.46	0.090	$< 2*10^{-16}$
depth	0.93	0.086	$< 2*10^{-16}$
shipping intensity	0.66	0.096	$1.4*10^{-11}$
fishing effort	-0.18	0.10	0.087
distance to shore	-0.22	0.088	0.015
Trawl			
Variable	Coefficient/estimate	Standard Error	p-value
area sampled	6.9	1.2	$3.2*10^{-8}$

median year	-0.15	0.050	0.0027
net mesh	-1.1	0.056	$<2*10^{-16}$
depth	-0.45	0.031	$<2*10^{-16}$
slope	-0.36	0.040	$<2*10^{-16}$
shipping intensity	-0.25	0.046	$4.6*10^{-8}$
fishing effort	-0.15	0.040	0.00011
distance to shore	-0.52	0.044	$<2*10^{-16}$

The prediction heat map for ROV shows densities of macroplastic pollution ranging from 0 to 1719.30 kg/km^2, with the highest predicted density in the Baltic Sea (**Figure 4)**. From the Trawl predictions, we find that the highest predicted densities are clustered in the Western Pacific Ocean basin (**Supplementary Information Figure S5)**.

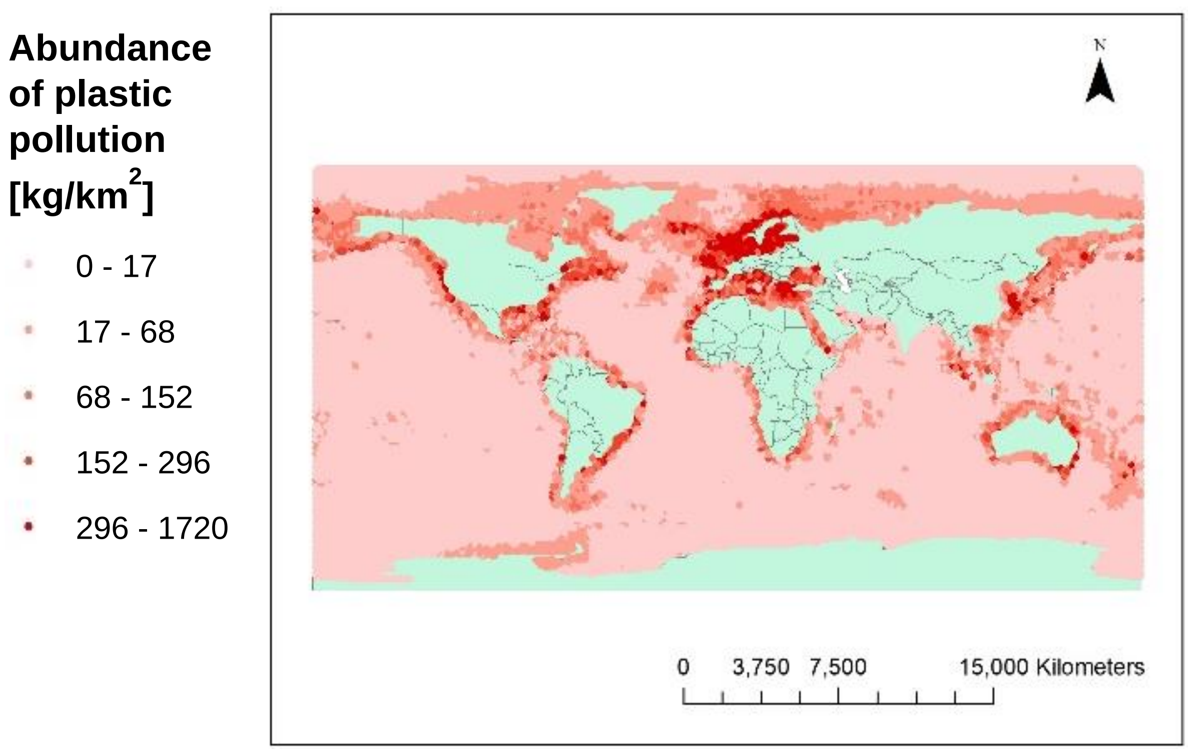

Figure 4. Heat map showing predictions of the mass [kg/km^2] of plastic pollution for 1º x 1º grid cells of the ocean floor using the best ROV model (**Table 1**).

