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# Seasonal variation in the abundance of marine plastic debris in Banderas Bay, Mexico

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A B S T R A C T

A floating plastic monitoring program was conducted for two years on a weekly basis in Banderas Bay, Mexico. A total of 94 samples were collected from May 2016 to April 2018 in the southern part of the bay. Half (57%) of them contained plastic debris; 79% of it being < 5 mm in length. Polypropylene and Polyethylene were the most abundant polymers, accounting for 45% and 43% of the plastic pieces (pp), respectively. The highest abundance of plastic pieces was found in July 2016, with a maximum of 0.3 pp/m$^3$ found in one sample. The amount of floating plastics was significantly higher in the hurricane season compared to the dry season ($p < 0.001$). This suggests that rainfall may play a significant role in the offload of plastics from land-based sources into the bay.

## 1. Introduction

Plastics are a diverse group of materials derived from oil or gas, and are usually made from these with the addition of various chemical additives (Thompson et al., 2009). Due to their light weight and durability, plastics are suitable for the manufacture of a very wide range of everyday products. Additionally, due to their durability, they can be a serious hazard in both marine and terrestrial environments (De Souza-Machado et al., 2018; Kühn et al., 2015).

It has been estimated that petroleum-based plastic makes up 60–80% of marine debris, the rest being mainly glass and metals (Derraik, 2002). Understanding the sources of plastic pollution is very important to facilitate better debris management and potentially reducing the input of plastic into the marine environment (Eriksen et al., 2014; Sebille et al., 2012; Thompson et al., 2009). Every year, an estimate of 4.8 to 12.7 million metric tons of plastic debris enters the oceans worldwide from terrestrial sources. But this is only a portion of the total amount of plastics that enters in the marine ecosystem because there is no estimation for other sources of plastic pollution, such as lost fishing gear, inputs from natural disasters (e.g. tsunami, hurricanes etc.) and losses from at-sea vessels (Jambeck et al., 2015). Once in the sea, plastic debris has been proven to cause negative impacts at various scales: socio-economic, biological and ecological (Eriksen et al., 2014). These effects are visible not only close to the pollution source, but can also reach remote habitats, due to ocean currents and wind driven transport of floating debris (Barnes et al., 2009; Sebille et al., 2012). Interactions between megafauna and marine litter have been reported since the 60s (Laist, 1997) through entanglement, ingestion and nest construction, while in the last decades it has been investigated also for potential toxicological effects (Fossi et al., 2017; Germanov et al., 2018; Rios et al., 2007). Under UV degradation and mechanical stress, plastic debris gradually breaks down into smaller particles that adsorb persistent organic pollutants (POPs) (Rios Mendoza and Jones, 2015). These can be transferred to the tissues of the organisms that ingest the plastic and cause toxic effects (Bakir et al., 2014; Mato et al., 2001; Teuten et al., 2009). Smaller pieces enter the food web at a lower level, and the POPs can bioaccumulate and biomagnificate through the food chain, reaching higher concentrations and worse effects in long living and top predator species (Germanov et al., 2018; Marsili et al., 2016; Stewart et al., 2018).

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Rivers play a significant role in the offload of land-based plastic debris (Rech et al., 2014) and it has been observed that during the rainy season, increased river flows cause more plastic items to accumulate on beaches close to river sources (Araújo and Costa, 2007; Cheung et al., 2016). Adopting seasonal monitoring in areas with seasonally variable rainfall is important to avoid the underestimation of marine plastic debris during the dry season, or overestimation in the rainy season.

Many studies have focused on mapping the distribution of plastic debris in the oceans worldwide, mainly in open waters, but less effort has been dedicated to monitoring the floating plastic abundance through time in coastal areas. The high spatial and temporal heterogeneity of plastic debris distribution make trends difficult to discern, both in small and large scale studies (Goldstein et al., 2013). Understanding the distribution, composition and seasonal abundance of floating debris is prerequisite for the study of its environmental effects on the marine environment (Kang et al., 2015). This study investigates the abundance, seasonality and composition of floating plastics in the southern part of Banderas Bay in the Mexican Pacific Ocean. Due to the high number of protected or endangered species that are present in the bay, an evaluation of the current situation on plastic pollution in the area is important to understand what threats these megafauna species may be facing. Many rivers and creeks discharge into the bay, which could potentially be a continuous source of plastic pollution in the area that is exacerbated by hurricane-driven input. Since plastic removal from the environment is not a viable way to reduce the current plastic pollution issue, detecting the main sources of input in the environment is the first step in avoiding more plastic debris reaching the ocean and implementing effective plastic-reduction solutions (Wessel et al., 2019).

