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Macrodebris and microplastics from beaches in Slovenia

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ABSTRACT

The amount of marine debris in the environment is increasing worldwide, which results in an array of negative effects to biota. This study provides the first account of macrodebris on the beach and microplastics in the sediment (shoreline and infralittoral) in relation to tourism activities in Slovenia. The study assessed the quality and quantity of macrodebris and the quality, size and quantity of microplastics at six beaches, contrasting those under the influences of tourism and those that were not. Beach cleanliness was estimated using the Clean Coast Index. Tourism did not seem to have an effect on macrodebris or microplastic quantity at beaches. Over 64% of macrodebris was plastic, and microplastics were ubiquitous, which calls for classification of plastics as hazardous materials. Standard measures for marine debris assessment are needed, especially in the form of an all-encompassing debris index. Recommendations for future assessments are provided for the Adriatic region.

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1. Introduction

Global population is expected to reach 9.5 billion people by 2050, with the highest growth registered in developing nations (UN/DESA, 2014). It is likely that there will also be an increase in the demand for disposable consumables – the annual plastic production in 2011, for example, was 280 million tons, more than 186 times the amount produced in the 1950s (Depledge et al., 2013). An estimated ten percent of this accumulates as persistent plastic debris in the ocean (Barnes, 2002; Derraik, 2002; Thompson et al., 2009b), converging to mid-ocean sub-tropical gyres (Kaiser, 2010; Kershaw et al., 2011). In 2010, the North Pacific gyre contained more than double the amount of marine debris (750.000 pieces km^{-2}) detected nine years earlier (330.000 pieces km^{-2}) (Moore et al., 2001; Boerger et al., 2010). Microplastic (plastic particles < 5 mm) convergence zones have also been observed in the South Pacific and in the North Atlantic (Law et al., 2010; Eriksen et al., 2013). In the North Pacific and in the South Atlantic, larger plastic debris accumulate to form giant 'garbage patches' (Pichel et al., 2007; Ryan, 2013), reinforcing the idea that marine debris is a global issue that needs to be addressed urgently (Barnes et al., 2009; Kershaw et al., 2011; Depledge et al., 2013).

Ocean currents spread large amounts of debris from industrialized and densely populated areas to even the most remote and unpopulated coastal regions (McDermid and McMullen, 2004; Barnes et al., 2009; Santos et al., 2009; Hirai et al., 2011). Yet, only a few of the main sources and sinks of marine debris have been identified worldwide (Ryan et al., 2009; Browne et al., 2011). In an effort to counter this issue, current studies aim to assess the global (coastal and offshore) distribution of the two main categories: macrodebris (size > 5 cm) and microplastics (Thompson et al., 2004; UNEP, 2005; Claessens et al., 2011; Collignon et al., 2012; Van Cauwenberghe et al., 2013). In Europe, this knowledge will help countries to conform to the Marine Strategy Framework Directive and achieve 'good environmental status' by 2020 (Galgani et al., 2010).

Marine debris is defined as any persistent, man-made solid waste discarded into the marine environment (Galgani et al., 2010; CBD, 2012). Most of it is made of plastic (Barnes et al., 2009) that originates from both land- and ocean-based sources, and which interacts with at least 663 species worldwide (CBD, 2012). Plastics foster a myriad of negative effects on marine organisms, such as entanglement, intestinal blockage, suffocating,

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smothering, and ghost fishing (Gregory, 2009). These further cause negative physiological effects, lower fitness, reproductive failure, changes in community structure, and death (Spear et al., 1995; Barnes, 2002; Derraik, 2002). Approximately 370 species have been found entangled in or having ingested marine debris worldwide (CBD, 2012; Galgani et al., 2013). For example, all seven species of marine turtles, at least 14 cetacean species, 20 pinniped species, and 56 marine or coastal bird species have been found entangled in plastics worldwide (Katsanevakis, 2008). Additionally, marine birds are known to ingest considerable amounts of plastic and accumulate plastic-derived chemicals in their tissues (Tanaka et al., 2013; Acampora et al., 2014).

Microplastics were first detected in the North Atlantic four decades ago (Carpenter and Smith, 1972). They are minute fragments of plastic debris, which are divided into small (<1 mm in diameter) and large (1–5 mm in diameter) particles (Gregory and Andrady, 2003; Betts, 2008; Moore, 2008; Fendall and Sewell, 2009; Imhof et al., 2012). Microplastics consist of nylon, polyester, acrylic, polypropylene, polyethylene, poly(ethylene–propylene), polyvinyl chloride, polyvinyl alcohol, polystyrene, polyester, polyurethane, polyacrylonitrile, alkyd, alkyd resin, and polyamide fibers, though their main component is usually synthetic polymer(s) (Barnes et al., 2009; Leslie et al., 2011; Vianello et al., 2013). Degradation processes of plastics are extremely slow, such that particles persist for very long periods of time in the marine environment (Hidalgo-Ruz et al., 2012) and become readily available to biota. Microplastic ingestion has been observed in a wide range of marine taxa, including crustaceans, molluscs, fish, birds, and mammals (Thompson et al., 2009a; Fossi et al., 2012; Lusher et al., 2013; Wright et al., 2013; Watts et al., 2014), and can result in a wide range of negative effects, such as blockage of the intestinal tract and abrasion in small organisms (similarly to the effects of macroplastics in large biota) (Wright et al., 2013). Microplastic ingestion could also disrupt the endocrine and reproductive systems, diminish energy rates, and increase toxic load in smaller organisms (Galgani et al., 2010). Moreover, these particles are incorporated into marine food webs (Farrell and Nelson, 2013; Setälä et al., 2014) and provide a substrate for leached contaminants, which could also bioaccumulate (Teuten et al., 2009).

Tangible damages to humans caused by marine debris are difficult to estimate. The tourism industry, for example, faces monetary loss due to both a decrease in activity on polluted beaches and the costs of beach cleaning (Sheavly and Register, 2007; Jang et al., 2014). Beachgoer safety issues arise from broken glass, medical waste, fishing lines, discarded syringes, and possibly from bacterial contamination of discarded hygiene waste (Sheavly and Register, 2007). On the other hand, fishermen face propeller entanglement, damage to fishing gear, and time losses due to gear cleaning as a result of macroplastic pollution (Nash, 1992; van Franeker et al., 2005). It is still uncertain, though, whether marine debris can reduce fish quality through debris ingestion or tainting (van Franeker et al., 2005). Moreover, indirect economic impacts result from the degradation of the marine environment. An increase in tourism may enhance debris accumulation in the Adriatic Sea, which already faces a dense concentration of debris in the seafloor (Galgani et al., 2000). In the case of Slovenia, the amounts and types of debris found along the 46.7 km appear to be different (Palatinus, pers. comm.), suggesting that human populations may have distinct impacts in each beach location.

