### ENVIRONMENTAL RESEARCH

### **LETTERS**

#### **LETTER • OPEN ACCESS**

# Floating microplastic loads in the nearshore revealed through citizen science

To cite this article: William P de Haan et al 2022 Environ. Res. Lett. 17 045018

View the <u>article online</u> for updates and enhancements.

#### You may also like

- Development of a low-cost method for quantifying microplastics in soils and compost using near-infrared spectroscopy L Wander, L Lommel, K Meyer et al.
- Climatic modulation of recent trends in ocean acidification in the California Current System
   G Turi, Z Lachkar, N Gruber et al.
- A spatially variable scarcity of floating microplastics in the eastern North Pacific Ocean

Matthias Egger, Rein Nijhof, Lauren Quiros et al.

#### **ENVIRONMENTAL RESEARCH**

**LETTERS** 



#### **OPEN ACCESS**

#### RECEIVED

7 January 2022

REVISED

4 March 2022

ACCEPTED FOR PUBLICATION 15 March 2022

PUBLISHED

29 March 2022

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



#### **LETTER**

# Floating microplastic loads in the nearshore revealed through citizen science

William P de Haan<sup>1,4</sup>, Oriol Uviedo<sup>1,4</sup>, Maria Ballesteros<sup>2</sup>, Íngrid Canales<sup>1</sup>, Xavier Curto<sup>2</sup>, Montse Guart<sup>1</sup>, Sara Higueras<sup>1,2</sup>, Alex Molina<sup>1</sup>, Anna Sanchez-Vidal<sup>1,\*</sup> and The Surfing for Science Group<sup>3</sup>

- <sup>1</sup> GRC Geociències Marines, Departament de Dinàmica de la Terra i de l'Oceà, Universitat de Barcelona, 08028 Barcelona, Spain
- <sup>2</sup> Surfrider Foundation Europe, Spanish Delegation, 20012 Donostia, Spain
- <sup>3</sup> Surfing for Science Group: Olívia Álvarez, Guillem Arrufat, Pol Bassols, Juan Bautista, Olga Bantysh, Cintia Bavera, Elisabet Bonfill, Andrea Comaposada, Augustina Dinovska, Oriol Domingo, Neus Estrada, Sergi Franch, Laura Galeano, Martí Llorente, Eduard Marquès, Patricia Martí, Júlia Ortega, Bernat Peralta, Joaquim Planells, Martí Ramírez, Aurora Requena, Laura Sánchez, Gisela Solà.
- <sup>4</sup> These authors contributed equally to this work.
- \* Author to whom any correspondence should be addressed.

E-mail: anna.sanchez@ub.edu

**Keywords:** citizen science, floating plastics, microplastics, nearshore, coastal water, Mediterranean Sea Supplementary material for this article is available online

#### **Abstract**

Research on plastic pollution has rapidly expanded in recent years and has led to the discovery of vast amounts of microplastics floating on the surface of subtropical oceanic gyres. However, the distribution of floating plastic in the ocean is still poorly constrained, and there is a lack of information from a few meters from the coastline where the largest plastic emissions take place. Here, we provide a comprehensive study on the loads of plastic debris in the coastal surface waters of the NW Mediterranean Sea using data from 124 manta trawl deployments collected along 7 months by citizen scientists. Our results reveal that pollution by microplastics in the nearshore is likely subject to seasonal variations associated to a combination of hydrodynamic and anthropogenic pressures. The high proportions of microplastics found indicate that potential breakdown of plastics in the nearshore may take place in line with previous works. We prove that citizen science is a powerful tool in plastic research to monitor microplastics in the nearshore as it provides scientifically meaningful results while stimulating citizen engagement. Future studies may benefit from targeting specific scientific open questions by using the citizen science methodological approach presented here.

#### 1. Introduction

Investigations on plastic pollution began in the remote open ocean far away from the coastal zone. (Carpenter and Smith 1972) became the first to document what 30 years later would be known as 'microplastics'—plastic particles smaller than 5 mm (Thompson et al 2004)—in the Sargasso Sea. In the decade of the 90s, large accumulations of plastics were found floating in the North Pacific Subtropical Gyre (Moore et al 2001), and the North Atlantic Subtropical Gyre (Law et al 2010). Since then, extended research has focused on the role of ocean gyres and the open ocean on plastic accumulation (Law et al 2010, van Sebille et al 2012, 2015, Cózar et al 2014, Eriksen et al 2014, Lebreton et al 2018). However,

there appears to be a major fraction of all plastic dumped into the ocean since 1950 that is missing as it has not been found in surveys tracking floating plastic debris in the open ocean by now. The current estimates ranging from 14.4 to 269 Mt of plastic accumulated at the open ocean surface layer (Cózar et al 2014, Eriksen et al 2014, van Sebille et al 2015) are significantly lower than the predicted tens of millions of metric tons that should be floating in the ocean based on accumulated global plastic emissions (Jambeck et al 2015), although Weiss et al (2021) recently demonstrated 2–3 orders of magnitude lower microplastic inputs by rivers relative to current estimates.

During the last decade, several studies have suggested that plastic entering the ocean likely sinks to the seafloor, either because of negatively buoyancy or because biofouling increases density of floating plastic (Woodall et al 2014, Kaiser et al 2017, Kane et al 2020). But there are recent evidences that a natural sorting for plastic debris is occurring in coastal environments, where a major part of entering plastics are stranded and captured, and only a small fraction eventually escapes and accumulates in the open ocean (Lebreton et al 2019, Onink et al 2021). Considering the predicted growth in plastic waste (Borrelle et al 2020), knowledge of the occurrence and fate of microplastics in the coastal zone and the mechanisms governing their temporal variability and capture and release is a key challenge that needs to be urgently addressed. This is also required to detect potential hot-spots, current trends in floating plastic budgets (Galgani et al 2021), constrain and calibrate numerical models (Kaandorp et al 2020) and eventually assess the implementation of regulatory and management frameworks, such as the Marine Strategy Framework Directive (Directive 2008/56/EC), or the Single-Use Plastics Directive (Directive (EU) 2019/904).

In 2020 we initiated the citizen science project 'Surfing for Science' based on floating microplastics collection by volunteers, so-called citizen scientists, with enhanced spatial and temporal coverage. During 7 months, starting from October 2020, 14 social, environmental and sports associations distributed along 330 km in the north-western Mediterranean coast organized citizen scientists to acquire scientific samples in the nearshore from paddle surf boards or other boats with a weekly/biweekly frequency (figure 1). This project represented a paradigm shift in microplastic research, allowing to fill the gap in knowledge of this transition coastal area, and actively involving citizens in the acquisition of scientific samples and the generation of new scientific data.

#### 2. Methods

#### 2.1. Participatory process and sample acquisition

Camins et al (2020) provided the scientific community with the design of an affordable and easy to use manta trawl to be attached to a paddle surf board, a kayak, or any other paddling or rowing boat to acquire scientific samples to study microplastic pollution in the nearshore. The trawl comprised the net, with a mesh size of 0.33 mm and a collector bag (or cod end) at the end. The net dimensions used were 0.38 × 0.30 m in most locations. Exceptionally, a net of 0.34  $\times$  0.26 m was used in one single location (i.e. Sant Sebastià beach; figure 1). The Wikiloc Outdoor, S.L. free App (Wikiloc 2019) installed in a smartphone was used for geolocation while trawling (including latitude, longitude, time, and distance trawled). Flowmeters could not be handed out to all participatory associations. Instead, previous work was conducted to determine the distance shift between the track

distance measured by the GPS systems and flow-meter measurements (figure S1 available online at stacks.iop.org/ERL/17/045018/mmedia).