## 2. Materials and methods

### 2.1. Study area

Banderas Bay is located on the Pacific coast of Mexico (Fig. 1) and belongs to the states of Jalisco and Nayarit. With its 100 km of coastline, it is one of the biggest bays in Mexico. The bathymetry of the bay is characterized by the presence of a deep canyon (> 2000 m depth) located in the southern part of the bay and east-west oriented. The main freshwater input of the bay is the Ameca River, 200 km long and with a drainage basin of > 12,000 $km^2$, while in the southern part of the bay many smaller rivers flow from the adjacent mountainous region (rivers Pitillal, Cuale, Nogalito, Mismaloya, Tomatlán, Quimixto, Tuito, Yelapa) (Cotler Ávalos, 2010). Tropical cyclones are the most important element in the rainfall seasonality of the area, with a rainy season that starts in June and ends in October (García-Oliva et al., 1991). The bay is characterized by a diverse marine megafauna community, with the presence of 18 different species of marine mammals that are seasonal visitors or residents in the area (Pompa-Mansilla and García-Gutiérrez, 2017), seasonal aggregations of oceanic manta rays (*Mobula birostris*) (Stewart et al., 2016a) and visitation by other devil rays (*Mobula* spp.) which are filter feeders that may be particularly impacted by plastic ingestion (Germanov et al., 2018).

### 2.2. Sampling

Surface sampling of plastic debris took place in the same transect in the southern part of the bay once a week from May 2016 to April 2018, opportunistically during the manta rays monitoring conducted by Proyecto Manta Pacific Mexico. A zooplankton net (0.3 m diameter, 333 μm mesh size) was towed horizontally in surface waters at a speed of approximately 2 knots, for 5 to 30 min from a small boat. The volumes of water filtered through the mesh was determined and standardized using a General Oceanics 2030R mechanical flowmeter attached across the center of the net opening and the area of ocean surface sampled was calculated by multiplying the length of surface water sampled (calculated with the flowmeter) by the width of the net opening (0.3 m). Samples were stored in aluminum foil and kept frozen until analysis.

### 2.3. Sample analysis

Plastic debris was separated from organic material under a Zeiss Stemi DV4 dissecting microscope (8–30× magnifications) and categorized by size classes of 1 mm each, color and type (fragment, line, fiber, pellet or film). A Thermo Fisher Scientific microscope Nicolet iN™ 10 FT-IR Spectrometer with attenuated total reflectance (μFTIR-ATR) with germanium crystal (equipped with a liquid nitrogen-cooled mercury cadmium telluride detector) was used to determine composition of the plastic debris identified by visual examination. Particle counts were converted to number of particles per cubic meter of seawater (pp/$m^3$)