The present study assessed (1) the quality and quantity of macrodebris, and (2) the quality, size and quantity of microplastics on beaches in Slovenia, contrasting those which were under the influences of tourism (touristic, T) and those that were not (non-touristic, NT). Finally, it assessed the cleanliness of Slovenian beaches using the Clean Coast Index (Alkalay et al., 2007). The results provide the first assessment of macrodebris at the beach and microplastics in the sediment in relation to tourism activities along the coast of Slovenia.

2. Methods

2.1. Study area

Slovenian tourism has increased by 160% in the last fifteen years, and the country welcomed approximately three million tourists in 2011 (Maja Pak, Director of Slovenian Tourist Board, pers. comm.). The present study took place during the peak of the tourist season, in July 2012. Point samples were collected at six beaches along the Slovenian coast (Fig. 1A), Debeli Rtič (T1), Jadranska (NT1), Simonov Zaliv (T2*), Bele Skale (NT2), Portorož (T3*), and Seča (NT3). Sampling sites were chosen based on the level of urbanisation and human presence, such that areas of high urbanisation and flux were considered as touristic (T1, T2*, and T3*) and those with limited (or absence of) urbanisation and visit as non-touristic (NT1, NT2, and NT3).

The Slovenian coast is part of the Gulf of Trieste, which is a shallow (20 m depth), semi-enclosed basin with horizontal bathymetry on its southern part (Malačič et al., 2012). Four rivers contribute to fresh water input to the Gulf, two in Italy (Isonzo and Timavo), one in the proximity of Koper (Rižana), and the other further south, in Seča (Dragonja), shown in Fig. 1B.

2.2. Macrodebris

2.2.1. Sampling

Beaches are cleaned on a monthly basis in Slovenia, though two of the three touristic ones, Portorož (T2*) and Simonov Zaliv (T3*), were cleaned daily (represented by the symbol "*") throughout the summer at 6 a.m. In order to account for this and to estimate the macroplastics accumulated in the last 24 h, sampling was performed before the beach cleanup (5 a.m.). One 50-m transect was placed randomly along the beach, parallel to the shoreline. All debris ⩾2 cm was collected in the area ranging from the shoreline to the upper beach limit (determined by the presence of vegetation, dunes, or rocks) within the 50-m transect, as shown in Fig. 2. Sampling was performed according to the operational guidelines for rapid beach debris assessment described by Cheshire et al. (2009).

2.2.2. Analysis

Particles were classified in relation to 59 categories and 8 major groups (according to a combination of the approaches used by Cheshire et al., 2009 and Palatinus, pers. comm.), counted, and weighed (only major groups). Cigarette filters were analysed separately from other plastic items due to the high relevance of this category to infer the land-based origin of the debris (Oigman-Pszczol and Creed, 2007). Macrodebris quantity (count and weight) was extrapolated for six of the debris categories (Table 1) for the two beaches with daily cleaning (Portorož – T2* and Simonov Zaliv – T3*), in order to compare with that of beaches cleaned monthly. The extrapolation was possible because the date of last monthly cleaning event of all beaches was known (June 26th, 2012) and because the Slovenian local authorities recorded the quality and estimated quantity (count and weight) of macrodebris collected daily at Portorož (T2*) and Simonov Zaliv (T3*) during weekdays and weekends in July 2012. Extrapolation values were obtained with the equation:

$$\begin{aligned}&\text{Extrapolated macrodebris quantity}\\&\quad= \text{sampled quantity} + (\text{estimated quantity per weekday} * \text{Tw})\\&\qquad+ (\text{estimated quantity per weekend day} * \text{Tw-e})\end{aligned}$$

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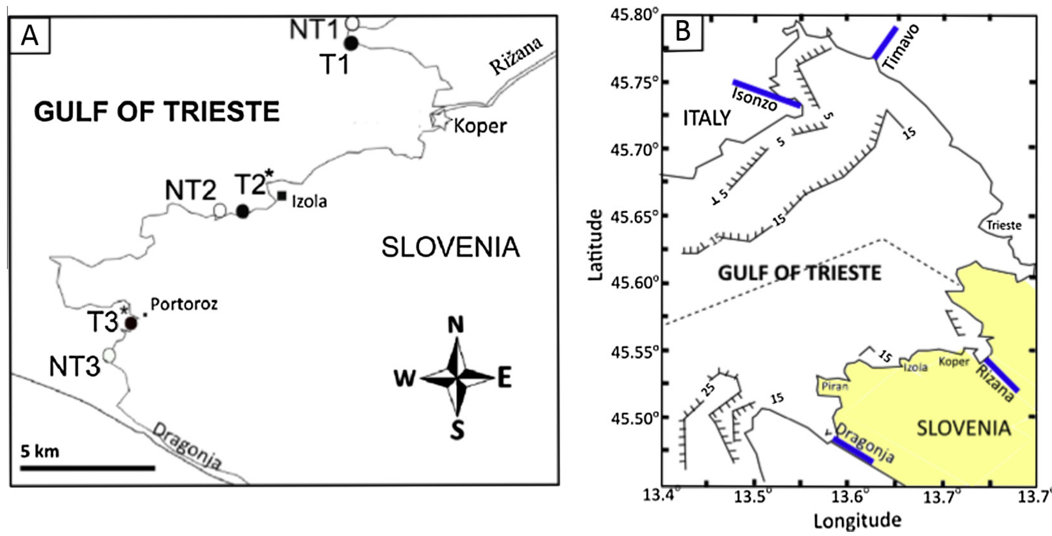

Fig. 1. (A) Location of sampling sites with indication of the major cities (Koper, Izola and Portorož) and rivers (Rižana and Dragonja) along the Slovenian coast. Black and white dots represent touristic and non-touristic beaches, respectively. T1: Debeli Rtič; NT1: Jadranska; T2*: Simonov Zaliv; NT2: Bele Skale; T3*: Portorož; NT3: Seča. B: Main freshwater input (rivers Isonzo, Timavo, Rižana and Dragonja) in the Gulf of Trieste is represented in blue. Adapted from Turk et al. (2010).