For every trawl, the citizen scientist entered the water with the trawl on the surf board or other boat, to which it was attached, and paddled/rowed to the beginning of the transect. Then the volunteer started paddling for about 1 h (between 1 and 2 km; figure 1(C)) following a consistent parallel transect to the coast when possible. Alternatively, concentric transects were performed in locations with beaches bounded by breakwaters or harbors to ensure representativeness of the area (e.g. Barcelona; figure 1(B)). After each trawl, the net was carried onboard before reaching back to shore and GPS recordings were interrupted. Once back to the beach, the paddle trawl was rinsed thoroughly with freshwater to ensure that all the plastic debris ended up into a replaceable collector bag, which was then sent directly back to the laboratory at the University of Barcelona.

#### 2.2. Sample processing

Once in the laboratory the collector bag was inverted, and all debris were washed out in a 0.33 mm sieve. Plastics were carefully extracted using standard stainless-steel tweezers under a stereo-microscope (10× to 50×) in a clean laboratory. For all collected samples, microplastics between 0.33 and 5.00 mm and mesoplastics (i.e. 5.00-25.00 mm) were captured with multi-staged 0.33 and 5.00 mm sieves, respectively. Macroplastics (i.e. >25.00 mm) were manually extracted with forceps and carefully washed to assure that no smaller plastics remained attached to its surface. Plastics were then dried at room temperature and placed separately on a 90 mm glass Petri dish to obtain plastic count, measurements and properties. Each Petri dish containing plastic particles was scanned twice with a modified and color-calibrated HP G4050 flatbed scanner with a charge-coupled device sensor at high resolution (1200 dpi;  $47.2 \text{ pixels mm}^{-1}$ ). To enhance the background contrast with plastics, a dark background was used in the first scan, whereas a diffused and illuminated background was used in the second scan. Both scans were precisely aligned with custom scan software and processed with ImageJ v1.53 software (Schneider et al 2012). Images were uploaded to the Instagram social network (Surfing For Science Lab 2019) accompanied by the code of the sample and the map of the transect performed, and the associations involved were tagged.

Plastics were counted and the maximum length and surface area of each particle was recorded. Plastic items were also manually classified according to their nature and shape in rigid fragments, flexible/rigid films or sheets, filaments, foam, pellets and spheruloid or granular microbeads. Synthetic or cellulose fibers were not considered in this study, as fibers could pass through the net and external fiber

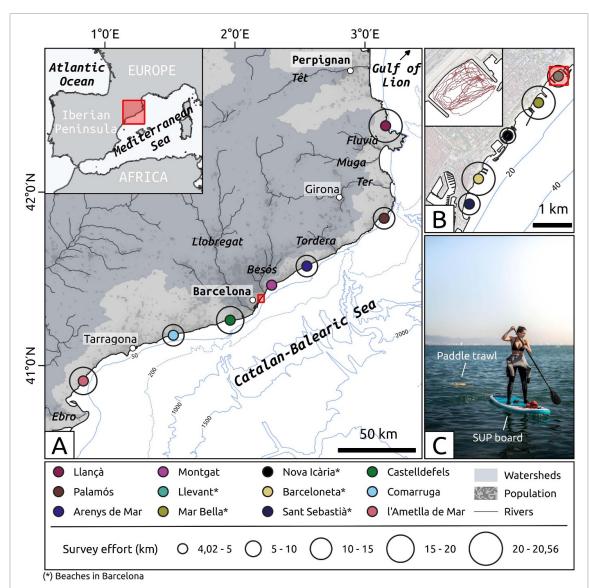


Figure 1. The study area, showing nearshore sampling locations conducted by citizen scientists over a 330 km stretch along north-western Mediterranean coast (A), a zoom-in on five beaches sampled in Barcelona city (B) and a volunteer conducting a survey with the paddle trawl and a stand-up paddle board (C). The associations that provided the structure for implementing the citizen science project where SK Kayak (Llançà), Ocean Cats (Palamós), Base Nàutica (Arenys de Mar), Escola del Mar (Montgat), Blue Salt School (Llevant—Barcelona), Anèl·lides, Oceanogami i Base Nàutica (Mar Bella—Barcelona), Ungravity Freestyle Company (Nova Icària—Barcelona), Manihi Surf School (Barceloneta—Barcelona), Anywhere Watersports (Sant Sebastià—Barcelona), Escola Garbí (Castelldefels), Club Nàutic (Comarruga), and Plàncton Diving (l'Ametlla de Mar).

contamination was not prevented. The mean color of each plastic was measured and automatically assigned to the colors in the reference color palette employed by Martí et al (2020), which recently provided a systematic method for color measurements of plastics. The color palette categorizes 120 colors into 13 main colors and 9 hues, besides transparent and translucent, and is based on standard Pantone® RGB scores. The Euclidean Distance between the mean color values of each plastic and the reference color palette was used to assign the color codes to each plastic.

After image processing, each sieved size fraction was weighted to the nearest 0.1 mg. Consistency between digital measurements and sieving of plastics was assured by manually transferring and reweighing all macroplastics and mesoplastics present in the

sieved microplastics fraction, thus preventing overestimation of microplastics due to sieve fractionation (Michida *et al* 2019).

Finally, a subset of 285 random-selected microplastics (~1.1% of the total) from two samples of each location were chemically identified using a Perkin Elmer Frontier FT-IR Spectrometer with a diamond crystal ATR accessory at the Scientific and Technological Centres of the University of Barcelona (CCiTUB). Microplastics were selected introducing an observer bias following the calculated proportions of colors and nature of microplastics found (i.e. the most common colors and shapes found were more often selected and analyzed). FT-IR spectroscopy allowed the identification of the polymer composition of each item based on IR absorption bands

that represent the presence or absence of specific functional groups in the material. The spectral range analysed was between 4000 and 220 cm<sup>-1</sup> with a 4 cm<sup>-1</sup> resolution and 16 accumulations. The spectra collected were analysed with Open Specy v0.9.3 software (Cowger *et al* 2021) and OMNIC<sup>TM</sup> Picta<sup>TM</sup> (Thermo Fisher 2021) to identify the compounds by comparing them to spectra references in library databases.

#### 2.3. Quality control and quality assurance

Efforts were made to assure quality and consistency of the data during sampling acquisition and treatment. The project enrolled volunteers with and without scientific background, including college and graduate students, and devoted volunteers selected by the participating associations. Either way, project coordinators were reachable by volunteers in case of any eventualities in the sampling process. A sampling protocol was handed-out to participating associations with instructions for app usage and GPS recordings, approximate tow lengths and duration, sample storage and net washing after each use. After sample collection the collector bag was sent to the laboratory within zip-lock bags for scientifically reliable sorting. This is very important, as a sample contamination during the collected debris from the collector bag to a bottle, or volunteer bias if plastic debris are sorted in-situ would result in a bias in plastic abundances or characteristics. For instance, in this study >2000 plastic items were found in a single trawl, with an average size of 2.37 mm (range 0.39-49), so stringent and controlled sample processing in the laboratory by professionals is needed (Bonney et al 2014).

Back in the laboratory, selection of plastics and microplastics was carried out by a small group of observers associated to the University of Barcelona and the Surfing for Science project, including students, researchers and laboratory technicians. However, samples and selected particles were routinely verified by a single trained observer so that observer bias was reduced. Samples, sieves, and petri dishes were covered wherever possible to minimize periods of exposure, and a clean workspace was maintained by keeping all surfaces and equipment clean using ethanol wipes.