The ocean floor reservoir

We estimate the size of the ocean floor reservoir to be 3 to 11 MMT (middle estimate of 7 MMT) using the ROV model. The estimate using the Trawl model is 5 to 571 MMT (middle estimate of 255 MMT).

Discussion

Although we have estimates of the ocean floor reservoir from both models, we focused on the ROV model. The distribution of plastic mass with respect to size for the objects collected by both ROV and trawl methods are surprisingly similar, in that both distributions are bimodal near zero and near their upper size cutoff (**Supplementary Information Text 4, Figure S6**). Their agreeable mass frequency distributions initially supported the use of both prediction maps to inform the ocean floor reservoir. However, the ROV and trawl data differ in important ways. There is a strong bias in the trawl sampling data as trawls are limited to deployment in shallow, relatively flat regions of the ocean floor. Consequently, the coverage of the ocean floor by trawling is poor (**Figure 2**), meaning global predictions encounter conditions well outside of the covariate ranges covered by our observation data (**Supplementary Information Figure S7**). As a consequence, predictions of plastic abundance by the ROV and Trawl models in regions with a similar set of values for covariates sometimes differ substantially (**Supplementary Information Figure S8**). This is shown in Figure S8, where the covariate values associated with each sample, or the set of conditions under which the sample was taken, were used to plot the samples in multivariate space, with each point representing the difference in mass of plastic for a ROV-

Trawl pair. Even for samples that are taken under very similar conditions (depth, slope, shipping intensity, fishing effort, latitude, longitude), the difference in masses of plastic pollution measured by ROV and trawls sometimes spanned as much as six orders of magnitude (**Supplementary Information Figure S8**). As the difference between sampling contexts (measured by Euclidean distance) increases, it also seems that Trawl tends to be biased high, suggesting that trawling often occurs in dirtier places. Considering this, we have higher confidence in the results obtained from the ROV model.

What predicts patterns of accumulation?

For both models, plastic abundance increased as more area was sampled. The positive correlation between plastic abundance and sampling effort found here could be the result of the increased probability of detecting an outlier as area sampled increases[44]. When the outliers are orders of magnitude higher in plastic mass than the rest of the observations, they generate a significant effect on the plastic mass-area relationship, as is represented here by the large coefficient for the area sampled covariate for the Trawl model (**Table 1**).

<u>ROV Model</u>

The ROV model predicted large amounts of plastic pollution clustered along continental shelves. The high predictions of plastic mass by the ROV model along continental boundaries are likely driven by the distance to shore and shallowness or depth (**Table 1**). The high predictions in the Mediterranean Sea, the Arctic Ocean, and in coastal seas along the northern border of continents in the Northern Hemisphere including the North Sea, Barents Sea, and Norwegian Sea are likely driven by the high density of shipping traffic in those areas (**Table 1**). In addition, there is also a strong correlation between the masses of plastic pollution detected using ROV and median year of sampling (**Table 2**). This positive correlation between plastic mass and median year could be the result of increasing plastic concentrations on the ocean floor, or the increasing attention to plastic in ROV surveys. Most likely, it reflects both.

Trawl Model

The Trawl model predicted large pools of plastic in ocean basins, particularly in the Western Pacific Ocean. This seems to be driven by a combination of depth, slope, and distance to shore: e.g., deep, flat areas offshore contain high quantities of plastic. These high predictions may also be a consequence of how trawls operate, because trawling on flat, shallow sediments is much more feasible than trawling on deep, steep, or rocky areas, hence reflecting survey bias. Coincidentally, these are also the areas that are subject to more intense vessel activity (https://knb.ecoinformatics.org/view/resource_map_doi:10.5063/F1NZ85ZN) and are located closer to land-based sources, and this may also contribute to the large abundances of plastic in shallower, flatter areas near the coast. Furthermore, there is also a strong negative correlation between the masses of plastic sampled using trawls and mesh size of the trawl net. This correlation is expected because as net mesh increases, the mass of plastic found in trawls is expected to decrease due to the loss of smaller-sized plastic objects.