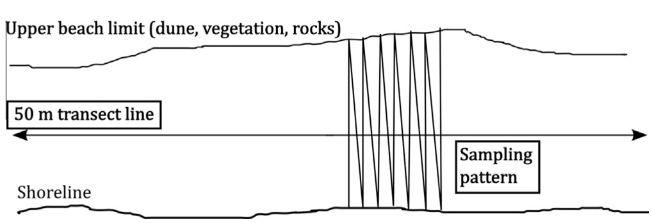

Fig. 2. Macrodebris sampling scheme, which comprised the area between the shoreline and upper beach limit along the 50-m transect.

where the sampled quantity is the macrodebris count recorded in the present study; estimated quantity per week and weekend day is that recorded by Slovenian authorities; Tw is the number of weekdays from the last cleaning event (26th June) to the day before sampling (12th July 2012, for Portorož – T2* and Simonov Zaliv – T3*); and Tw-e is the number of weekend days in that period.

Beach cleanliness was assessed with the Clean Coast Index (CCI) (Alkalay et al., 2007). The CCI was obtained by applying the equation.

$$\mathrm{CCI} = (\text{Total plastic parts on transect}/\text{Total area of transect}) * k$$

where the CCI is the number of plastic items m^{-2}, the total area of transect is the product of the transect length and width, and k (constant) = 20. Beaches were classified from clean to extremely dirty according to the scale provided for the number of plastic particles on the coast (Table 2).

2.3. Microplastics

2.3.1. Sampling

Sediment samples were obtained from the centre of the 50-m transect line used for macroplastic sampling (i.e., $\sim$ at the 25-m mark) by randomly placing three 25-cm^2 quadrats within (each) the shoreline (SHORE – between the high and low tide marks) and infralittoral (INFRA – a 10 m distance perpendicular to the shoreline) zones (Fig. 3). SHORE samples were extracted from the first 5 cm of sediment below each quadrat using a metal spatula (Thompson et al., 2004); while INFRA samples were extracted using a 500 mL corer used in a horizontal, circular motion, in order to prevent re-suspension of particles. All samples were placed in plastic bags and stored at ambient temperature for further analysis.

2.3.2. Analysis

The protocol for microplastic extraction from sediments provided by Thompson et al. (2004) was adapted in order to account for varying types of sediments at the sampling locations, and combined decantation (in a 1.2 kg L^{-1} NaCl solution) and inverse filtration (through a 250-µm sieve to separate particles by density and by size). Samples were pooled (3 per each beach for SHORE and INFRA) onto aluminium foil and dried for 24 h at 60°, after which 150 g were placed in a 500 mL high saline concentration solution (360 g NaCl L^{-1}) before undergoing a two-step decantation. The solution was manually shaken twice for two minutes before leaving it to rest for 30 min. The two subsequent supernatants were poured into a glass beaker and washed through a 250-µm sieve. Particles were recovered on a glass Petri dish using a 100 mL wash bottle. In order to isolate microplastics, six subsamples of 2.5 mL each were examined under a light microscope. The microplastic particles were isolated on another Petri dish and further examined under an Olympus SZX16 imaging microscope (DP-Soft software). Pictures of the particles were taken for further measurement using ImageJ software (ver. 2.0.0), and classified into four types (Claessens et al. 2011), according to their shape (fibres, granules, plastic films, plastic fragments).

2.4. Statistical analyses

Statistical analyses of macrodebris and microplastics data were performed using multidimensional scaling (MDS) in Primer v6 (Clarke and Gorley, 2006). Data were log-transformed ($\log X + 1$) before a Bray–Curtis similarity matrix was computed. Macrodebris quality and quantity (by count and by weight) was compared between beaches (T, NT) within 59 categories across eight major groups. Microplastic quantity was also compared between beaches (T, NT) and littoral zones (SHORE, INFRA) across four categories.

3. Results

3.1. Macroplastics

3.1.1. Quality

A total of 5870 macrodebris items were classified into 59 categories and eight major groups (Table 2). The majority (64%) was

Table 1
Macrodebris classification system for Slovenia. Amount of macrodebris per each of the 59 categories and eight major groups on a 50 m-transect at six beaches. Empty spaces represent zero items.

	Debeli Rtič (T1)	Simonov Zaliv (T2*)	Portorož (T3*)	Jadran-ska (NT1)	Bele Skale (NT2)	Seča (NT3)
Plastics						
Caps and lids	12	63[a] (13[b])	68[a] (18[b])	2	14	4
Lolly sticks, cutlery, cups	12	323[a] (23[b])	329[a] (29[b])	2	16	1
Drink bottles < 1 l	1	50[a] (0[b])	14[a] (4[b])			
Drink bottles > 1 l	2	50[a] (0[b])	94[a] (4[b])	1		
Straws	1		8	2	5	
Packaging for food	21	27	21	6	34	10
Bags	26	2	1	3	6	2
Toys & party poppers	3	15	5			
Cigarette lighter					3	
Cigarette filter	162	1012	347	144	8	15
Syringes					1	
Mussel bags + pieces	1	2		8	2	1
Monofilament line		2		6	2	
Cotton bud sticks	27	15		2	13	
Shipping lines					15	
Fishing ropes, string, cord	3	5	2	5	14	1
Cosmetics packaging		1			1	
Fishing net floats	1					
Foam (pieces)	3	13	1	6	19	3
Styrofoam pieces	19		6	10	118	6
Plastic pieces (unrecognizable)	28	94	64	13	69	25
Jerry cans					67	
Masking tape	2	2			2	
Condoms + packaging				1		
Packaging for tissues	1					
Tampons + applicators				1		
Panty liners + packaging	1		1	1	4	2
Construction waste	2					
Cigarette box	7	21	10	10	11	
Buckets, flower pots					5	
Pens		1			1	
Biomass holder	1	1				
Other	1	24	2	3	3	2
Total	336	1724	973	226	433	72
Rubber						
Balloons, balls, toys	2	15	1	2	1	
Shoes	1					3
Gummies	1	16		3	2	1
Other pieces	5	5	1	1	2	1
Total	9	36	2	6	5	5
Cloth						
Clothing, shoes, hats, towels	3				4	2
Ropes	2		1	1	5	1
Other	3		6	6	11	
Total	8		7	7	20	3
Glass/ceramics						
Pieces	264	19	25	87	23	47
Bottles, glasses		20[a] (0[b])	52[a] (2[b])			
Plates, pots (cups)	50			1	1	1
Construction material	8		3			59
Total	322	39	80	88	24	107
Paper/cardboard						
Cardboard (pieces, boxes)	1	2	1			
Paper (incl. magazines)	1					
Other (pieces)	7	526[a] (26[b])	591[a](91[b])	7	2	2
Total	7	528	593	8	2	2
Metal						
Caps, can lids	1	26	7	6		1
Drink cans	2	11[a] (1[b])	13[a] (3[a])		2	1
Aluminium wrapping	3	20	3	7	2	1
Pieces	4	3	1	3		1
Wire, barbed wire						6
Construction	9				2	5
Other				2		1

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Table 1 (*continued*)

	Debeli Rtič (T1)	Simonov Zaliv (T2*)	Portorož (T3*)	Jadran-ska (NT1)	Bele Skale (NT2)	Seča (NT3)
Total	19	60	24	18	6	16
Wood (machined)						
Cork	2			1	1	
Ice lolly sticks	1	10	2	1		
Matches, fireworks			1			
Other		1	1			
Total	3	11	4	2	1	
Other						
Medical waste (container)	16	9	8	1		
Total	0	16	9	8	1	0

[a] Extrapolated data.
[b] Count.