#### 2.4. Data analysis

All data management and analyses were carried out using R v4.0.5 software (R Core Team 2021) using packages dplyr, ggplot2, stats, agricolae, car and rstatix and mapped and spatially analyzed using Quantum GIS v3.20 software (QGIS Development Team 2021). Tracks recorded by the volunteers using a smart-phone built-in GPS were manually corrected by removing inaccurate data points falling onshore or far from the expected trawl path. Unrealistic features, such as small deviations in the track were

corrected by smoothing the tracks with the QGIS built-in algorithms.

The numerical and mass (dry weight) concentrations of plastic debris (items  $m^{-2}$ ,  $mg m^{-2}$ ) were calculated by multiplying the manta trawl mouth length by the tow length (determined by the flowmeter and the Wikiloc App). Plastic abundance and mass concentrations were log-transformed and compared among locations using one-way ANOVA's followed by Tukey's HSD post-hoc pairwise comparisons test on the means for significant responses. Any temporal trends were formally tested using a non-parametric Mann-Kendall's trend test. Wind and current speed and direction data for each sampling location was sampled from daily gridded data available from the Copernicus Marine Environment Monitoring Service (Clementi et al 2021) and the Environmental Research Division's Data Access Program data-sets (Remote Sensing Systems 2021), respectively. Further, population density (hab. km<sup>-2</sup>) around a 10 km circular buffer at each location was calculated using data from the Statistical Institute of Catalonia (IDESCAT 2016). The fractal dimension as a measure of rugosity of the coastline (i.e. Compa et al (2020)) was also calculated within this buffer area. Physical and anthropogenic forcing data was compared with plastic concentrations using Pearson correlations. A rolling average was calculated to test the influence of wind and current data on the previous 14 d of sampling. The normality of the residuals of the fitted values was checked using Shapiro-Wilk's test for the fixed factors and the homogeneity of variance using Levene's test where applicable. The data is presented as the mean  $\pm$  standard deviation (SD) and the level of statistical significance level was set at 5%. 95% BCa bootstrapped confidence intervals (CI) of the mean concentrations are reported.

#### 3. Results and discussion

#### 3.1. Floating plastic debris in the nearshore

Early acknowledgment of the problem posed by plastic debris to ocean health involved observations by citizen scientists, such as local fishermen or beach users (Cundell 1973, Holmström 1975, Gregory 1991). Since then, our common understanding of the sources, pathways and sinks of plastics has been mainly attributed to growing research on beaches and in coastal and offshore areas (Cózar et al 2014, Suaria et al 2016, van Sebille et al 2020, Simon-Sánchez et al 2022). Unfortunately, far less is known about the concentrations, properties and composition of plastics in the nearshore, which seems to play an important role in beaching and trapping processes globally (Morales-Caselles et al 2021, Onink et al 2021, Sanchez-Vidal et al 2021). Over the past years, only some studies have shared insights on how plastics behave in the nearshore by means of numerical,

laboratory and field studies under controlled or isolated boundary conditions (Hinata et al 2017, Ho and Not 2019, Forsberg et al 2020, Kerpen et al 2020, Alsina and van Sebille 2021). Furthermore, only few studies have successfully monitored floating microplastics in the nearshore at constant shallow depths and close distances from shore. For instance, van der Hal et al (2017), Vianello et al (2018) and Compa et al (2020), have sampled microplastics at distances as close as 5–10 m from shore and up to  $\sim$ 5 m depths, Pedrotti et al (2016) and Ruiz-Orejón et al (2018) have sampled microplastics beyond ~100 m from shore, whereas Zeri et al (2018) and Baini et al (2018) targeted areas beyond ~500 m. In this study, a topdown citizen science approach was used to engage volunteers to collect scientific samples. The enrollment of volunteers and nature of sampling equipment allowed the collection of a total 129 samples of floating plastics at previously overlooked distances from shore and shallow depths (table 1). Five samples  $(\sim 4\%)$  were discarded due to inaccurate or absent GPS tracks and excluded from the study. The total recorded area and filtered volume of the survey was approximately 65 264 m<sup>2</sup> and 19 469 m<sup>3</sup>, respectively. Previous work showed that flowmeter measurements significantly decreased the average trawl distance by 23.1% (range 10.4-31.9), which likely had an impact on subsequent measurements of plastic mass and abundances (figure S1). Hereby, we discuss our results considering them only a minimum estimate of plastic loads in the nearshore of the investigated locations.

3.1.1. Plastic loads and variability in the nearshore We found a total 24 970 plastics in all samples collected across locations. Among all plastics found, 93.9% were microplastics, 5.7% mesoplastics and 0.4% macroplastics (table S1). This resulted in an overall average microplastic abundance of  $0.41 \pm 0.81$ items m<sup>-2</sup> (CI: 0.31-0.61), which was close to the total overall abundance (table 1). Average microplastic mass was  $0.07 \pm 0.19 \text{ mg m}^{-2}$  (CI: 0.05–0.12) and was closely related to microplastic abundances (r = 0.76, p < 0.001). Coastal population has been among the main factors explaining (>60%) plastic loads in coastal waters of the Mediterranean Sea, followed by rivers (32%) and fisheries (6%) (Kaandorp et al 2020). Accordingly, we found rather bell-curved trend from north to south of the study area, and closely followed the year-round coastal population density profile (r = 0.45, p < 0.001 for abundance and r = 0.30, p < 0.001 for mass; figure 2). Despite statistical differences were found across locations regarding abundances (ANOVA,  $F_{11} = 3.47$ , p < 0.01) and mass (ANOVA,  $F_{11} = 2.46$ , p < 0.01), significant differences were only constrained to the low microplastic concentrations found in nearshore waters of Llançà—i.e. hosting >4.7 thousand inhabitants and a density of >170 hab km<sup>-2</sup> (IDESCAT 2016)—compared to highly loaded samples collected in nearshore waters of Barcelona city-i.e. hosting >1.6 million inhabitants and a density of >16.4 thousand hab  $km^{-2}$  (IDESCAT 2016)—(figure 2). Overall, the estimated plastic loads were around the same levels found offshore in the central gyres of the world's oceans (e.g. Lebreton et al 2019, Wilcox et al 2020), and higher than most studies conducted within the Mediterranean Sea (Simon-Sánchez et al 2022), including samples taken at only  $\sim$ 4 km from shore in the study area (de Haan et al 2019). Our results depict generally higher microplastic mass loads nearshore (r = 0.18, p = 0.04), as found by Pedrotti et al (2016) and Compa et al (2019), and suggests that it may harbor part of the missing floating plastic stocks globally (Thompson et al 2004, Onink et al 2021), together with the deep-sea floor, water column, beaches or animal lattices—i.e. see review by van Sebille et al (2020). However, we found lower average loads compared to previous work conducted nearshore around the Balearic Islands (Ruiz-Orejón et al 2018, Compa et al 2020), which seems to fit with both influence of seasonal population increase in summer leading to higher amounts of mesoplastics and macroplastics found there, and the seasonal variations of hydrodynamic structures occurring in summer that may potentially retain plastics nearshore (Macias et al 2019, Mansui 2020). Indeed, between October 2020 and June 2021, a trend towards lower microplastic loads was generally found towards February and March—e.g. see clear trends at Llançà and Castelldefels—, especially observed north and south of the study area, whereas higher concentrations were found before and after the summer months (figures 3 and S2). A decrease in microplastic loads nearshore was associated to higher nearshore wind and current speeds in February and March, suggesting that dilution by beaching, mixing in the water column of horizontal spreading of plastics may play an important role (figure S3). Furthermore, an increasing monotonic trend in abundance was only observed for Mar Bella (figure 3; Kendall's tau = 0.51, p < 0.001), where most of the sampling effort was concentrated (table 1 and figure 2). Meanwhile, plastic size also decreased over time (Kendall's tau = -0.44, p < 0.001), suggesting effective plastic breakdown in a period of only weeks to months and little alongshore and crossshore transport during the survey. We suggest that artificial or naturally semi-enclosed beaches in the nearshore—e.g. limited by breakwaters or harbors, such as Mar Bella-may trap plastics more effectively leading to the formation of local temporary hotspots. We further support these findings as higher microplastic loads positively associated to the coastal rugosity (r = 0.21, p = 0.01), as also previously found by Compa et al (2020) in the nearshore of the Balearic Islands. Furthermore, the high loadings of microplastics commonly found in some locations, for instance up to 5.62, 4.07 and 2.74 items  $m^{-2}$  in

