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Monitoring multi-year macro ocean litter dynamics and backward-tracking simulation of litter origins on a remote island in the South China Sea

Chia-Ying Ko[1,2,7,8], Yi-Chia Hsin[3,7], Teng-Lang Yu[4], Kuo-Lieh Liu[5], Fuh-Kwo Shiah[3] and Ming-Shiou Jeng[6,8]

1   Institute of Fisheries Science, National Taiwan University, Taipei, Taiwan
2   Department of Life Science, National Taiwan University, Taipei, Taiwan
3   Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan
4   Taijiang National Park, Tainan, Taiwan
5   Coast Guard Administration, Executive Yuan, Taipei, Taiwan
6   Biodiversity Research Center, Academia Sinica, Taipei, Taiwan
7   These authors contributed equally.
8   Authors to whom any correspondence should be addressed.

E-mail: cyko235@ntu.edu.tw and jengms@gate.sinica.edu.tw

Abstract

Ocean litter has accumulated rapidly and is becoming a major environmental concern, yet quantitative and regular observations and exploration that track litter origins are limited. By implementing monthly sample collections over five years (2012–2016) at Dongsha Island, a remote island in the northern South China Sea (SCS), we assessed macro ocean litter dynamics, identified source countries of individual plastic bottles, and analyzed the origins of the litter by a backward-tracking model simulation considering both the effects of current velocity and windage. The results showed that large amounts of litter, which varied monthly and annually in weight and quantity, reached the island during the study years, and there were spatial differences in accumulation patterns between the north and south coasts. Styrofoam and plastic bottles were the two primary sources of macro ocean litter both annually and monthly, and most of the litter collected on the island originated from China and Vietnam, which were collectively responsible for approximately 47.5%–63.7% per month. The simulation indicated that current advection at the near-surface depths and low windage at the sea surface showed similar patterns, while medium to high windage exhibited comparable expression patterns in response to potential source regions and drifting time experiments. At either the surface with low windage or current advection at depths of 0.5 m and 1 m, macro ocean litter in the Western Philippine Sea, i.e. through the Luzon Strait between Taiwan and the Philippines, was an important contributor to the litter bulk from October to March, whereas the litter was predicted to mainly originate from the southwestern SCS from April to September. With an increasing windage effect, litter in the Taiwan Strait was predicted to be an additional major potential source. Surprisingly, a small proportion of the macro ocean litter was predicted to continuously travel in the northern SCS for a long duration (> 2 years) before drifting onto Dongsha Island. The estimated drifting time of macro ocean litter also showed monthly and directional variability. This study demonstrated that a tremendous quantity of macro ocean litter, which may cause great damage to the marine ecosystem, drifts in the ocean surface layer and is finally pushed onto beaches. Therefore, we proposed an action plan for effective ocean litter management development at regional and global spatial scales, which is vital for improving and restoring the health and sustainability of the oceanic environment.