Table 2
Clean Coast Index. Values, grades and visual assessment of the Clean Coast Index (Alkalay et al., 2007).

Value	Grade	Visual assessment
0–2	Very clean	No debris is seen
2–5	Clean	No debris is seen over a large area
5–10	Moderate	A few pieces of debris can be detected
10–20	Dirty	A lot of debris on the shore
20+	Extremely dirty	Most of the beach is covered with plastic

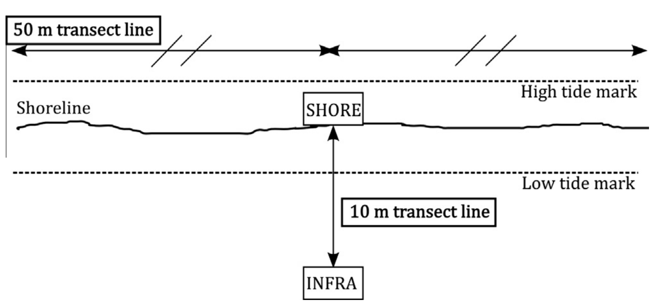

Fig. 3. Microplastics sampling scheme. Shoreline (SHORE) samples were collected between the high and low tide marks, at the centre of the 50-m transect line used for macroplastic sampling. Infralittoral (INFRA) samples were collected at a 10 m distance perpendicular to the shoreline.

made of plastic, a category generally dominant within beaches (Fig. 4). Paper was the second most abundant group at beaches (19%), followed by glass and ceramics (11%), metal (2%), and rubber (1%) (Fig. 4). Seča (NT3) and Debeli Rtič (T1) were dominated by glass and ceramics, which accounted for 52.2% and 45.7% of macrodebris, respectively (Fig. 4). Cigarette filters accounted for a median of 41.9% of the plastics at beaches. They dominated the plastic group in Jadranska (NT1) and Simonov Zaliv (T2*), representing 63.7% and 58.7% of total plastic items, respectively (Table 2). The largest number of cigarette filters, 1012 in one 50 m-transect, was recovered from Simonov Zaliv (T2*). Fishing gear density (mussel bags/pieces, monofilament line, shipping line, fishing rope/string, fishing net floats) was higher in Bele Skale (NT2-0.096 items m^{-2}) and Jadranska (NT1-0.069 items m^{-2}), while other beaches had much lower densities (<0.02 items m^{-2}).

3.1.2. Quantity

In Slovenia, median macrodebris count density was 1.25 items m^{-2}, ranging from 0.81 items m^{-2} in Seča (NT3) to 3.45 items m^{-2} in Simonov Zaliv (T2*). Macrodebris density by weight was 4.45 g m^{-2}, ranging from 2.84 g m^{-2} in Bele Skale (NT2) to 19.12 g m^{-2} in Seča (NT3). The high macrodebris density by weight in Seča (NT3) was due to the high proportion of glass and ceramics in this location (Figs. 4 and 5). The MDS revealed that macrodebris quantity (Fig. 5A) and weight (Fig. 5B) did not vary depending on the level of human use of beaches when considering the 59 categories across the eight major groups. Debeli Rtic (T1) and Jadranska (NT1) were more similar to each other than to other beaches in terms of macrodebris quantity and weight, as were Simonov Zaliv (T2*) and Portoroz (T3*) (Fig. 5).

3.1.3. Index

Beaches in close proximity had similar CCI classification. Simonov Zaliv (T2*) was the most polluted beach with a CCI grade of 49.29, followed by Bele Skale (NT2) with a CCI of 21.92. Both beaches ranked as 'extremely dirty' (Fig. 6). Three beaches ranked as 'dirty': Jadranska (NT1), Debeli Rtič (T1), and Portorož (T3∗), with a CCI of 15.61, 13.58, and 10.28 respectively (Fig. 6). Seča (NT3), with a CCI grade of 5.67, was the less polluted beach, and ranked as 'moderate'.

3.2. Microplastics

3.2.1. Quality

All samples but one (Seča-NT3, INFRA) contained microplastic fibres, which accounted for 96% of the total microplastic concentration in INFRA samples, and 75% in SHORE samples. Fragments were the second most dominant group (21%) in the shoreline, though none were found in the infralittoral (Fig. 7). INFRA and SHORE samples contained equal proportions of plastic films (4% each) and none contained granules (Fig. 7). Debeli Rtič (T1-SHORE) had the highest microplastic diversity and was the only beach that contained fibres, films and fragments (Fig. 8).

3.2.2. Size

The majority of microplastics (74%) was larger than 1 mm (Fig. 9). If observed on a distribution curve for all size fractions, however, microplastic size was skewed towards the left, with a non-negligible quantity being smaller than 1 mm (Fig. 9). The size-fractions with the highest frequency were 0.25–1.0 mm and 2.0–3.0 mm (Fig. 9). Median size varied among samples, from 0.8 mm in Simonov Zaliv (T2*, INFRA) to 3.3 mm in Portorož (T3*, SHORE).

3.2.3. Quantity

Median microplastic density was higher in the infralittoral (155.6 particles kg^{-1}) than in the shoreline (133.3 particles kg^{-1}) (Table 3). Microplastic concentration was not different between

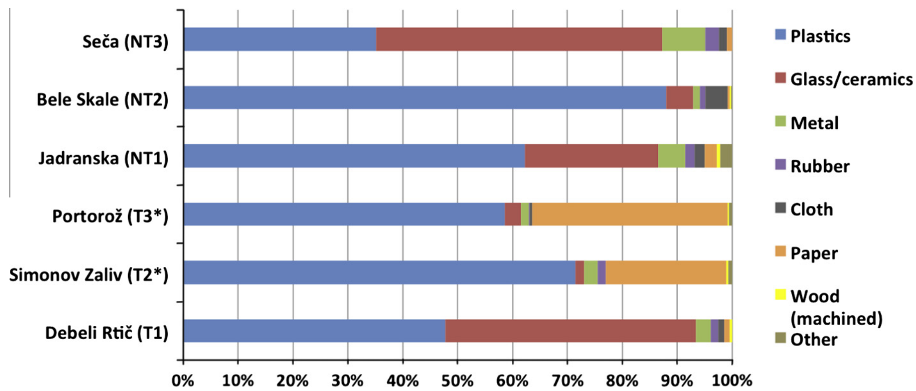

Fig. 4. Proportion (in% of number of items per m^2) of macrodebris of each of eight major groups at each beach.