**Table 1.** Overview of the sampling conditions of each location and average total plastic concentrations with 95% BCa bootstrapped confidence intervals of the mean abundances and mass. Plastic concentrations expressed in items m<sup>-3</sup> and mg m<sup>-3</sup> are reported in table S2.

							lotal plastic concentrations	ncentrations	
			Distance from			Abundance (items m <sup>-2</sup> )	ems m <sup>-2</sup> )	$Mass (mg m^{-2})$	$m^{-2}$ )
Location	Tows	Date (start-end)	shore (m)	Tow depth (m)	Tow length (km)	Mean (±SD)	95% CI	Mean (±SD)	95% CI
Llançà	12	2020-12-04-2021-05-17	99.3 ± 9.4	$4.5 \pm 0.8$	$1.7\pm0.1$	$0.07 \pm 0.08$	0.03-0.13	$0.13 \pm 0.30$	0.01-0.40
Palamós	7	2020-11-29-2021-05-02	$320.9 \pm 114.6$	$18.9 \pm 7.6$	$2.0 \pm 0.0$	$0.16\pm0.15$	0.09 - 0.32	$0.91 \pm 1.93$	0.14 - 4.55
Arenys de Mar	6	2020-12-19-2021-05-09	$264 \pm 106.9$	$4.7 \pm 0.6$	$1.3 \pm 0.5$	$0.15\pm0.13$	0.08 - 0.25	$0.02 \pm 0.01$	0.01 - 0.03
Montgat	5	2021-02-25-2021-05-22	$76.1 \pm 60.7$	$2.5 \pm 1.6$	$0.8 \pm 0.3$	$0.32 \pm 0.19$	0.15 - 0.45	$0.14 \pm 0.14$	0.04 - 0.27
Llevant <sup>a</sup>	12	2020-10-31-2021-05-23	$126.8 \pm 32.5$	$2.9 \pm 0.7$	$0.9\pm0.2$	$0.60\pm0.64$	0.34 - 1.03	$0.15\pm0.27$	0.06 - 0.44
Mar Bella <sup>a</sup>	26	2020-10-09-2021-05-22	$178.2\pm80.3$	$2.9 \pm 2.4$	$1.0 \pm 0.3$	$0.35\pm0.33$	0.26 - 0.51	$0.24 \pm 0.63$	0.06 - 0.60
Nova Icària <sup>a</sup>	5	2021-01-02-2021-04-03	$157.9 \pm 27$	$2.4 \pm 0.7$	$1.2 \pm 0.3$	$1.08 \pm 1.79$	0.20 - 3.44	$0.37 \pm 0.42$	0.06 - 0.71
Barceloneta <sup>a</sup>	11	2020-12-19-2021-04-09	$114.7 \pm 28.3$	$0.4\pm0.2$	$1.9 \pm 0.3$	$0.32 \pm 0.34$	0.19 - 0.68	$0.14 \pm 0.13$	0.08 - 0.23
Sant Sebastià <sup>a</sup>	12	2020-10-17-2021-04-01	$122.3 \pm 83.2$	$1.6 \pm 1.2$	$1.2 \pm 0.4$	$1.40 \pm 2.01$	0.57 - 3.01	$0.54 \pm 1.10$	0.08 - 1.55
Castelldefels	10	2020-12-15-2021-05-23	$127.8\pm44.0$	$2.4 \pm 0.7$	$1.8 \pm 0.3$	$0.31 \pm 0.46$	0.12 - 0.81	$0.17 \pm 0.25$	0.05 - 0.35
Comarruga	9	2020-12-16-2021-04-18	$153.5 \pm 77.3$	$2.3 \pm 1.6$	$1.7\pm0.1$	$0.16\pm0.26$	0.05 - 0.48	$0.07 \pm 0.10$	0.01 - 0.17
l'Ametlla de Mar	6	2020-12-14-2021-04-29	$60.4\pm22.6$	$2.3 \pm 0.6$	$1.9 \pm 0.1$	$0.42 \pm 0.92$	0.08 - 1.40	$0.18 \pm 0.33$	0.04-0.53
Overall	124	2020-10-09-2021-05-23	$150.1 \pm 90.4$	$3.6\pm4.4$	$1.4\pm0.5$	$0.44\pm0.87$	0.33-0.65	$0.25 \pm 0.67$	0.16-0.41
MinMax.	5–26		10.0 - 860.0	0.2–34.0	0.31–2.36	<0.01–6.18		<0.01–5.25	

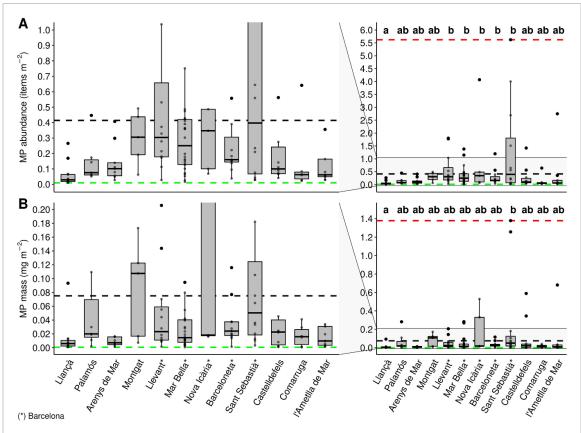
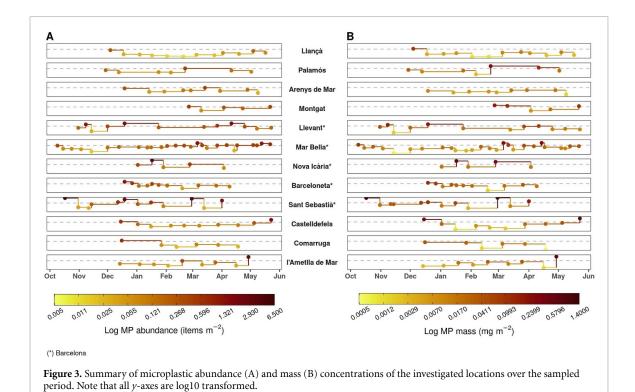
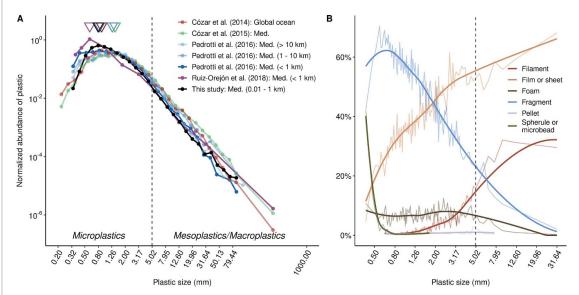


Figure 2. Abundance and mass concentrations of microplastics across locations in the north-western Mediterranean Sea (A) and (B). Dashed lines indicate survey averages (in black), minimum (in green) and maximum (in red) microplastic concentrations. Shared letters above each bar in (A) and (B) mean no significant difference according to Tukey's HSD pairwise comparison test with a 95% confidence interval.