Introduction

Ocean litter has accumulated rapidly over the last few decades, causing considerable damage to the global marine ecological environment, and it has become a key issue in marine pollution prevention and control (Laist 1987, Stefatos *et al* 1999, Derraik 2002, Law *et al* 2010, Cózar *et al* 2014, van Sebille 2015, Cheung *et al* 2016). In the early 21st century, the international *Our Ocean* conferences have driven commitments to reduce marine pollution and protect the marine environment through immediate, forward-looking actions linking government, businesses and civil society. Due to the lack of appropriate marine management and regulations as well as concepts of environmental sustainability in the past, the intensive consumption and rapid disposal of various products have led to the visible accumulation of a 'garbage patch/soup' that both threatens marine ecosystems worldwide and their accompanying services to human beings (van Sebille 2015). The impacts of ocean litter on individual marine organisms vary widely, with fatalities caused by ingestion leading to gastrointestinal obstruction, the bioaccumulation of contaminants added during manufacturing and entanglement (Laist 1987, Gregory 1991, Derraik 2002, Rochman *et al* 2013, Gall and Thompson 2015). Furthermore, accumulating litter physically changes habitats, disrupting marine communities (Uneputty and Evans 1997, Derraik 2002, Thiel and Gutow 2005). However, there is limited understanding of the effects of ocean litter accumulation at consistent sites with regular sampling (e.g. monthly) or long-term (e.g. multiple years) time scales. Thus, additional studies are needed to facilitate more accurate estimates of the abundance and drivers of litter movement in the water from the regional to the global scale.
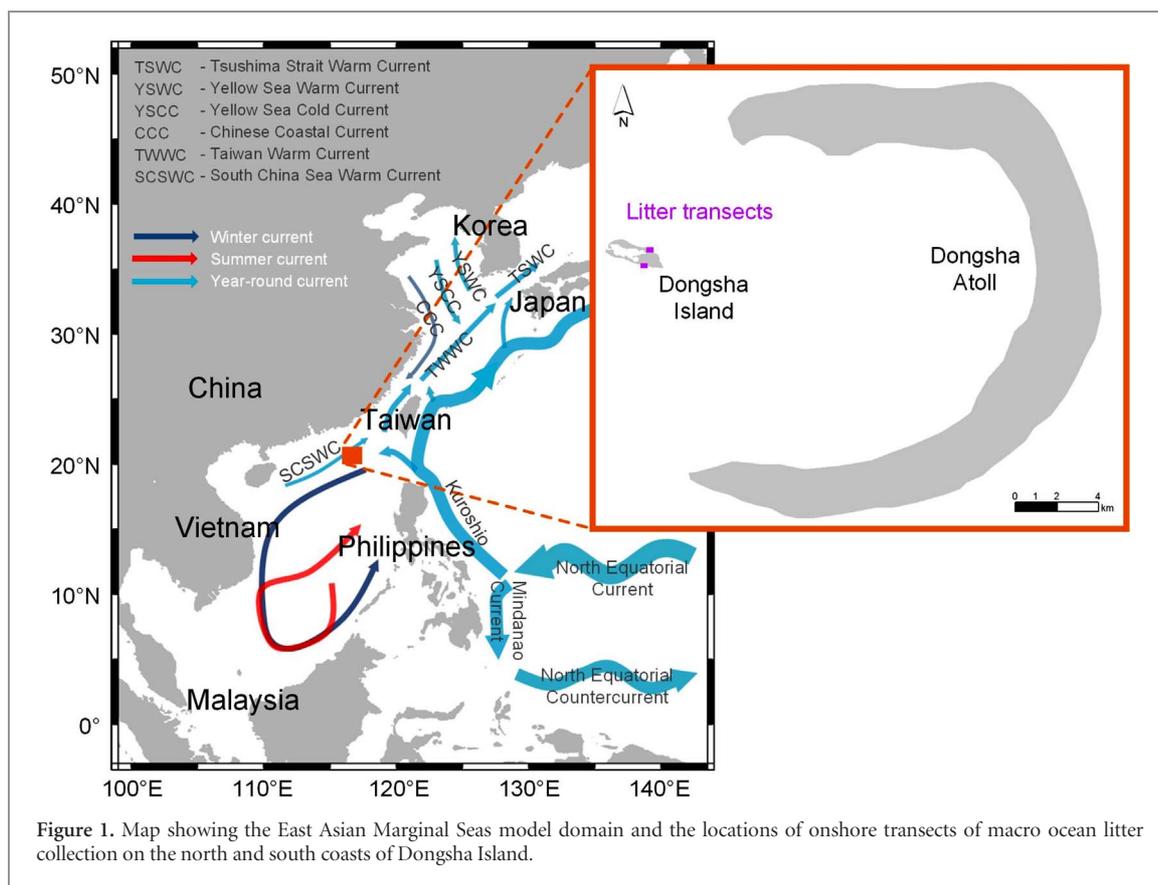
Recent advances in marine sciences have revealed that, due to the Coriolis effect and frictional forces, the ocean is full of vortices or eddies that contain considerable energy and alter the pathways of water and the ocean litter it carries so that the litter reaches even the most remote areas of the planet (Cózar *et al* 2014, van Sebille 2015, NOAA Marine Debris Program 2016). Both observations and ocean circulation model simulations have identified regions of ocean litter accumulation from tropical to subtropical Pacific gyres (Lebreton *et al* 2012, Maximenko *et al* 2012, van Sebille *et al* 2012), and the Kuroshio, the western boundary current in the northwest Pacific Ocean, further concentrates the litter (Hu *et al* 2015). In addition to the effect of advection by oceanic currents and waves, there was a force exerted by the wind against parts of objects sticking out of the water, i.e. the windage. The ocean currents control ocean litter traveling beneath the sea surface, while the windage effect might be taken into account as ocean litter drifts at the sea surface, i.e. ocean litter in direct contact with the atmosphere. Depending on the size, degree of aerial exposure, and other physical attributes of materials, the windage coefficient could be in the range of 1%–5% (Duhec *et al* 2015, Allshouse *et al* 2017).