Predicted global spatial distribution

Approximately half (46%) of the predicted plastic mass on the global ocean floor resides above 200 m depth, which is often used as the contour for continental shelves. The remainder of the ocean, from 200 m to as deep as 11,000 m contains the remainder of plastic mass (54%). Although inland and coastal seas cover much less surface area than do oceans (11% vs 56% out of the entire Earth's area), the bottom of these areas hold as much plastic mass as does the rest of the ocean floor (44% vs 41%). Underwater features such as trenches and submarine canyons hold relatively little plastic mass (0.6% and 0.2%, respectively), which is in contrast to the previous suspected notion that deep ocean features are repositories for plastic[45–49]. This result, however, is consistent with what Martin et al.[27] found for bulk ocean sediment globally – that abundance of non-fibrous microplastics decreases with depth. The three ocean basins that hold the most plastic mass on the ocean floor are the North Atlantic Ocean (14%), North Pacific Ocean (7%), and South Atlantic Ocean (6%) basins.

Comparisons with other studies

Our estimate for the ocean floor reservoir is similar in magnitude to preliminary estimates of other marine reservoirs of plastic pollution (**Figure 5**). This observation agrees with the conclusions of Wilcox et al.[50] The authors looked at temporal trends in ocean surface concentrations of plastic pollution in the western North Atlantic and found that masses of plastic in reservoirs should increase over time, because their long residence times allow reservoirs to reflect increases in global plastic production. However, their estimate of how much the plastic on the ocean surface increased by in 2010 – 506,000 T of plastic or 0.2% of global production – was unexpectedly a whole order of magnitude lower than how much Jambeck et al. estimated entered the global ocean, which was between 2% and 5% of global plastic production. Our findings are consistent with their finding that reservoirs are not increasing in size exponentially, though plastic inputs to the oceans are predicted to be exponentially increasing. There are two possible reasons for this inconsistency: there is a huge missing reservoir we have not accounted for, or the inputs are incorrect, i.e., plastic pollution leaving the coastal area are not actually making its way into the ocean.

In terms of the first possibility, recent studies have suggested that degradation and fragmentation into micro- and nano-sized plastic particles could be considerable sinks [50–53]. However, the rate of disappearance of plastic from global reservoirs must be increasing exponentially at a rate greater than the production rate in order for reservoir sizes to remain constant. This is highly unrealistic, as we know that degradation processes are unlikely to be increasing on a per capita basis adequately to account for an exponential increase in inputs[53,54].

In terms of the second possible explanation for the similar sizes of inputs and reservoirs, and stemming from the logic of the above argument, it is possible that inputs are not as large as anticipated: the global model by Onink et al.[55] found that at least 77% of positively buoyant marine plastic debris released by their model did not escape beyond the coastal zone. Chubarenko et al.[56] also found that large plastic items are continuously trapped in swash waves in the coastal area until they break into small enough pieces to escape into the open ocean. Furthermore, Olivelli et al.[11] found that coastal zones, in particular the backshore area of the coast, is a huge sink for plastic pollution. Likewise, numerous simulations have found that negatively buoyant plastics sink immediately upon entering the ocean, forming a ring around coastlines, so a large portion of them remain deposited relatively close to land (e.g. [38]) – this is consistent with our findings. Overall, more and more studies are suggesting that perhaps a relatively small fraction of terrestrial inputs into the marine environment actually escapes the coastal zone and enters the open ocean. This implies that the Jambeck et al.[8] is not being interpreted correctly; it is actually measuring the amount of plastic leaving the land at the coastal margin, not the amount of plastic that escapes the coastal zone and enters the open ocean. Future studies that further investigate this mismatch between annual inputs and the amounts of plastic accumulating in reservoirs would be useful.