Sant Sebastià, Nova Icària and l'Ametlla de Mar, suggest that litter windrows (i.e. aggregation of floating litter at the submesoscale domain) may also play

a role in nearshore waters by concentrating plastics on the order of  $\ge 10$  relative to the background concentrations (Cózar *et al* 2021). For instance, this



**Figure 4.** Normalized plastic size distributions across studies (A) and plastic size moving averages of 200 plastics for each plastic shape found (B). In figure (A), data from the global ocean (red line; n=7359) and the Mediterranean Sea (green line; n=3901) is obtained with a 0.2 mm-mesh Manta Trawl. Blue lines include data from the Mediterranean Sea offshore at >10 km (light blue; n=4469) and 1-10 km (medium blue; n=1830) and nearshore at <1 km (dark blue; n=8053) sampled with a 0.3 mm-mesh Manta Trawl. Purple line includes data from nearshore waters at <1 km (n=3145) obtained with a 0.3 mm-mesh Manta Trawl around the Balearic Islands (Mediterranean Sea). In this study we counted a total 24 970 plastics within nearshore waters between 0.01 and 1 km (average  $0.15\pm0.12$ ) from shore. Data from Pedrotti *et al* (2016) includes measurements from Cózar *et al* (2015). Size classes in the x-axis follow a 0.1-log series of 28 size classes starting from 0.2 mm. Note that the y-axis is  $\log 10$  transformed.

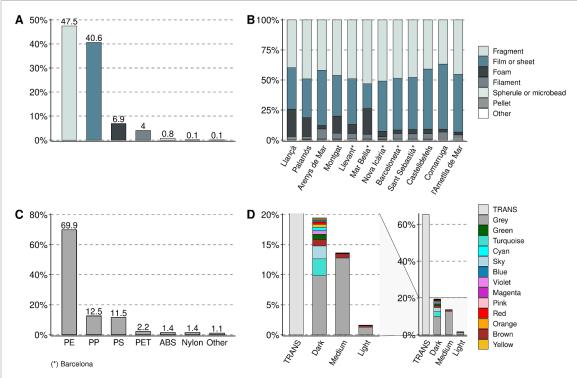
may be particularly important during moderate and steady winds or near river plume fronts (Cózar *et al* 2021).

## 3.1.2. Size distributions and plastic properties in the nearshore

Microplastics were almost exclusively found within nearshore waters (93.9%; see above and table S1). Plastics <1 mm represented 29.5% whereas most plastics were within the 1–5 mm size range (table S1). In figure 4(A) we show the particle size distributions (PSDs) of plastics compared to other studies conducted in the Mediterranean sea nearshore and offshore, and global ocean, which displays a power law regime up to 1 to 0.5 mm in length before decreasing towards smaller sizes. Our findings show that the nearshore may highly contribute to the floating microplastic oceanic stocks, as anticipated by (Onink et al 2021). The apparent higher relative amounts of microplastics found compared to other studies offshore (Cózar et al 2014, 2015) may result from the combination of effective fragmentation nearshore (Pedrotti et al 2016) and long residence times due to slow degradation of floating plastics in the coastal zone, which has been suggested to drive the current floating stocks of plastics, and likely respond to plastic inputs from years to decades back from now (Lebreton et al 2019, Weiss et al 2021). In any case, comparison of PSDs shows that our results are fairly comparable to those found by Pedrotti et al (2016) and Ruiz-Orejón et al (2018) in nearshore waters (<1 km), but progressively differ with offshore waters as plastic size becomes larger. This agrees with

findings from Ryan (2015), suggesting that higher relative surface area to volume ratios of smaller plastics may lead to increased epiphytic growth and ballasting in coastal areas. We find little evidence for expected coastal trapping of larger plastics due to onshore Stokes drift (Isobe *et al* 2014). As pointed out above, seasonality in physical conditions during sampling may be responsible, for instance seasonal differences in onshore Stokes drift transport leading to increased beaching (Olivelli *et al* 2020), or windage (Ryan 2015), potentially reducing larger floating plastics in the nearshore.

Information about the sources can be inferred from the types of plastics found and chemical analysis. We only found a few pellets and spherules and microbeads (<1%), although the latter may have not been effectively captured by the 0.33 mm-mesh net due to their small size (figures 4 and 5). Foams e.g. sourced from food containers and fishing activity—and filaments—e.g. sourced from the fishing activity—constituted almost 11% of the plastics found (figure 5). However, the vast majority of plastics found were composed of fragments and films and sheets (>80%), which potentially originated from the breakdown of larger plastic pieces. We find a strong predominance of thin films and sheets compared to offshore areas, where fragments are usually found in much higher proportions (e.g. Suaria et al 2016). This observation fits with the higher amounts of wrappers (39%), bags (22%) and beverage containers (11%) selectively occurring in nearshore waters (Morales-Caselles et al 2021). Furthermore, rigid sheets may ultimately resemble fragments as their



**Figure 5.** Percentages of different properties of floating plastics ( $n = 24\,970$ ) sampled by volunteers in the northwestern Mediterranean Sea. Plastics categorized by shape or category of all locations together (A) and across locations (B). A random subset (n = 285) of microplastics chemically identified with ATR-FTIR spectroscopy (C). Finally, all colors and color hues found associated to floating plastics including TRANS or transparent and translucent plastics without any associated color (D).

area-to-thickness ratios become more equal over time due to fragmentation. Small-sized plastics following breakdown can more easily escape nearshore dynamics (e.g. Isobe *et al* 2014), which may partly explain why more fragment-like plastics are identified in offshore waters. This can be observed in figure 5(B), where films and sheets loose predominance towards smaller sizes, as opposed to fragments. Differences in local sources may also potentially explain the differences of types of plastics found across locations—e.g. foams predominated towards the north, where also more fishing activity takes place—(Chi squared test, p < 0.001; figure 5(B) and table S1).

Figure 5(C) shows that almost 70% of microplastics were identified as low and high density polyethylene (PE), followed by polypropylene (PP) and polystyrene (PS). Polyolefins (PE and PP) are the most produced polymers in Europe with over 49% demand, and used mainly in single-use food packaging and automotive parts (Plastics Europe 2020), which reasonably fits with our findings. Together with PS (in expanded form), which is mainly used in food packaging, fishing or insulation, these polymers are positively buoyant in seawater ( $\rho$  < 1.02 g cm<sup>-3</sup>) and consistently represent a great fraction of the microplastics found floating in nearshore waters in the Mediterranean Sea (Zeri et al 2018, Compa et al 2020), and elsewhere globally (Suaria et al 2016). Interestingly, a few polymers were found with higher density than seawater ( $\rho > 1.02 \text{ g cm}^{-3}$ ), which may be explained by a combination of intensive mixing by waves and wind causing them to surge to the surface, and closeness to coastal sources. These added to 6.1% of the total, including polyethylene terephthalate—e.g. mainly used in plastic bottles and cosmetic packaging—, acronitrile butadiene styrene—e.g. required in multiple shock-absorbing or heat-resistant applications—, nylon—e.g. used in fishing gear—and others (<1%), including ethylenevinyl acetate and PE/PP co-polymers.

Finally, over half out of the 120 colors of the reference palette were used for classification. Transparent and translucent plastics were most frequently found (65.3%), as they were associated to films and sheets, spherules or microbeads and pellets (see above). Plastics of different tones of gray, including black and white followed (23.9%). Other colors, grouped into bluish-green (i.e. sky, blue, cyan, turquoise and green), amber (i.e. yellow, brown and orange) and reddish (i.e. red, pink, violet and magenta) were less frequent, accounting only 6.8%, 2.8% and 1.2% of colors, respectively (table S1). Overall, the prevalence of transparent and translucent plastics is similar to findings of Martí et al (2020) globally (i.e. 47%). Conversely, we found less variety of colors in the nearshore than they found floating in enclosed seas at  $\sim$ 5 km from shore. However, the low prevalence of amber-like plastics associated to yellowing or oxidative stress aligns with views that plastics in the nearshore may be relatively short-lived before reaching remote areas (Andrady 2011, Martí *et al* 2020). In any case, it is unclear how different colors can impact the ingestion rates of plastics by marine organisms, especially in coastal areas where marine biodiversity peaks. Recent findings show transparent and translucent and black plastics prevail in fish (~40% and 30%), whereas white and blue plastics prevail in turtles (~67% and 40%) and cetaceans (~38% and 30%), which may respond to different feeding strategies or environmental exposure of organisms (see review by López-Martínez *et al* 2021).