The South China Sea (SCS) ecosystem is characterized by typical tropical elements paralleled with the Philippine-New Guinea-Indonesia Coral triangle typical tropical faunal center and is important as a nesting, feeding and roosting habitat for thousands of species (Liu 2013). The transport in and around this area varies seasonally (figure 1). Specifically, the surface circulation in the SCS is mainly driven by the East Asian Monsoon, which blows from the northeast in the winter and southwest in the summer (Shaw and Chao 1994, Hu *et al* 2000). A cyclonic (counterclockwise) gyre dominates the full SCS basin in the winter, while the summertime circulation consists of a cyclonic gyre in the northern SCS and an anticyclonic gyre in the southern SCS, with a northeastward jet in between. Aside from the basin-scale, monsoon-driven circulation in the SCS, the westward intrusion of the Kuroshio Current from the Luzon Strait connects the SCS to the Western Philippine Sea and plays a very important role in regulating the surface circulation in the northern SCS (Hu *et al* 2000, Wu and Chiang 2007, Hsin *et al* 2012). The Kuroshio intrusion is stronger in the winter and delivers warmer and saltier water westward up to the west of 117°E in the northern SCS (Shaw and Chao 1994, Wu and Hsin 2012). Another important current is the South China Sea Warm Current (SCSWC), which flows to the northeast along the continental slope off the southeastern China. It is permanent in the summer but shows up intermittently in the winter during the releasing period of northeasterly wind (Chiang *et al* 2008). Through the Taiwan Strait Warm Current (TSWC) in the Taiwan Strait, which consists of the SCSWC, the Kuroshio branch, or the Chinese Coastal Current (CCC) based on the season, the SCS is connected to the East China Sea.

Besides, due to the rapid population growth and economic development in many countries with marine coastlines in recent years, the ocean has become a focus of Asia and an economic lifeline (World Bank 2005). However, awareness of the importance of ocean litter pollution is limited, and basic questions remain unresolved. Additionally, oceanic resources and services are typically common-pool resources that have recently been the focus of discussions to develop an essential strategy for resource stewardship through the assignment of resource property rights to maintain potential co-benefits (Gaines *et al* 2010, Stavins 2011, Rickels *et al* 2016). The quantity and final destination of ocean litter, which jointly affects neighboring countries due to their shared waters and ecosystems, remain unknown.

Here, we implemented a study using monthly samples collected over 5 years from Dongsha Island, which is a remote island in the northern SCS, 440 km off the coast of the southern Taiwan. Located at a crossroads of the aforementioned currents, the seasonal variability of macro ocean litter that drifted onto Dongsha

Figure 1. Map showing the East Asian Marginal Seas model domain and the locations of onshore transects of macro ocean litter collection on the north and south coasts of Dongsha Island.