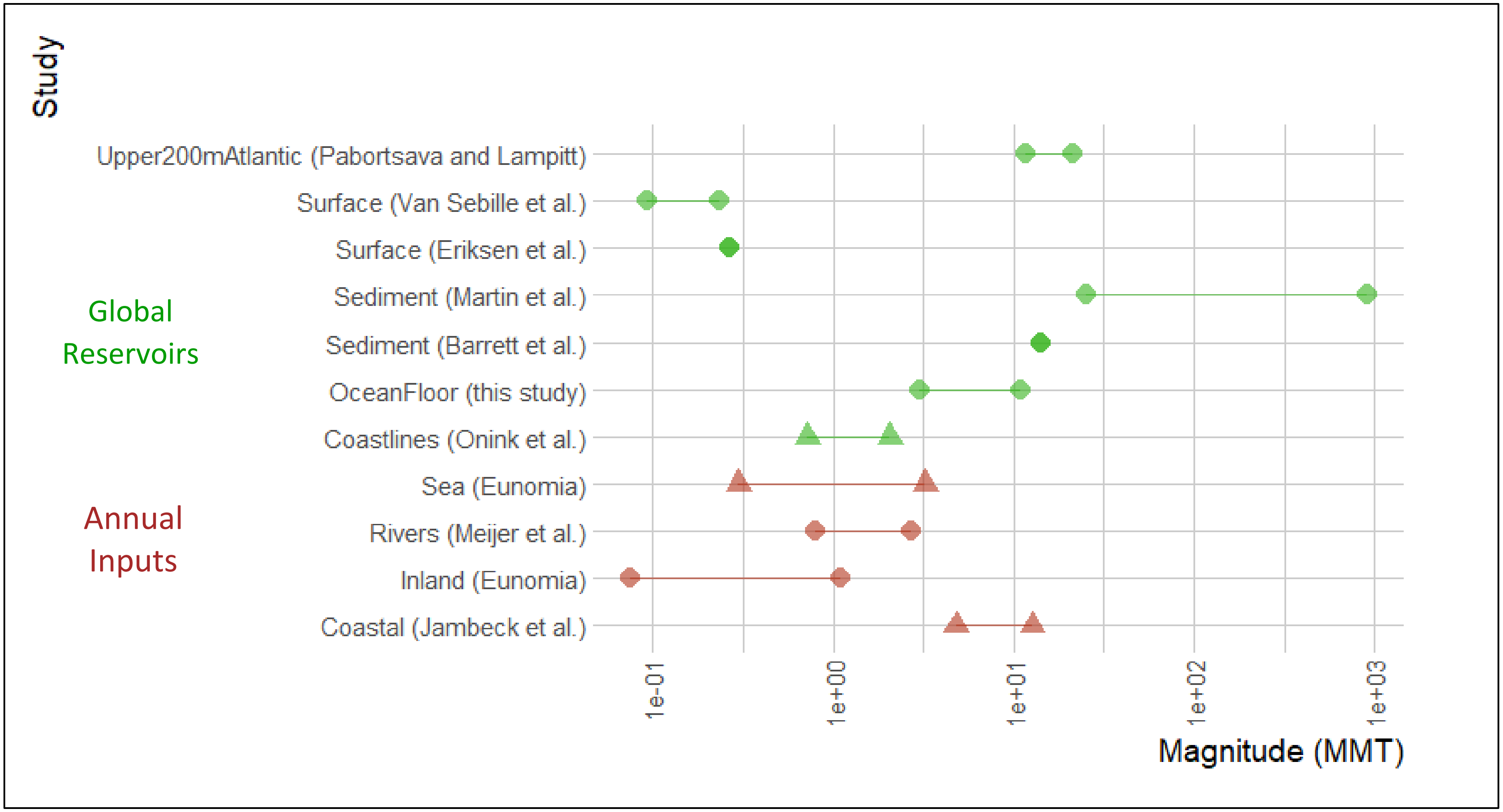

Figure 5. Lolliplot plot comparing the sizes of global marine reservoirs of plastic pollution to one another and to those of annual inputs globally. The plot shows lower and upper estimates of each input or reservoir in MMT. Data used in plot is from Borrelle et al.[7], Eunomia[3], Jambeck et al.[8], Meijer et al.[57], Onink et al.[55], Barrett et al.[28], Martin et al.[27], Eriksen et al.[21], van Sebille et al.[14], and Pabortsava and Lampitt[58]. Triangles indicate the study derived its estimate using a simulation approach and did not incorporate actual