## 3.2. The success of citizen science in plastic pollution studies

Citizen science in plastic pollution studies is not new, successful programs have incorporated volunteers to provide repeated sampling for time series as well as synoptic collections over wide geographic regions, and providing access to unexplored sites (van der Velde *et al* 2017, Zettler *et al* 2017). These programs have provided key contributions to the understanding of the impact of plastic pollution on the marine environment, and even though most projects have focused on macroplastics—as they are more easily sampled—microplastics have been recently in the spotlight.

Beach surveys and clean-up initiatives such as 'International Coastal Cleanup', 'World Cleanup Day', 'Marine Litter Watch', or 'International Pellet Watch', have increased our understanding on the nature and extent of plastic pollution in beaches at regional and global scales (Takada 2006, Storrier et al 2007, Hidalgo-Ruz and Thiel 2015, Bergmann et al 2017, Bosker et al 2017, 2017, Lots et al 2017, Nelms et al 2017, Haarr et al 2020, Roman et al 2020). The shallow seafloor has been investigated by volunteer divers of the 'Dive Against Debris' initiative that have provided scientific information on the abundances and characteristics of underwater litter (Consoli et al 2020). Furthermore, integrated large data-sets of marine litter collected by citizen science programs in rivers, beaches and shallow seafloors have provided a first overview of the origin, transport and ultimate fate of litter items as small as 0.5 mm up to 1 m in the global ocean (Hidalgo-Ruz and Thiel 2013, Rech et al 2015, Morales-Caselles et al 2021), and entanglement and ingestion of plastic debris by wildlife (Wilcox et al 2016) including fish destined for human consumption (Liboiron et al 2016) has also been documented through citizen science initiatives.

In contrast, there are less citizen science contributions to monitor plastic floating in the sea surface. The Trawlshare program developed by the 5-Gyres Institute engages sailors to collect scientific samples across the five subtropical gyres. Samples are sorted onboard using simplified protocols (Trawl For Plastic 2021). The same team of researchers went on several expeditions through all 5 subtropical gyres and

published the first global estimate of all plastic of all sizes floating in the world's oceans, totaling 270 000 metric tons from 5.25 trillion particles (Eriksen *et al* 2014).

There is an ongoing need to provide scientifically robust data sets on floating plastic abundances and characteristics making use of the citizen science, as it provides clear advantages over conventional science by operating at greater geographical and temporal scales, reducing project costs and raising awareness (Paradinas *et al* 2021). Citizen science not only empowers volunteers as they participate in the collection of valuable scientific data, but it also provides health benefits and well-being by spending time and interacting with marine and coastal ecosystems (Borja *et al* 2020, Britton *et al* 2020).

#### 4. Conclusions and final remarks

In the present work, a top-down citizen science approach was used to determine microplastic loads in the nearshore, an area previously undersampled by the scientific community. We demonstrate along with previous works around the globe that citizen science is a reliable and powerful tool that can provide invaluable scientific data at long and wide spatiotemporal scales. Accordingly, our findings show considerable microplastic pollution in nearshore waters, and a high spatial and temporal variability. A trend with decreasing loads towards February and March could be observed and was likely conditioned by local hydrodynamic conditions, such as surface currents and winds lowering floating microplastic loads. Furthermore, microplastic concentrates in the nearshore, either because of effective breakdown, coastal rugosity or seasonal changes in hydrodynamic conditions. The variety and closeness of sources in the nearshore and population density further contributed to the high variability of concentrations found. Our data, together with data on estimated plastic inputs from land and rivers, and from beach and offshore surveys can been used to constrain numerical models, which ultimately contribute to develop comprehensive risk assessments and our understanding of the cross-shore and vertical transport pathways, sinks, beaching and fragmentation processes of plastics and microplastics in the marine environment (van Sebille et al 2020). Samplings did not target specific sub-domains within the nearshore, such as the outer or inner nearshore (i.e. swash and surf zone), which is often affected by different turbulent motions affecting plastic abundance and mass (Ho and Not 2019). However, in the future, more targeted surveys demanding particular needs to answer specific scientific questions around plastic occurrences, distribution and dynamics in the nearshore may also benefit from the citizen science approach presented here.

#### Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: 10.34810/data149.

#### Acknowledgments

We sincerely thank all volunteers involved in sample collection. The success of the Surfing for Science project is driven by their efforts and motivation to paddle for about 1 h even in winter conditions. We thank the Oceans and Human Health Chair and Rycsa.cat for their support with the trawls. We would also like to extend our gratitude to Guillermo Asensio and Vidal Martínez from Asensio Comunicació Visual for their amazing creative support, and Núria Ferrer and Pilar Hermo from the Scientific and Technical Centres of the University of Barcelona for technical assistance with the FT-IR spectrometer. This research has been supported by the Fundación Española para la Ciencia y la Tecnología (FECYT) Project FCT-19-14747, the Ajuntament de Barcelona Grant 20S02426-00, the Facultat de Ciències de la Terra, and a Catalan Government Grups de Recerca Consolidats grant to GRC Geociències Marines (ref. 2017 SGR 315). The authors declare nofinancial and non-financial competing interests.

#### **ORCID** iDs

William P de Haan https://orcid.org/0000-0002-4192-191X

Oriol Uviedo https://orcid.org/0000-0001-7362-3629

Maria Ballesteros (https://orcid.org/0000-0003-0627-6537

**Xavier Curto** https://orcid.org/0000-0003-4193-6190

Montse Guart https://orcid.org/0000-0002-1313-6068

Alex Molina https://orcid.org/0000-0002-7155-353X

Anna Sanchez-Vidal https://orcid.org/0000-0002-8209-1959

#### References

- Alsina J M and van Sebille E 2021 Medidas Experimentales Obtenidas con Videocámaras del Movimiento de Partículas Plásticas Inducido por el Oleaje *OmniaScience* **2** 253–73
- Andrady A L 2011 Microplastics in the marine environment *Mar. Pollut. Bull.* **62** 1596–605
- Baini M, Fossi M C, Galli M, Caliani I, Campani T, Finoia M G and Panti C 2018 Abundance and characterization of microplastics in the coastal waters of Tuscany (Italy): the application of the MSFD monitoring protocol in the Mediterranean Sea *Mar. Pollut. Bull.* 133 543–52
- Bergmann M, Lutz B, Tekman M B and Gutow L 2017 Citizen scientists reveal: marine litter pollutes Arctic beaches and affects wild life *Mar. Pollut. Bull.* 125 535–40