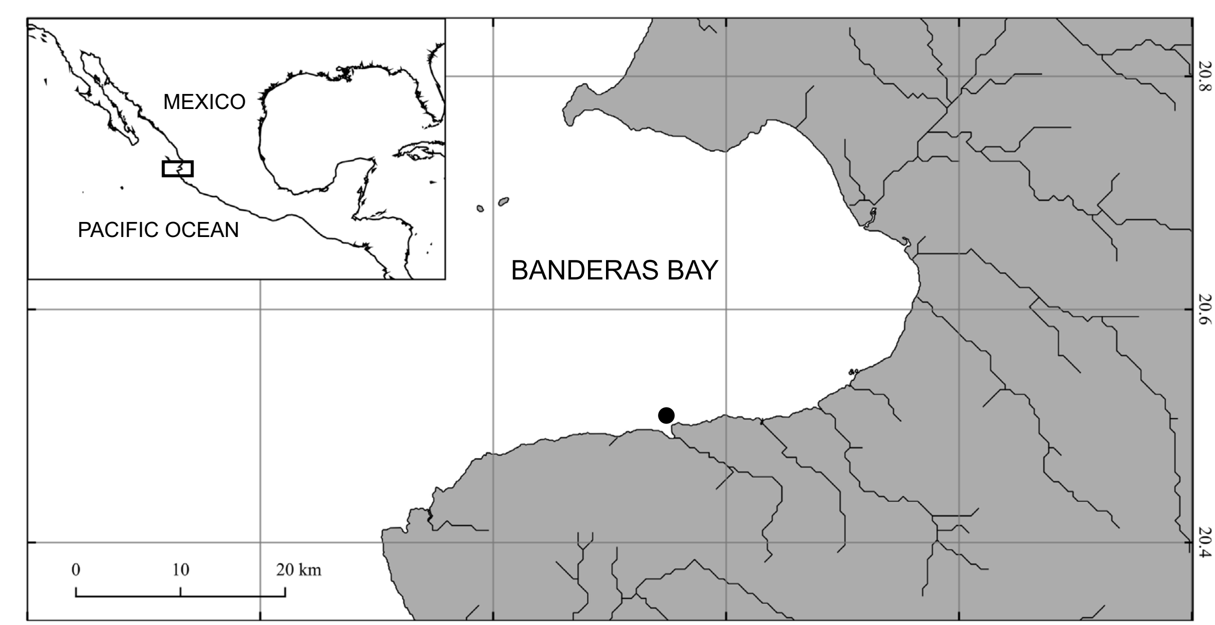


**Fig. 1.** The study area of Banderas Bay and the sampling site (black dot).

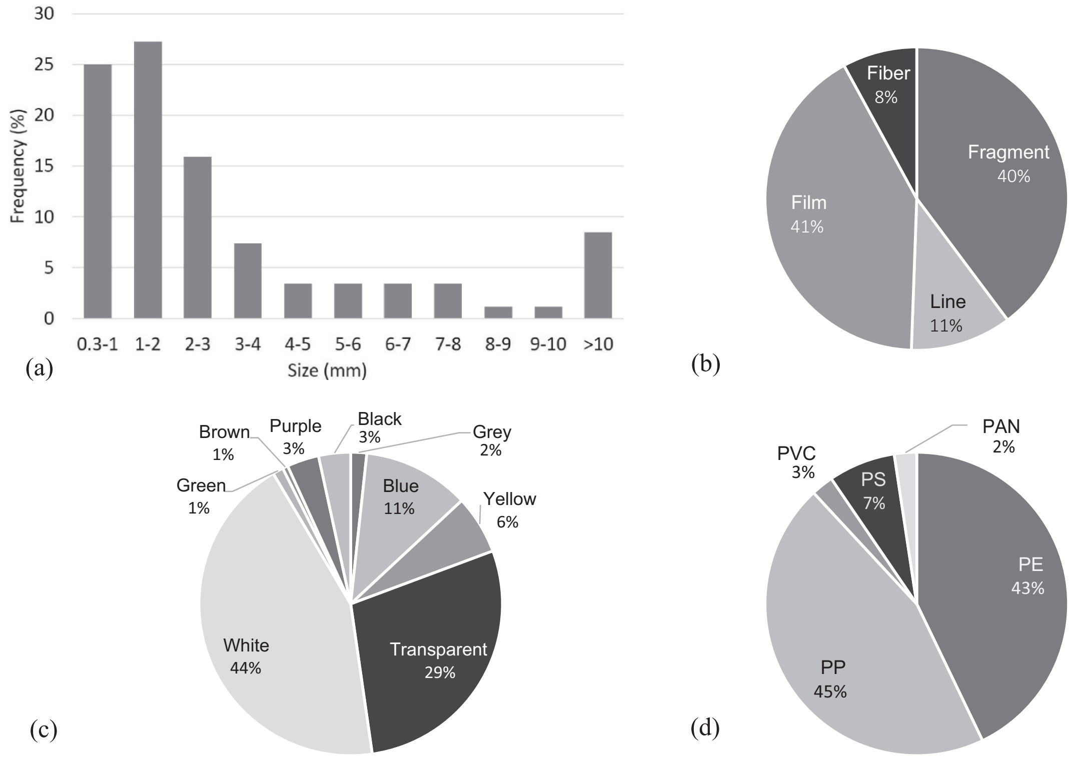


**Fig. 2.** Characterization of plastic debris found: size classes (a), type (b), colors (c) and polymers (d).

by dividing the number of particles found in each sample, by the volume of water filtered. We determined also the number of particles per 1000 square meters of sea surface (pp/1000 $m^2$) by dividing the number of particles found in each sample, by the area of sea surface sampled. Samples were separated into two seasons: Dry (November–May) and Hurricane season (June–October).