measurements. Circles indicate the study incorporated empirical measurements in its derivation of the size of the input or reservoir of interest. Data used to make this figure can be found in **Supplementary Information Table S4.**

To further reconcile the discrepancy between inputs and reservoirs, it helps to collect more samples using harmonized methods to improve modelling efforts. We discuss next steps in sample collection in the section below.

Shortcomings and recommendations

We used data that was available to us from the scientific literature to inform one of the first global estimates of the ocean floor reservoir of plastic pollution. We provide recommendations from this exercise of building models using empirical data to improve future modelling efforts. We encourage this approach rather than the approach of building entirely theoretical models that are not grounded in empirical data (see **Figure 5**, simulation studies versus empirical studies).

First, we suggest that not all data is good data. Researchers should not feel the need to always use all of the data that is at their disposal, especially if the quality of a dataset precludes it from being useful for a given purpose. In the case of Trawl measurements of plastic pollution, its limited spatial distribution precludes it from informing an understanding of the global distribution of plastic pollution on the ocean floor. Secondly, we recommend not combining ROV and trawl samples in the same model, because there are differing biases in the sampling methodologies which in turn create bias in the observations. For instance, trawls can only operate on flat, hard substrate. There are some plastic objects detected using ROVs that trawls are not seeing, and vice versa, and more work is needed to reconcile these measurements. The third recommendation is that we need more sampling of the ocean floor: sampling that covers a greater diversity of ocean floor topographies and habitats, replicate sampling, and paired sampling. Most sampling efforts to date have been concentrated in nearshore marine environments. In order to obtain equivalent or relatively consistent probability of detection, there is a need for some experiments to understand how much detection probabilities vary from sample to sample. This requires replicate sampling attempts in the same location, and in an ideal world, ROV and trawl samples are both taken in the same area – a process referred to as "paired sampling" – so that we can begin to better understand the differences between them. The lack of paired sampling efforts to date prevented us from combining the data.

Finally, the prohibitively expensive nature of deploying such sampling devices can be a major barrier to the recommendation of greater sampling effort. However, this barrier can be surmounted through co-monitoring of plastic with other variables of interest such as biology and other forms of pollution, and with help from automation.

Conclusion

Using the best available data, we estimate that 3 to 11 MMT of plastic pollution reside on the ocean floor, thereby providing one of the first estimates of the ocean floor reservoir of plastic pollution. This robust estimate fills a longstanding knowledge gap and can be used to better understand the behaviour of plastic in the marine environment. We show how greatly the abundances of plastic measured by two very common ocean floor sampling methodologies differ, raising the question of how we can reconcile measurements across datasets. In this respect, future work that focuses on comparing the size classes, mass, and count abundances of plastic pollution captured by these two sampling methodologies would undoubtedly prove useful. To improve quality assurance and quality control, replicate samples would allow one to better quantify the precision of each methodology or survey approach. Our decision to exclude the predictions by our Trawl model from further consideration shows that not all data should be used just because they exist, and our finding of how incredibly limited the spatial coverage is of deep ocean plastic sampling - to date - calls for renewed efforts to further monitor the contamination of the deep ocean by plastic pollution. The key to large scale monitoring of ocean floor macroplastics likely lies in automation of the process to cut down costs, and the ability to monitor plastic pollution in the context of other activities.

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Data Availability Statement

All data used in this study can be accessed free of charge at https://doi.org/10.5683/SP3/MTELIM.