Island could be highly influenced by the combined effect of these currents. We first conducted an annual and monthly assessment of ocean litter with a special focus on macro ocean litter (i.e. >5 mm) obtained from multi-year, onshore field collections. Based on a global standard barcode system, this study identified the source countries of individual plastic bottles among the subsets of macro ocean litter items, and then we utilized the East Asian Marginal Seas (EAMS) model output to simulate the trajectory of macro ocean litter by the backward-tracking method and assess its role in shaping macro ocean litter composition patterns in each location of Dongsha Island. Because it experiences limited human interference and coastal activities, the island tends to receive naturally floating ocean litter and can thus provide a snapshot of ocean litter ecology.

Methods

Monthly onshore field data collection

Macro ocean litter was collected monthly along fixed, 50 m onshore transects on the north and south coasts of Dongsha Island from 2012–2016 (figure 1). The litter within the onshore transects was removed one month before the first official litter collection in January 2012. The litter was transported to the laboratory in garbage or bulk bags, and water and dirt were manually removed to the greatest extent possible. All the collected litter was weighed separately for each side of the island, i.e. south and north, and each litter item was then categorized by

material type and function and counted. We classified the macro ocean litter into nine groups: plastic bottles, other plastic products, Styrofoam, fishing gear (e.g. buoys and shrimp cages), glass, metal, shoes and toys, lamps and bulbs, and others. Additionally, the source countries of the individual plastic bottles were identified according to the global standard barcode system under the assumption that the macro ocean litter was discarded at its origin and eventually reached Dongsha Island. Then, an annual amount of litter for a year was obtained by summing the monthly amounts up.

Backward-tracking simulation

To evaluate the possible pathways and drifting time of the macro ocean litter surrounding Dongsha Island, a total of 400 trajectories were released at three depths from the surface to 1 m (0 m, 0.5 m, and 1 m) and traced backward for two years based on the simulated three-dimensional flow field of the EAMS model (Wu and Hsin 2005, Hsin *et al* 2008, Hsin *et al* 2012). This model has been broadly applied to investigate the variability in the hydrography and circulation of the Taiwan Strait (Wu and Hsin 2005, He *et al* 2014), the Kuroshio (Kao *et al* 2006, Hsin *et al* 2008, Wu *et al* 2008, Hsin *et al* 2010, Sheu *et al* 2010), and the SCS (Hsin *et al* 2012, Bai *et al* 2015) at various timescales, and it has been validated for the seas around Taiwan with observational data in previous studies (Wu and Hsin 2005, Hsin *et al* 2008, Hsin *et al* 2010, Hsin *et al* 2012). The backward-tracking simulation of the trajectories was performed for a 20 year period from 1995–2014.

The EAMS model is based on the Princeton Ocean Model (Mellor 2004), which is a numerical, three-dimensional, primitive-equation, sigma-coordinate ocean circulation model, and it covers a domain of 99°E-143.5°E and 3°S-52°N (figure 1) with a horizontal resolution of $1/8° \times 1/8°$ and 26 vertical sigma levels. The open lateral boundary conditions of the EAMS model are one-way nested in a $1/4° \times 1/4°$ North Pacific Ocean (NPO) model, which has an extended domain of 99°E-71°W and 30°S-65°N. Driven by monthly climatological surface fluxes from the $2.5° \times 2.5°$ National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) Atmospheric Model Intercomparison Project (AMIP-II) reanalysis (www.esrl.noaa.gov/psd/data) and the hydrography and current from the $0.5° \times 0.5°$ Simple Ocean Data Assimilation (SODA; http://apdrc.soest.hawaii.edu/) oceanic reanalysis, the NPO model was initially spun up for 50 years. Subsequently, we drove the NPO model with six hourly NCEP-DOE AMIP-II reanalysis surface fluxes and monthly SODA data from 1948–2014. The topography of the EAMS model is a blend of the $1/30° \times 1/30°$ TaiDBMv6 (Ocean Data Bank, Nation Center for Ocean Research, Taiwan) and the $1/12° \times 1/12°$ ETOPO5 (National Geophysical Data Center, NOAA, National Environmental Satellite, Data and Information Service) bathymetric data. At the sea surface, the EAMS model was forced by the 6 hourly quarter-degree Cross-Calibrated Multi-Platform (CCMP; www.remss.com/measurements/ccmp) wind and heated (or cooled) by the six hourly $2.5° \times 2.5°$ NCEP-DOE AMIP-II reanalysis heat flux from 1989–2014. Finally, the 22 year output of the EAMS model from 1993–2014 was adopted in this study to trace the possible trajectories of macro ocean litter and to estimate its drifting time.