### 2.4. Precipitation data

Precipitation data measured in a weather station near Puerto Vallarta (29°, 39′40″N, 105°, 14′37″W) were used as a proxy of fresh water input into the Banderas Bay. Data was obtained from the automated weather stations of Mexico's National Weather Service (*Servicio Meteorológico Nacional*) at https://smn.cna.gob.mx/es/estaciones-meteorologicas-automaticas. The database included daily measurements of precipitation (mm), evaporation (mm), minimum and maximum ambient temperature (°C) from January 2007 to December 2017.

### 2.5. Statistical analysis

Tests for potential differences between seasons (dry vs hurricane season) of plastic abundance (pp/$m^3$) were performed. First, the hypothesis that the plastic abundance vector was normally distributed was tested using a Kolmogorov-Smirnov test. This hypothesis was rejected at the 95% confidence level ($D = 0.29$; $p < 0.05$). Then, a Fligner-Killeen test of homogeneity of variances was applied. We decided to use this test over the more common tests (such as Levene's or Bartlett's test), because the Fligner-Killeen test is more suitable for non-normally distributed data (Crawley, 2012). Again, the null hypothesis that the variance of plastic abundance in Banderas Bay was equal during dry and hurricane seasons ($FK_{(1,93)} = 18.64$; $p < 0.05$) was rejected. Since both the normality and homogeneity of variance assumptions were violated, non-parametric tests were applied.

Monthly means of precipitation and plastic abundance (pp/$m^3$) were used to test for temporal correlation of the fresh water input proxy and plastic particle abundance in Banderas Bay. A cross-correlation function was used to calculate the linear correlation coefficient of the two time series at different time lags. All statistical analysis were carried using base functions (ks.test, fligner.test, kruskal.test, ccf) of the R environment (R core team, version 3.3.1, 2016) and Microsoft Office Excel 2016.

## 3. Results

A total of 94 surface samples were collected in the two years of sampling effort. During March 2017, for logistical reasons no samples were collected. Plastic debris were found in 54 samples, 57% of all tows. We recorded a total of 193 pieces of plastic debris, ranging from 0.5 to 100 mm of length. Most of the plastic pieces (79%) were microplastics (< 5 mm in length). It was found that the most represented size class was the 1-2 mm (27% of the pieces) (Fig. 2a). The most common type of debris found was film (41%) followed by fragments (40%). No resin pellets or microbeads were detected in any tow (Fig. 2b). All the plastic pieces found had shapes far from being spherical, suggesting they resulted from the breakdown of larger items. Most plastics were white (44%), transparent (29%) and blue (11%) while other colors accounted for 16% of plastic pieces (Fig. 2c). The μFTIR-ATR revealed that Polypropylene (PP) and Polyethylene (PE) were the most abundant polymers, accounting for 45% and 43% of the pieces, respectively (Fig. 2d). The highest abundance of pp was found in July 2016, with a maximum of 0.295 pp/$m^3$ (equivalent to 69 pp/1000 $m^2$) found in one sample (Fig. 3). We found a significantly higher abundance of floating plastics during the hurricane season ($H_{(1,93)} = 14.15$;test, $p < 0.05$). The abundance of plastics (mean pp/$m^3$ ± SD) was 0.013 ± 0.028 in the dry season and 0.044 ± 0.064 in the hurricane season (Supplementary Data). Results of the cross-correlation analysis showed that the correlation between precipitation and plastic abundance time series was higher (~0.50) and statistically significant with +1 month lag, suggesting that higher plastic particle densities in Banderas Bay occur one month after the first peak of precipitation (Fig. 4).