- Bonney R, Shirk J L, Phillips T B, Wiggins A, Ballard H L, Miller-Rushing A J and Parrish J K 2014 Next steps for citizen science *Science* 343 1436–7
- Borja A *et al* 2020 Moving toward an agenda on ocean health and human health in Europe *Front. Mar. Sci.* **7** 37
- Borrelle S B *et al* 2020 Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution *Science* 369 1515–8
- Bosker T, Behrens P and Vijver M G 2017 Determining global distribution of microplastics by combining citizen science and in-depth case studies *Integr. Environ. Assess. Manage.* 13 536–41
- Britton E, Kindermann G, Domegan C and Carlin C 2020 Blue care: a systematic review of blue space interventions for health and wellbeing *Health Promot. Int.* 35 50–69
- Camins E, de Haan W P, Salvo V-S, Canals M, Raffard A and Sanchez-Vidal A 2020 Paddle surfing for science on microplastic pollution *Sci. Total Environ.* **709** 136178
- Carpenter E J and Smith K L 1972 Plastics on the Sargasso sea surface Science 175 1240-1
- Clementi E et al 2021 Mediterranean Sea physical analysis and forecast (CMEMS MED-Currents, EAS6 system):

  MEDSEA\_ANALYSISFORECAST\_PHY\_006\_013 (available at: https://resourcesmarinecopernicuseuoptioncom\_csw view details product\_id=MEDSEA\_ANALYSISFORECAST\_PHY\_006\_013)
- Compa M, Alomar C, Mourre B, March D, Tintoré J and Deudero S 2020 Nearshore spatio-temporal sea surface trawls of plastic debris in the Balearic Islands *Mar. Environ. Res.* 158 104945
- Compa M, March D and Deudero S 2019 Spatio-temporal monitoring of coastal floating marine debris in the Balearic Islands from sea-cleaning boats *Mar. Pollut. Bull.* 141 205–14
- Consoli P *et al* 2020 Characterization of seafloor litter on Mediterranean shallow coastal waters: evidence from Dive Against Debris®, a citizen science monitoring approach *Mar.* Pollut. Bull. 150 110763
- Cowger W, Steinmetz Z, Gray A, Munno K, Lynch J, Hapich H, Primpke S, De Frond H, Rochman C and Herodotou O 2021 Microplastic spectral classification needs an open source community: open specy to the rescue! *Anal. Chem.* 93 7543–8
- Cózar A et al 2014 Plastic debris in the open ocean Proc. Natl Acad. Sci. 111 10239–44
- Cózar A, Aliani S, Basurko O C, Arias M, Isobe A, Topouzelis K, Rubio A and Morales-Caselles C 2021 Marine litter windrows: a strategic target to understand and manage the ocean plastic pollution *Front. Mar. Sci.* 8 1–9
- Cózar A, Sanz-Martín M, Martí E, González-Gordillo J I, Ubeda B, Gálvez J Á, Irigoien X and Duarte C M 2015 Plastic accumulation in the Mediterranean Sea *PLoS One*
- Cundell A M 1973 Plastic materials accumulating in Narragansett Bay *Mar. Pollut. Bull.* 4 187–8
- de Haan W P, Sanchez-Vidal A and Canals M 2019 Floating microplastics and aggregate formation in the Western Mediterranean Sea Mar. Pollut. Bull. 140 523–35
- Eriksen M, Lebreton L C M, Carson H S, Thiel M, Moore C J, Borerro J C, Galgani F, Ryan P G and Reisser J 2014 Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea *PLoS One* 9 e111913
- Forsberg P L, Sous D, Stocchino A and Chemin R 2020 Behaviour of plastic litter in nearshore waters; first insights from wind and wave laboratory experiments *Mar. Pollut. Bull.* 153 111023
- Galgani F et al 2021 Are litter, plastic and microplastic quantities increasing in the ocean? Microplastics Nanoplastics 1 2
- Gregory M R 1991 The hazards of persistent marine pollution: drift plastics and conservation islands *J. R. Soc. N.Z.* **21** 83–100
- Haarr M L, Pantalos M, Hartviksen M K and Gressetvold M 2020 Citizen science data indicate a reduction in beach litter in

- the Lofoten archipelago in the Norwegian Sea Mar. Pollut. Bull. 153 111000
- Hidalgo-Ruz V and Thiel M 2013 Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project *Mar. Environ. Res.* 87–88 12–18
- Hidalgo-Ruz V and Thiel M 2015 The contribution of citizen scientists to the monitoring of marine litter *Marine* Anthropogenic Litter ed M Bergmann, L Gutow and M Klages (Cham: Springer International Publishing) pp 429–47
- Hinata H, Mori K, Ohno K, Miyao Y and Kataoka T 2017 An estimation of the average residence times and onshore-offshore diffusivities of beached microplastics based on the population decay of tagged meso- and macrolitter *Mar. Pollut. Bull.* 122 17–26
- Ho N H E and Not C 2019 Selective accumulation of plastic debris at the breaking wave area of coastal waters *Environ*. *Pollut*. 245 702–10
- Holmström A 1975 Plastic films on the bottom of the Skagerack Nature 255 622–3
- IDESCAT 2016 Població de Catalunya georeferenciada a 1 de gener de 2016 (Barcelona: Generalitat de Catalunya)
- Isobe A, Kubo K, Tamura Y, Kako S, Nakashima E and Fujii N 2014 Selective transport of microplastics and mesoplastics by drifting in coastal waters Mar. Pollut. Bull. 89 324–30
- Jambeck J R, Geyer R, Wilcox C, Siegler T R, Perryman M, Andrady A, Narayan R and Law K L 2015 Plastic waste inputs from land into the ocean Science 347 768–71
- Kaandorp M L A, Dijkstra H A and van Sebille E 2020 Closing the Mediterranean marine floating plastic mass budget: inverse modeling of sources and sinks *Environ. Sci. Technol.* 54 11980–9
- Kaiser D, Kowalski N and Waniek J J 2017 Effects of biofouling on the sinking behavior of microplastics *Environ. Res. Lett.* 12 124003
- Kane I A, Clare M A, Miramontes E, Wogelius R, Rothwell J J, Garreau P and Pohl F 2020 Seafloor microplastic hotspots controlled by deep-sea circulation Science 368 1140–5
- Kerpen N B, Schlurmann T, Schendel A, Gundlach J, Marquard D and Hüpgen M 2020 Wave-induced distribution of microplastic in the surf zone Front. Mar. Sci. 7 979
- Law K L, Morét-Ferguson S, Maximenko N A, Proskurowski G, Peacock E E, Hafner J and Reddy C M 2010 Plastic accumulation in the North Atlantic subtropical gyre Science 329 1185–8
- Lebreton L et al 2018 Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic Sci. Rep. 8 4666
- Lebreton L, Egger M and Slat B 2019 A global mass budget for positively buoyant macroplastic debris in the ocean *Sci. Rep.* 9 12922
- Liboiron M, Liboiron F, Wells E, Richárd N, Zahara A, Mather C, Bradshaw H and Murichi J 2016 Low plastic ingestion rate in Atlantic cod (Gadus morhua) from Newfoundland destined for human consumption collected through citizen science methods Mar. Pollut. Bull. 113 428–37
- López-Martínez S, Morales-Caselles C, Kadar J and Rivas M L 2021 Overview of global status of plastic presence in marine vertebrates *Glob. Change Biol.* **27** 728–37
- Lots F A E, Behrens P, Vijver M G, Horton A A and Bosker T 2017 A large-scale investigation of microplastic contamination: abundance and characteristics of microplastics in European beach sediment *Mar. Pollut. Bull.* 123 219–26
- Macias D, Cózar A, Garcia-Gorriz E, González-Fernández D and Stips A 2019 Surface water circulation develops seasonally changing patterns of floating litter accumulation in the Mediterranean Sea. A modelling approach Mar. Pollut. Bull. 149 110619
- Mansui J 2020 Predicting marine litter accumulation patterns in the Mediterranean basin: Spatio-temporal variability and comparison with empirical data *Prog. Oceanogr.* **182** 102268
- Martí E, Martin C, Galli M, Echevarría F, Duarte C M and Cózar A 2020 The colors of the ocean plastics *Environ. Sci. Technol.* 54 6594–601