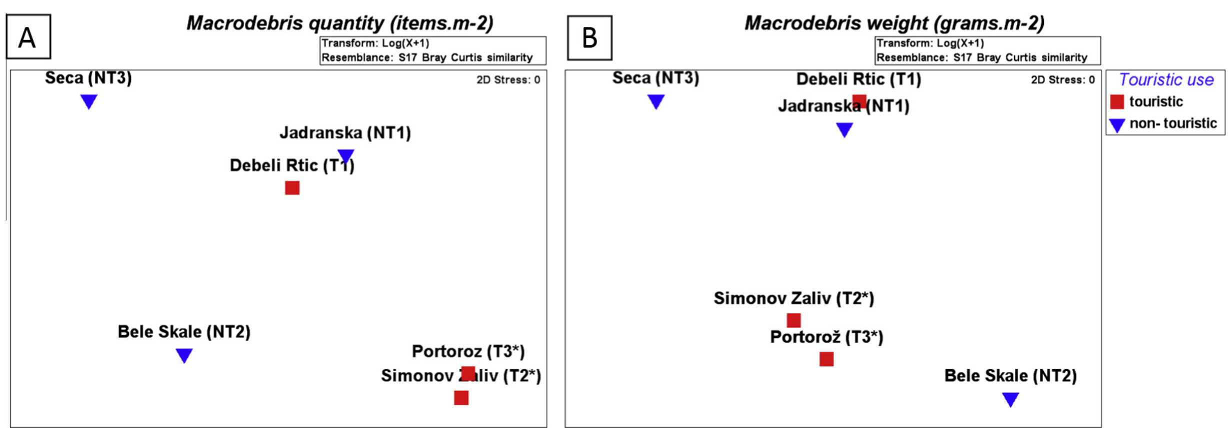

Fig. 5. (A) Multidimensional scaling (MDS) plot of Bray–Curtis similarities of macrodebris quantity (or units) (log-transformed, items per m^{-2}) within 59 categories across eight major groups, at six beaches. (B) MDS plot of Bray–Curtis similarities of macrodebris weight (log-transformed, grams m^{-2}) within eight major groups at six beaches. Red squares represent touristic beaches, and blue triangles represent non-touristic ones. 2-Dimensional stress is equal to 0. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

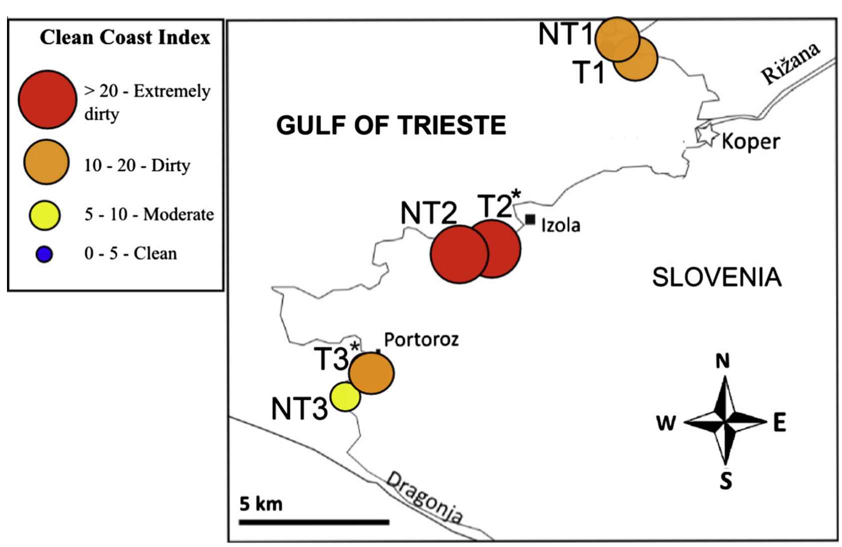

Fig. 6. Pollution status of six Slovenian beaches according to the Clean Coast Index. T1: Debeli Rtič; NT1: Jadranska; T2*: Simonov Zaliv; NT2: Bele Skale; T3*: Portorož; and NT3: Seča.

beaches of distinct level of human use (touristic, non-touristic) or between littoral zones (infralittoral, shoreline) when considering the three particle types found (Fig. 10A). Samples that only contained fibers were clustered together (Fig. 10B). The infralittoral of Seča (NT3) was very dissimilar to other samples because no fibers were found in this location, only plastic films (Fig. 10A). The shoreline of Debeli Rtič (T1) had the highest particle diversity and the highest quantity of microplastics (444.4 part kg^{-1}), and the

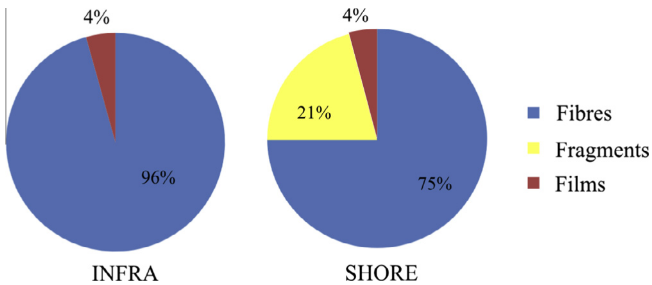

Fig. 7. Percentage distribution (%) of each microplastic type in infralittoral and shoreline sediment samples of Slovenian beaches.