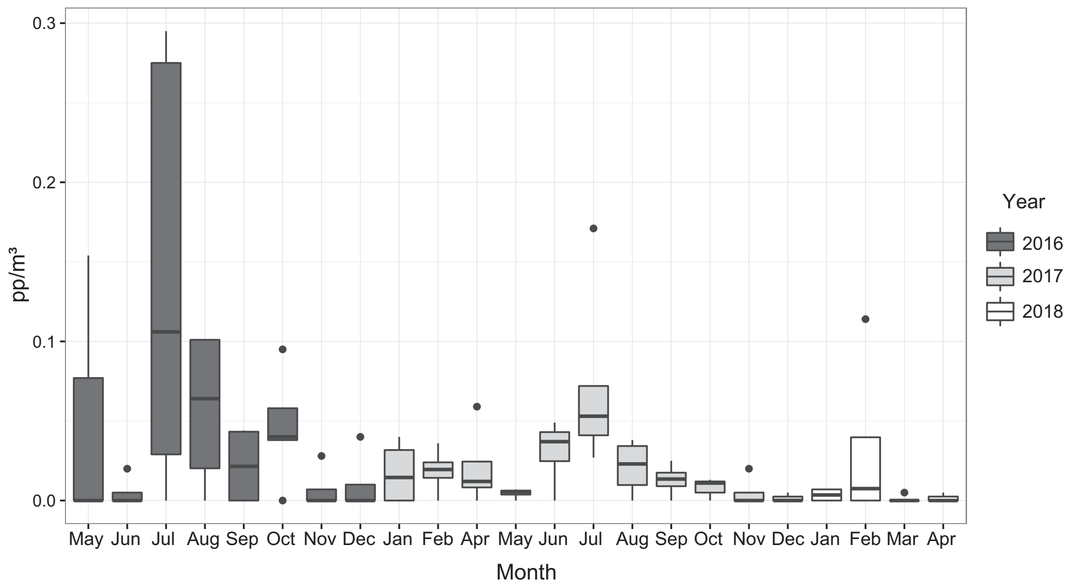


**Fig. 3.** Number of plastic pieces found for every cubic meter in the two years of sampling effort.

## 4. Discussion

The frequency of plastic debris found in our study area (57%) was relatively low compared to other studies in more polluted areas. In the Mediterranean Sea, plastic occurs in 90–100% of the samples (Collignon et al., 2012; Suaria et al., 2016), 96% in the South Pacific Gyre ( Eriksen et al., 2013) and up to 84% in the north-eastern Pacific Ocean (Doyle et al., 2011) (Table 1).

The mean abundance of plastic debris in the present study (0.01–0.04 pp/m$^3$ in dry and hurricane seasons, respectively) is low when compared to other floating debris studies (Table 1). This might be due to the relatively low human pressure in the area, compared to the other studies that were conducted in densely populated coastal areas (Mediterranean Sea, Southern California, Korea Sea etc.). Apart of the city of Puerto Vallarta (> 300,000 inhabitants plus 5 million tourists visiting every year), the southern part of Banderas Bay has only small rural villages (being part of Cabo Corrientes municipality with a total of 10,000 habitants) (INEGI, 2015a, 2015b).

The distribution of floating plastics in open ocean environments is very heterogeneous and is driven by different forces (wind, currents, tidal flow, source of plastic pollution etc.) (Barnes et al., 2009; Doyle et al., 2011). The waters adjacent to land have been shown to be a zone with elevated plastic abundance, high diversity of polymers and higher proportion of fragments smaller than 2.5 mm (Pedrotti et al., 2016). In the present study, the most frequent size class of plastic debris was 1–2 mm, followed by 0.3–1 mm, in accordance to what was found by Pedrotti et al., 2016 in the samples collected near shore in the Mediterranean Sea.

In the present study, 79% of the total plastics found were smaller than 5 mm in length meaning that the plastics in the bay have a much bigger surface area:volume ratio compared to big plastic objects (Ryan, 2015). It means that they can potentially adsorb a much higher quantity of POPs on their surface (Teuten et al., 2009), becoming potentially toxic for the many species of wildlife present in the area.

Even though there are > 5000 different synthetic polymers used in the plastic industry, 80% of the total plastic objects are made of polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and polystyrene (PS) (Lambert and Wagner, 2018). PE and PP are light polymers that are widely used for packaging, typically single-use disposable products that rapidly get from the user to the waste and litter stream. PE and PP accounted for 88% of the pp found in the present study, and the most abundant polymers found in other studies of floating debris (Pedrotti et al., 2016; Reisser et al., 2013; Rios et al., 2010). Due to their prevalence in the