- Michida Y *et al* 2019 Guidelines for harmonizing ocean surface microplastic monitoring methods. Version 1.1 (Japan: Ministry of the Environment) (available at: https:// repository.oceanbestpractices.org/handle/11329/ 1361)
- Moore C J, Moore S L and Leecaster M K 2001 A comparison of plastic and plankton in the North Pacific central gyre *Mar. Pollut. Bull.* 42 1297–300
- Morales-Caselles C *et al* 2021 An inshore–offshore sorting system revealed from global classification of ocean litter *Nat. Sustain.* 4 484–93
- Nelms S, Coombes C, Foster L, Galloway T, Godley B, Lindeque P and Witt M 2017 Marine anthropogenic litter on British beaches: a 10-year nationwide assessment using citizen science data *Sci. Total Environ.* **579** 1399–409
- Olivelli A, Hardesty B D and Wilcox C 2020 Coastal margins and backshores represent a major sink for marine debris: insights from a continental-scale analysis *Environ. Res. Lett.* **15** 074037
- Onink V, Jongedijk C, Hoffman M, Van Sebille E and Laufkötter C 2021 Global simulations of marine plastic transport show plastic trapping in coastal zones *Environ. Res. Lett.* **16** 064053
- Paradinas L M, James N A, Quinn B, Dale A and Narayanaswamy B E 2021 A new collection tool-kit to sample microplastics from the marine environment (sediment, seawater, and biota) using citizen science *Front*. *Mar. Sci.* 8 635
- Pedrotti M L, Petit S, Elineau A, Bruzaud S, Crebassa J-C, Dumontet B, Martí E, Gorsky G and Cózar A 2016 Changes in the floating plastic pollution of the Mediterranean Sea in relation to the distance to land *PLoS One* 11 e0161581
- Plastics Europe 2020(Plastics Europe)
- QGIS Development Team 2021 QGIS geographic information system (QGIS Association) (available at: www.qgis.org)
- R Core Team 2021 R: A Language and Environment for Statistical Computing (Vienna: R Foundation for Statistical Computing) (available at www.R-project.org/)
- Rech S, Macaya-Caquilpán V, Pantoja J F, Rivadeneira M M, Campodónico C K and Thiel M 2015 Sampling of riverine litter with citizen scientists—findings and recommendations Environ. Monit. Assess. 187 335
- Remote Sensing Systems 2021 Ocean surface winds—CCMP—daily (Near Real Time), 2016-present. v2.1 (available at: https://oceanwatch.pifsc.noaa.gov/erddap/griddap/ccmp-daily-v2-1-NRT.html)
- Roman L, Hardesty B D, Leonard G H, Pragnell-Raasch H, Mallos N, Campbell I and Wilcox C 2020 A global assessment of the relationship between anthropogenic debris on land and the seafloor *Environ. Pollut.* 264 114663
- Ruiz-Orejón L F, Sardá R and Ramis-Pujol J 2018 Now, you see me: high concentrations of floating plastic debris in the coastal waters of the Balearic Islands (Spain) Mar. Pollut. Bull. 133 636–46
- Ryan P G 2015 Does size and buoyancy affect the long-distance transport of floating debris? *Environ. Res. Lett.* **10** 084019
- Sanchez-Vidal A, Canals M, de Haan W P, Romero J and Veny M 2021 Sea grasses provide a novel ecosystem service by trapping marine plastics *Sci. Rep.* 11 254
- Schneider C A, Rasband W S and Eliceiri K W 2012 NIH image to ImageJ: 25 years of image analysis *Nat. Methods* **9** 671–5
- Simon-Sánchez L, Grelaud M, Franci M and Ziveri P 2022 Are research methods shaping our understanding of microplastic pollution? A literature review on the seawater and sediment bodies of the Mediterranean Sea *Environ*. *Pollut.* 292 118275
- Storrier K L, McGlashan D J, Bonellie S and Velander K 2007 Beach litter deposition at a selection of beaches in the Firth of Forth, Scotland *J. Coast. Res.* 23 813–22
- Suaria G, Avio C G, Mineo A, Lattin G L, Magaldi M G, Belmonte G, Moore C J, Regoli F and Aliani S 2016 The Mediterranean plastic soup: synthetic polymers in Mediterranean surface waters Sci. Rep. 6 37551

- Surfing For Science Lab 2019 Surfing for science lab [@surfingforsciencelab] (available at: www.instagram.com/ surfingforsciencelab/)
- Takada H 2006 Call for pellets! International pellet watch global monitoring of POPs using beached plastic resin pellets Mar. Pollut. Bull. 52 1547–8
- Thermo Fisher 2021 Software OMNIC<sup>TM</sup> specta online (available at: www.thermofisher.com/order/catalog/product/833-036200)
- Thompson R C, Olsen Y, Mitchell R P, Davis A, Rowland S J, John A W G, McGonigle D and Russell A E 2004 Lost at sea: where is all the plastic? *Science* **304** 838
- Trawl For Plastic 2021 Trawl for plastic 5Gyres.org (available at: www.5gyres.org/trawl-resources)
- van der Hal N, Ariel A and Angel D L 2017 Exceptionally high abundances of microplastics in the oligotrophic Israeli Mediterranean coastal waters *Mar. Pollut. Bull.* 116 151–5
- van der Velde T, Milton D A, Lawson T J, Wilcox C, Lansdell M, Davis G, Perkins G and Hardesty B D 2017 Comparison of marine debris data collected by researchers and citizen scientists: is citizen science data worth the effort? *Biol. Conserv.* 208 127–38
- van Sebille E *et al* 2020 The physical oceanography of the transport of floating marine debris *Environ. Res. Lett.* **15** 023003
- van Sebille E, England M H and Froyland G 2012 Origin, dynamics and evolution of ocean garbage patches from observed surface drifters *Environ. Res. Lett.* 7 044040
- van Sebille E, Wilcox C, Lebreton L, Maximenko N, Hardesty B D, Van Franeker J A, Eriksen M, Siegel D, Galgani F and

- Law K L 2015 A global inventory of small floating plastic debris *Environ. Res. Lett.* **10** 124006
- Vianello A, Da Ros L, Boldrin A, Marceta T and Moschino V 2018 First evaluation of floating microplastics in the Northwestern Adriatic Sea *Environ. Sci. Pollut. Res.* 25 28546–61
- Weiss L, Ludwig W, Heussner S, Canals M, Ghiglione J-F, Estournel C, Constant M and Kerhervé P 2021 The missing ocean plastic sink: gone with the rivers *Science* 373 107–11
- Wikiloc 2019 Wikiloc trails of the World (Wikiloc) (available at: www.wikiloc.com)
- Wilcox C, Hardesty B D and Law K L 2020 Abundance of floating plastic particles is increasing in the Western North Atlantic Ocean *Environ. Sci. Technol.* **54** 790–6
- Wilcox C, Mallos N J, Leonard G H, Rodriguez A and Hardesty B D 2016 Using expert elicitation to estimate the impacts of plastic pollution on marine wildlife Mar. Policy 65 107–14
- Woodall L C, Sanchez-Vidal A, Canals M, Paterson G L J, Coppock R, Sleight V, Calafat A, Rogers A D, Narayanaswamy B E and Thompson R C 2014 The deep sea is a major sink for microplastic debris *R. Soc. Open Sci.* 1 140317
- Zeri C *et al* 2018 Floating plastics in Adriatic waters (Mediterranean Sea): from the macro- to the micro-scale *Mar. Pollut. Bull.* 136 341–50
- Zettler E, Takada H, Monteleone B, Mallos N, Eriksen M and Amaral-Zettler A L 2017 Incorporating citizen science to study plastics in the environment *Anal. Methods* 9 1392–403