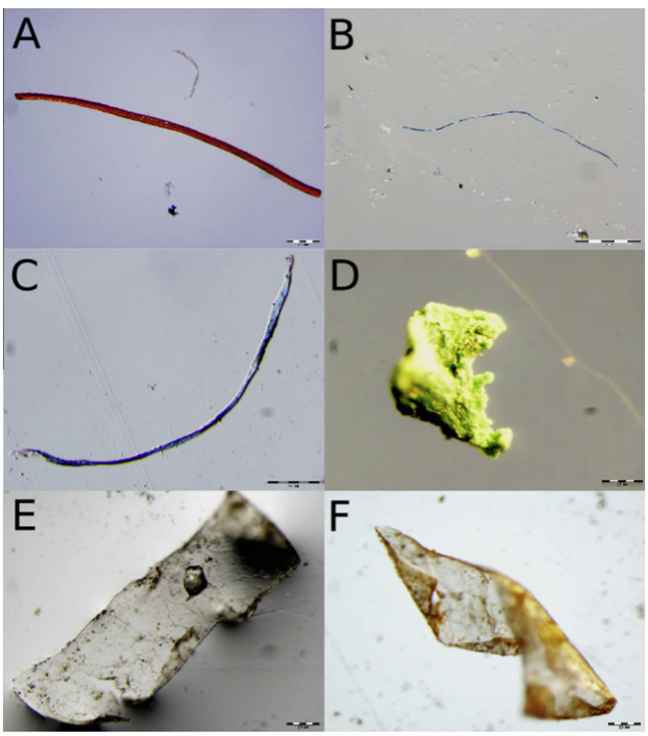

Fig. 8. Images obtained under a microscope of the three types of microplastics encountered along the coast of Slovenia, fibre (A–C), fragment (D), and film (E and F). (A) Red fibre from Jadranska (NT1) SHORE. (B) Blue fibre from Bele Skale (NT2) INFRA. (C) Blue fibre from Portorož (T3*) SHORE. D: Green plastic fragment from Debeli Rtič (T1) SHORE. E and F: Plastic film from Debeli Rtič (T1) INFRA. Scale bars = 0.2 mm (A, C–F) and 1 mm (B). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

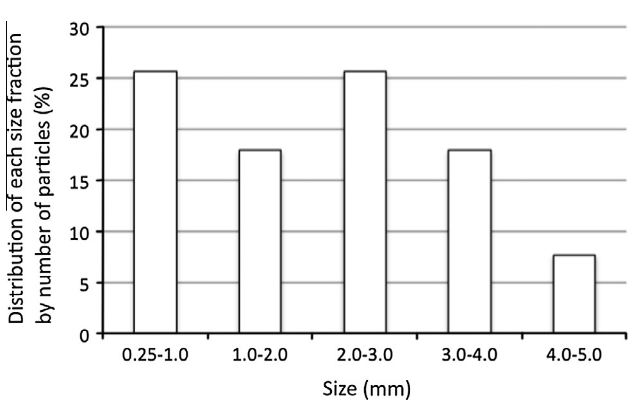

Fig. 9. Percentage distribution (%) of microplastics by size for all samples from both infralittoral and shoreline sediments in Slovenia.

shoreline of Jadranska (NT1) contained both fibers and plastic fragments, which makes them different to other samples (Fig. 10A).

4. Discussion

This is the first study to present an assessment of microplastic pollution in beaches along the Slovenian coast and to assess macrodebris in relation to tourism in the region. Marine macrodebris and microplastic are ubiquitous on beaches in Slovenia. Although studies rarely focus on both types of debris, biological processes ultimately link these size classes. Oxygen availability at beaches facilitates gradual photo-degradation of large plastic pieces to microplastics (Andrady, 2011), which could accumulate locally in downwind or sheltered sites (Costa et al., 2011), especially in the presence of high human pressure from tourism activities.

4.1. Macrodebris

Over 88% of the Slovenian coast was urbanised within fifteen years (Turk, 1999). The present study took advantage of the existence of both urbanized and (few) still non-urbanised beaches to carry out a comparative assessment of the marine debris present along the coast of Slovenia. The choice of eight major groups and further division into 59 debris categories is in accordance with the recommended by Galgani et al. (2010) of one to six debris groups to yield a low error rate and more consistency in data analysis. The inclusion of a higher resolution system of more than 20 categories allows for identification of changes in debris composition, source, and usage of items (Galgani et al., 2010).

The number and weight of macrodebris did not vary in relation to the level of human use at beaches (Fig. 5). The number of macrodebris on Slovenian beaches was higher than on beaches in Rio de Janeiro, Russia, South Korea, Northern Taiwan, and the South China Sea, although it was lower than on beaches in Chile, Japan and Santa Catarina (Table 3). This type of pollution is of high concern to the tourism sector, which operates within a relatively small portion of coastline in Slovenia, and competes with foreign beaches that are in close proximity. Beachgoers, especially foreign tourists, consider beach cleanliness first when choosing a recreational destination (Balance et al., 2000). Yet, they directly dispose of debris at the beach they visit, as indicated by the high percentage of cigarette filters within the plastics group (up to 63.7% in Jadranska-NT1). Though beach cleaning practices have been put in place in Slovenia and occur monthly and, in some cases, daily, inadequate disposal practices prevail.

Visual descriptions of beach cleanliness provided by Alkalay et al. (2007) were usually consistent with the index values obtained (Table 1). However, because the CCI only considers plastic particles, beach cleanliness was likely underestimated in Seča (NT3) and Debeli Rtic (T1), where glass/ceramics and metal account for a large proportion of the debris. Moreover, the CCI indicates that geographical distribution of beaches in Slovenia seems to be correlated with plastic abundance, in spite of tourist affluence.

Macrodebris count revealed that beaches in the vicinity of Koper harbour and Rižana river contain more plastic debris than beaches further South. The activities that are likely to affect marine water quality in the region of Koper include: waste water release, industry, pollution from the port of Koper, tourism, sea traffic, and agriculture (Peterlin et al., 2005). However, the main pollution pathways in the region identified by a long-term study were outflow of wastewater from Koper treatment plant and untreated wastewater, which flows into the sea through the river (Peterlin et al., 2005). Macrodebris could originate from these pathways elsewhere and result in similar forms of beach pollution.

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Table 3
Macrodebris densities on the beach (items m^{-2}) found in Slovenia (present study data) and other regions of the world.

Region	Mean density (items m^{-2})	Author
Slovenia	1.51 (1.25[a])	Present study
Rio de Janeiro, Brasil	0.13	Oigman-Pszczol and Creed (2007)
Santa Catarina, Brasil	4.98	Widmer and Hennemann (2010)
Japan	3.41	Kusui and Noda (2003)
Russia	0.207	Kusui and Noda (2003)
Tasmania	0.28	Slavin et al. (2012)
Chile	1.8	Bravo et al. (2009)
South China Sea	0.0032	Zhou et al. (2011)
South Korea	1.0	Lee et al. (2013)
Northern Taiwan	0.149	Kuo and Huang (2014)

[a] Median density (items m^{-2}).