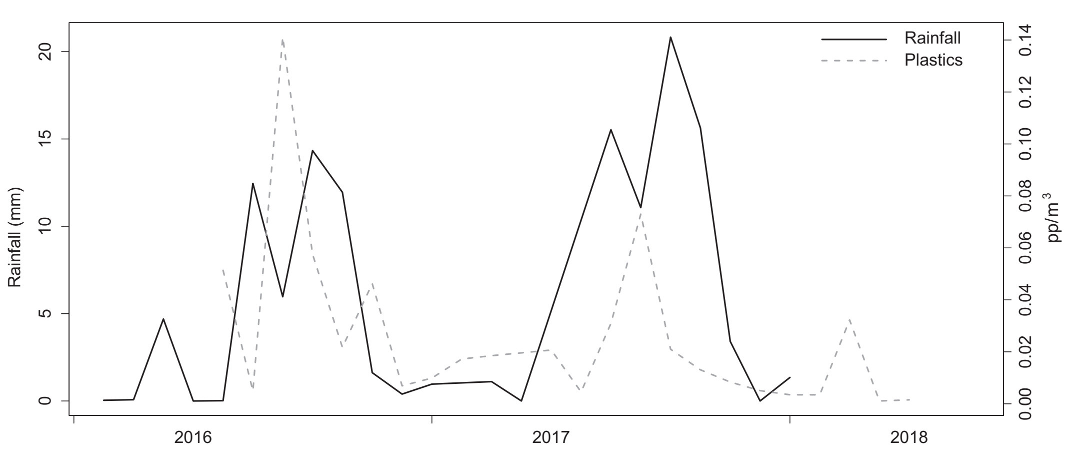


**Fig. 4.** Seasonality of daily rainfalls (mm) and plastic abundance (pp/m$^3$).

**Table 1**
Comparison of the occurrence and abundance of floating debris between this study and other areas around the world.

| Location | Collection device/mesh size (μm) | Habitat sampled | % samples with pp | Mean (pp/m$^3$) | Seasonality | References |
|---|---|---|---|---|---|---|
| Southern New England | Plankton net/333 | Coastal waters | NR | 0.01–2.58 | ND | (Carpenter et al., 1972) |
| Southern California | Manta trawl/333 | Coastal waters | 100[a] | 7.25 | Yes | (Moore et al., 2002) |
| Santa Monica Bay | Manta trawl/333 | Coastal waters | 100[a] | 3.92 | Yes | (Lattin et al., 2004) |
| Northeast Pacific Ocean | Manta trawl/505 | Coastal, offshore waters | 8–84 | 0.004–0.19 | ND | (Doyle et al., 2011) |
| Southeast Bering Sea | Manta trawl/505 | Coastal, offshore waters | 25–40 | 0.017–0.072 | ND | (Doyle et al., 2011) |
| North Western Mediterranean | Manta trawl/333 | Coastal waters | 90 | 0.116 | ND | (Collignon et al., 2012) |
| Portuguese coastal waters | Neuston net/280 | Coastal waters | 61 | 0.002–0.036 | ND | (Frias et al., 2014) |
| Goyana Estuary, Brazil | Neuston net/300 | Estuarine waters | NR | 0.26[a] | Yes | (Lima et al., 2014) |
| Southeastern Coast of Korea | Manta trawl/330 | Coastal waters | 100[a] | 1.92–5.51 | Yes | (Kang et al., 2015) |
| Mediterranean Sea | Neuston net/200 | Coastal, offshore waters | 100 | 1.25 | ND | (Suaria et al., 2016) |
| Southern Banderas Bay | Plankton net/333 | Coastal waters | 57 | 0.013–0.044 | Yes | Present study |

NR = not reported, ND = not determined.
[a] Inferred by the authors.

environment, PP and PE are also among the most abundant polymers found in the gastrointestinal tract of Mediterranean megafauna and sole (Claro et al., 2019; Pellini et al., 2018).

Studies have observed that plastic abundance on the beach is much higher after the rainy season, most likely due to the surface runoff that brings plastic debris from inland via rivers and eventually settling on the beaches close to estuaries (Brennan et al., 2018; Cheung et al., 2016; Wessel et al., 2019). Seasonality in floating plastic abundance has been poorly studied. In Table 1, a comparison between the present study and other coastal floating plastics studies is summarized. Moore et al., 2002 found a greater plastic/plankton ratio in Southern California in the samples collected on the day after a storm and attributed this to land-based runoff.