Moreover, with consideration of the windage that also plays a significant role in drifting ocean litter (Duhec *et al* 2015), the velocity field (U) at the sea surface (i.e. 0 m) used to backward track the ocean litter can be blended with the surface current velocity (U_c) and wind velocity (U_w) at a height of 10 m above the sea surface (Allshouse *et al* 2017). The velocity field was then given by $U = U_c + C_w U_c$, where C_w is the windage coefficient, which tends to depend on the size, degree of aerial exposure, and other physical attributes of materials. If $C_w = 0$, only the surface current velocity is taken into account in the trajectory estimation. Here, we adopted U with $C_w = 0, 0.01, 0.03, 0.05$, and 0.1 to examine the effect of windage on the macro ocean litter floating at the sea surface. Based on previous research, the litters could be classified into three groups: low ($C_w = 0-0.01$), medium ($C_w = 0.02-0.03$), and high windage ($C_w > 0.04$; Duhec *et al* 2015). Low windage items float below the sea surface and are not affected directly by winds, such as fishing nets, small furniture, and bottle caps. For medium windage items, surface currents and winds make compatible effect on

their movement. Capped plastic bottles partially filled with sea water, shoes, and empty capped glass bottles belong to this category. Items with low density floating on the surface of the water, such as Styrofoam, empty plastic bottles, and fishing buoys, are highly dragged by winds and considered as high windage items.

Data analysis

Differences in the weights and quantity, i.e. the numbers of items, of the macro ocean litter components were analyzed with a Wilcoxon rank sum test, and the litter trajectories were estimated by identifying five sections bordering the northern SCS according to the geographic distributions and characteristics of the SCS surface circulation (please see figure 6 for the location of each section). The five sections classified possible pathways of macro ocean litter from the Taiwan Strait, the Luzon Strait (i.e. the Western Philippine Sea), the southeastern SCS, the southwestern SCS, and the Gulf of Tonkin. When individual litter items drifted backward to any of the sections, the simulation was stopped, and the number of days to arrival was recorded. If the items could not reach any section, it implied that the items remained floating in the northern SCS for at least two years. The percentage of macro ocean litter items that drifted to the sections and the average number of days to arrival were calculated.