Land-based was an important source of macrodebris in this study, as could be expected from sampling during the peak tourist season in Slovenia. This is even clearer when looking at the high proportions (unit count) of cigarette filters (41.9% of total plastic), which are good indicators of land-based debris due to their rapid disintegration at sea. Jadranska (NT1) and Simonov Zaliv (T2*) contained especially high proportions of cigarette filters within the plastic group, which indicates that these items were discarded locally at these sites.

Though beaches are cleaned monthly in Slovenia, only particles larger than ~5 cm are removed (Palatinus, pers. comm.). Thus, smaller pieces such as cigarette filters are found in extremely high numbers. For example, 1012 filters were collected in Simonov Zaliv (T2*) on one 50-meter transect (Table 2). Additionally, alcoholic beverage bottles were found on the beaches of Jadranska (NT1), Simonov Zaliv (T2*) and Bele Skale (NT2), as a result of direct disposal by people drinking on the beach. This behaviour was witnessed in Simonov Zaliv during the 5 am debris sampling for the present study.

Ocean-based debris can include, for example, abandoned, lost or intentionally discarded fishing gear. These are an important source of marine pollution that is pervasive to sensitive habitats, marine organisms, and fisheries (from the loss of commercially valuable species) (Guillory, 1993; Matsuoka et al., 2005; UNEP, 2005; Bilkovic et al., 2012). Median fishing gear density was higher in Bele Skale (NT2-0.096 items m^{-2}) and Jadranska (NT1-0.069 items m^{-2}), although derelict fishing gear fell a few meters outside of the transect in Seča (NT3). Moreover, macrodebris are concentrated on the high tide mark in Bele Skale (NT2), which indicates that they originate from the ocean at this location (OSPAR, 2009).

Debeli Rtič (T1), Simonov Zaliv (T2*), Portorož (T3*), and Seča (NT3) beaches were sheltered either by built structures (*e.g.* pontoon) or by their configuration, which usually imply weaker currents. Reduced movement of water masses could limit the outward transport of locally disposed debris, causing them to accumulate on the beach and on the intertidal area (Galgani et al., 2010).

4.2. Microplastics

The approach used to isolate microplastics was successful in recovering particles from a wide range of sediment types. The combination of decantation with inverse filtration is hence recommended for microplastic extraction, in particular from fine sediment (*i.e.* silt, clay), which contains low-density particles that make density separation difficult (Vianello et al., 2013).

Small microplastics (0.25–1 mm) accounted for 26% of particles, while 74% were larger microplastics. Small size is a key factor in determining the bioavailability of microplastics to lower trophic organisms (Wright et al., 2013), which feed less selectively than larger biota (Moore, 2008). This mechanism enhances trophic accumulation of microplastics, as observed by Farrell and Nelson (2013) in the prey *Mytilus edulis* and its predator *Carcinus maenas*. Furthermore, it also raises health concerns for humans (Thompson et al., 2009b), given that microplastics can be lodged in the hemolymph and tissues of the crab (Farrell and Nelson, 2013) and, possibly, in other species, such as the fin whale (Fossi et al., 2012).

The present study shows that it is unlikely that pollution by microplastics is directly related to tourism activities in Slovenia, given that their concentration did not vary between touristic and non-touristic beaches or between infralittoral and shoreline samples. Debeli Rtič (T1) was different from other beaches in that it was the only one where records showed three types of microplastics: fibers, fragments, and films. Jadranska (NT1) contained two types of microplastic (fibers and fragments), while there were only plastic films in the infralittoral of Seča (NT3). All samples except this one contained fibers, which accounted for 96% of microplastics in the infralittoral, and for 75% of microplastics in the shoreline.

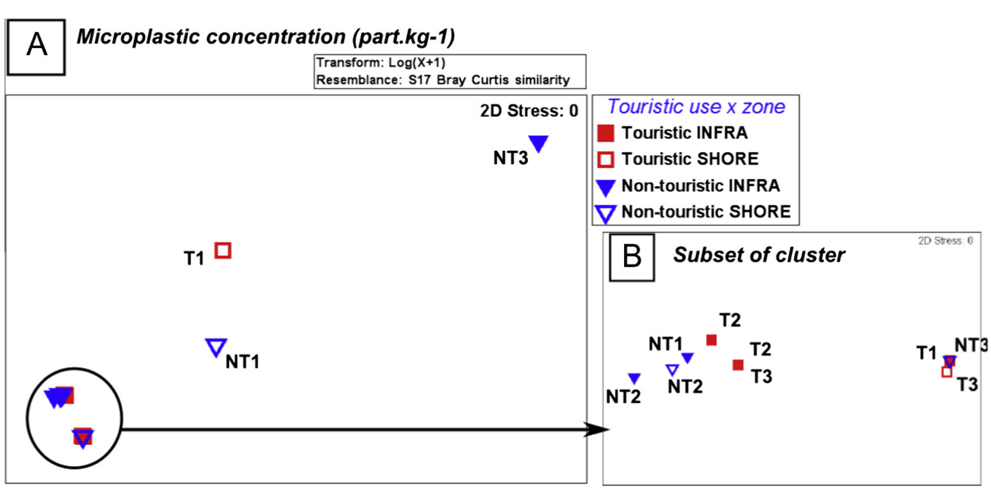

Fig. 10. (A) Multidimensional scaling (MDS) plot of Bray–Curtis similarities of microplastic quantity (log-transformed, particles per kg) within three categories across two zones (infralittoral and shoreline), at six beaches. (B) MDS subset of Bray–Curtis similarities representing circled cluster. Full red squares represent infralittoral samples of touristic beaches, empty red squares represent shoreline samples of touristic beaches, full blue triangles represent infralittoral samples of non-touristic beaches, and empty blue triangles represent shoreline samples of non-touristic beaches.2-Dimensional stress is equal to 0. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Microplastic concentrations in Slovenia are in the same range as those in Belgium, yet higher than the average reported for the United Kingdom, Singapore and Norderney Island, as shown in Table 4. Venice lagoon and the beaches of two East Frisian Islands contain, however, more microplastics than Slovenian shorelines and infralittoral habitats (Table 4). Though this pollution does not directly influence the tourism sector, microplastic abundance increases the likelihood of ingestion by a wide range of biota (Thompson et al., 2009b; Wright et al., 2013).

The totality of microplastics in the present study (fibres, plastic fragments, and plastic films) are secondary microplastics that arise from the fragmentation of macroplastics at sea or on land through light, heat, chemical, or physical processes (Cole et al., 2011; Andrady, 2011; Costa et al., 2010; Barnes et al., 2009). This hypothesis is supported by the fact that microplastic size distribution was skewed to the left, and irregular fragment sizes were present (Browne et al., 2010). No primary microplastics (spherical microplastic granules) were found in Slovenia, despite the close proximity of the port of Koper, and Rižana and Dragonja rivers. This information is crucial for management purposes, since control strategies should differ according to microplastic source (Arthur et al., 2009).