The authors suggest that the first raining events of the season, might be the source of the highest input of plastics from land-based sources, since during the dry season the debris accumulate and enhance the amount of runoff following the rain events during the dry season. This might explain the extraordinarily high amount of floating debris that was found in July 2016 in Banderas Bay. The hurricane season in 2016 started with tropical storm Agatha at the beginning of July and counted a total of 8 hurricanes/storms in the Mexican Pacific Ocean during the month. The high abundance of plastics found in July, might be due to the high number of hurricanes and tropical storms that formed in the Mexican Pacific Ocean in that period (CONAGUA, 2016).

Previous studies have reported that the distance from the coast is a proxy of the time at sea of plastic objects (Ryan, 2015). Since the samples of the present study have been collected nearshore (≃100 m from the coast), we can hypothesize a recent input of the plastics found. This is supported also by the low incidence of yellowish plastics (6% of the plastics found), that is considered as an indicator of the oxidation level and time spent in seawater by the plastic (Endo et al., 2005; Ogata et al., 2009). For this reason, we posit that the high abundance of plastic debris in the summer originates from rainfalls caused by hurricanes that hit the area and induce the runoff of plastic pollution from adjacent land into the ocean (Lima et al., 2014). Moore et al., 2002 observed that neustonic coastal samples show a higher abundance of small fragments compared to neuston from the North Pacific central gyre, where most of the plastic mass was composed by large objects. These small fragments near the coast are attributable to land-based runoff, while the large objects in the open ocean are associated mainly with the fishing and shipping industries.

Since the prevailing currents inside Banderas Bay should spread the debris offloaded by the Ameca River mainly into the central-northern part of the bay (Pantoja, 2017), it is likely that our results are showing only a small percentage of the actual load of debris present in the Bay. The plastics found in the present study may have origin from the smaller communities surrounding the numerous rivers that flow into the bay from the mountainous southern coast (rivers Pitillal, Cuale, Nogalito, Mismaloya, Tomatlán, Quimixto, Tuito, Yelapa) (Cotler Ávalos, 2010).

## 5. Conclusions and outlook

This work investigated the abundance, characteristics and seasonality of floating plastic in the southern part of Banderas Bay, Mexico. Two years of intense sampling effort showed a marked seasonality in plastic debris abundance. A higher amount of plastic debris was found following the beginning of the hurricane season, suggesting a recent terrestrial input caused by the rains that drain the debris accumulated in the creeks and rivers (Cheung et al., 2016; Lima et al., 2014). The small sizes of the pp that was found in the present study suggest that the debris is easily bioavailable for entering the food chain at a low level, impacting the ecosystem from the base up (Browne et al., 2007).

The present results are a baseline for the monitoring of plastic pollution in Banderas Bay. Further information is needed for better understanding the spatial distribution of the plastic debris throughout the bay. In particular, the vertical distribution of plastic debris plays a primary role in the potential impact it can have in the ecosystem, nevertheless it is still largely unknown. For example, mobulid rays presumably aggregate within Banderas Bay to feed, but may be accessing non-surface zooplankton, which may have lower plastic/plankton ratios (Stewart et al., 2017, 2016b).

Banderas Bay is a highly productive, high biodiversity area that hosts many endangered species that could potentially be affected by plastic debris pollution. Marine mammals and other megafauna species that frequent the bay are protected under Mexican law (NOM-059-SEMARNAT-2010, NOM-029-PESC-2006) and listed as vulnerable to extinction (www.iucnredlist.org). Understanding the threats that they are facing in their habitat distribution is important for supporting science-based management and conservation of these species.

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### CRediT authorship contribution statement

**Tania Pelamatti:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Iliana A. Fonseca-Ponce:** Methodology, Data curation, Writing - review & editing. **Lorena M. Rios-Mendoza:** Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing - review & editing. **Joshua D. Stewart:** Funding acquisition, Writing - review & editing. **Joshua D. Stewart:** Funding acquisition, Writing - review & editing. **Emigdio Marín-Enríquez:** Data curation, Formal analysis, Software, Visualization, Writing - original draft. **Ana J. Marmolejo-Rodriguez:** Conceptualization, Writing - review & editing. **Edgar M. Hoyos-Padilla:** Writing - review & editing. **Felipe Galván-Magaña:** Conceptualization, Funding acquisition, Writing - Review & editing.

**Rogelio González-Armas:** Conceptualization, Writing - review & editing.

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