Microplastics in Slovenia likely entered sediments from indirect sources. These particles can pass through filtration systems of wastewater treatment plants and be transported to the sea by rivers (Browne et al., 2010; Thompson, 2006). The two main rivers in Slovenia could possibly enable that transport, although currents could also transport microplastics from other parts of the Gulf of Trieste into the Slovenian coast. Once at sea, microplastics either sink due to (a) their composition of high-density materials (*e.g.* polyvinylchloride, polyester, polyamide), (b) fouling microorganisms (Lobelle and Cunliffe, 2011), or (c) waterfronts; or remain in the water column (buoyant, or neutrally buoyant) (Cole et al., 2011). It is expected that wind-driven ocean circulation could have an effect on microplastic accumulation at beaches, with higher concentrations reported in sheltered areas than exposed ones (Vianello et al., 2013). This hypothesis remains to be tested in future surveys at beaches in Slovenia.

4.3. Future directions

This study was limited in time and sampling size, therefore, it is desirable that a follow-up be performed, especially if including large sample sizes, and spanning winter and summer months. A comprehensive study of beach debris in Slovenia is under way for implementation of the Marine Strategy Framework Directive and reporting under Articles 8, 9 and 10, but locations of sampled sites do not coincide with those herein investigated.

On a broader scale, standardised assessment protocols are needed to compare debris abundance on coastlines worldwide, and to establish critical thresholds to be respected by stakeholders. It is advised that microplastic quantities be reported in number of particles kg^{-1} of sediment, while macrodebris be reported in number of items meter^{-2}. The Clean Coast Index was developed to assess the actual cleanliness of a beach in an objective and easy way, by quantifying the amount of waste removed, but an important drawback to this methodology is highlighted in the present study. Scientific studies claim that the major component of marine debris is plastic, which is used as the input variable for the index calculation, and indeed most of the beaches assessed in the present study had higher amounts of plastic than other debris groups. Nevertheless, it was possible to observe that plastic does not dominate on all beaches. Glass and ceramics were also an important debris group, highlighting the need for a standard index that accounts for all debris groups while also allocating higher importance to plastics, and potentially microplastics, on beaches.

According to the recommendations for debris assessment from the Marine Strategy Framework Directive (Galgani et al., 2010), criteria and methodologies for evaluating the environmental status of a location should include: (a) quantification, qualification and source of coastal debris, to measure inputs, aesthetic impacts, presence of toxic compounds, and socio-economical damage; (b) quantification and qualification of debris present in the water column and on the seafloor, to estimate debris dynamics, potential interaction with marine life, and to identify areas of debris accumulation; (c) quantification and qualification of debris ingested by animals, to assess temporal and spatial trends, and variation in debris input and impact on biota; and (d) quantification, qualification and distribution of nektonic and benthic micro-particles to measure quantities, types, degradation processes and potential sources of contaminants. The combined approach of monitoring the above parameters and researching social, economical and ecological impacts of debris can lead to a greater knowledge of the problem and aid in the implementation of more effective solutions.

Overall, it seems only reasonable to classify plastics and associated plasticizers as hazardous materials, due to the overwhelming evidence of their far-reaching negative effects (Rochman et al., 2013), including on human health (Sheavly and Register, 2007; Swan, 2008; Thompson et al., 2009b). These outweigh by far the economical advantages of their widespread distribution, and call for adequate disposal measures, until more environmentally friendly substitutes are in use.

Table 4
Microplastic concentrations (mean quantity, particles kg^{-1} of dry sediment) found in Slovenia (present study data) and other regions of the world.

Region	Habitat	Mean concentration (particles kg^{-1})	Author
Slovenia	Beach	177.8 (133.3[a])	Present study
	Infralittoral	170.4 (155.6[a])	Present study
Venice	Lagoon	1445.2	Vianello et al. (2013)
Kachelotplate, Spiekeroog	Beach	671	Liebezeit and Dubaish (2012)
Norderney	Beach	1.45	Dekiff et al. (2014)
Belgium	Harbour	166.7	Claessens et al. (2011)
	Beach	92.8	Claessens et al. (2011)
	Coast	91.9	Claessens et al. (2011)
United Kingdom	Subtidal	86[b]	Thompson et al. (2004)
	Estuarine	31[b]	Thompson et al. (2004)
	Beach	8[b]	Thompson et al. (2004)
Singapore	Mangrove	36.8	Mohamed Nor and Obbard (2014)
	Beach	2.3	Ng and Obbard (2006)

[a] Median concentration (particles kg^{-1} of dry sediment).
[b] Original unit: fibres per 50 mL.

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5. Conclusions

The present study provides the first assessment of macrodebris and microplastic pollution in six beaches along the Slovenian coast, and a further comparison of the results in relation to tourism activity at each location. A total of 5870 macrodebris units were recovered, with a median density of 1.25 items m^{-2} and weight of 4.45 g m^{-2}. Plastic was the dominant group (64% of total units), although glass and ceramics dominated at two beaches (Seča – NT3, and Debeli Rtič – T1). Cigarette filters accounted for a median of 41.9% of plastics, suggesting that a large proportion of macroplastics is land-based. All samples revealed secondary microplastics (85% of which were fibers), which were recorded at a median concentration of 155.6 particles m^{-2} in the infralittoral zone, and 133.3 particles m^{-2} on the shoreline. A relation between tourism activity and marine debris distribution at the sampling time could not be established. Other factors could be affecting the amount of macrodebris and microplastic at beaches in Slovenia, such as beach exposure, wind, waves, fishing fleet activity, and riverine inputs (Andrady, 2011; Browne et al., 2011), which should be assessed in future surveys.

Standardised debris monitoring protocols are needed to establish comparable baselines and to monitor the pollution of coastlines worldwide, and should include all types of marine debris (not just plastic). The present study provides novel insight into beach microplastic pollution of the Slovenian coast, and the first records of beach macrodebris in relation to tourism in Slovenia. The baseline assessment described herein can be used to obtain crucial data for management in the Adriatic region.

Author contributions

Experimental design and sampling: BJLL, MA-C, LB, RMF-S, MP, AP. Data analysis and manuscript ellaboration: BJLL, RMF-S, MA-C, LB, MP, MG. Manuscript revision: MG, AP.

All authors have approved the final version.

Integrity of research and reporting

Ethical standards

The experiments described in the present study comply with the current laws of the country in which they were performed.

Conflict of Interest

The authors declare that they have no conflict of interest.

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