Results

Field collection monitoring

Large amounts of macro ocean litter, whose weight and quantity varied annually and monthly, entered the northern regions of the SCS, i.e. Dongsha Island, over the five years of the study (figure 2). The annual macro ocean litter quantity ranged from 112.8 kg–320.6 kg, and the annual number of items from 2202–8502, with monthly averages ranging from 7.96 kg–43.44 kg and from 209–754 items, respectively. Both the highest weight and quantity of litter were recorded in 2014. There was no significant difference in annual weight between the north and south coasts of the island among years ($p > 0.05$), but the annual number of litter items differed significantly ($p = 0.016$). Macro ocean litter mainly accumulated from October to February, and the average of those months (629 items and 32.24 kg) was twice the average of the other months (300 items and 11.22 kg). In terms of spatial distribution, the litter on the north and south coasts showed significant differences in both monthly average weight ($p = 0.012$) and quantity ($p = 0.039$), and except for 2013, there was more macro ocean litter annually in the north than in the south, mainly due to the accumulation in winter (October–May), which comprised 76.7%–95.5% of the weight and 85.7%–95.2% of the total items in one year. In contrast, the south coast had more macro ocean litter in summer (June–September), with approximately 6–8 kg composed of 114–220 items observed per month.
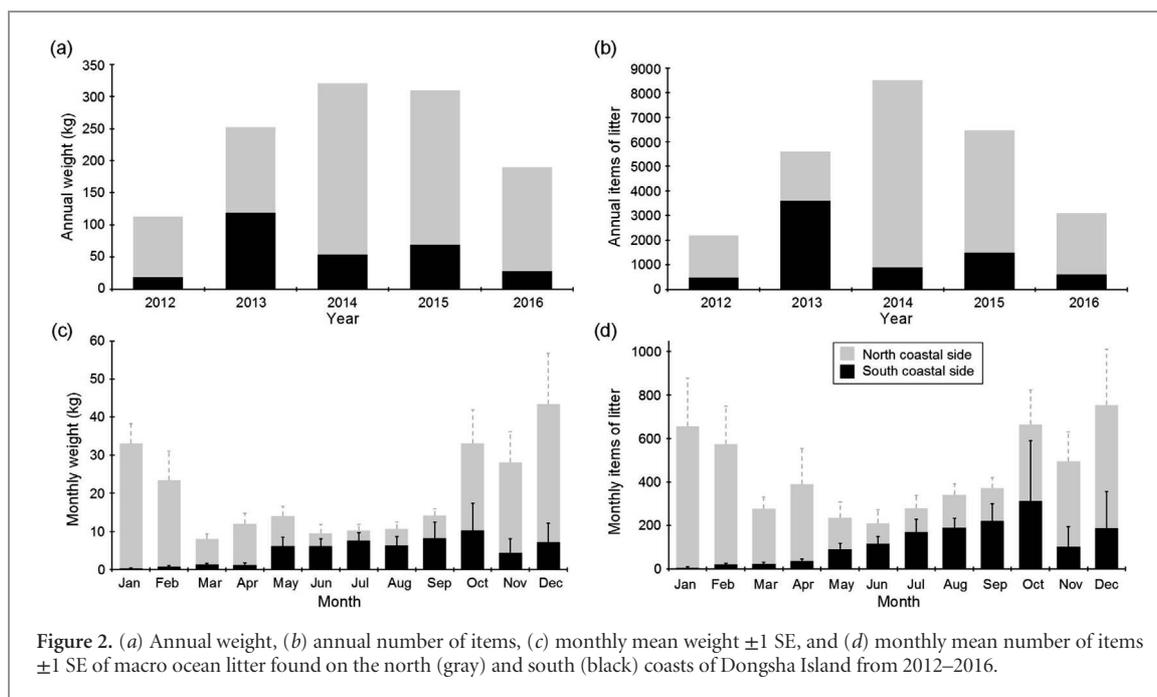
Figure 2. (*a*) Annual weight, (*b*) annual number of items, (*c*) monthly mean weight ± 1 SE, and (*d*) monthly mean number of items ± 1 SE of macro ocean litter found on the north (gray) and south (black) coasts of Dongsha Island from 2012–2016.

A wide variety of macro ocean litter was found on the coasts of Dongsha Island, mostly in an undegraded form (figure 3). With an annual average of 41.6% ± 4.04% of the total items, Styrofoam was the primary source of both annual and monthly macro ocean litter in the waters surrounding the island, followed by plastic bottles (26.4% ± 2.2%), fishing gear (11% ± 1.04%) and other plastic products (10.8% ± 2.5%; figure 4). Together, the Styrofoam and plastic bottles accounted for more than 60% of the monthly composition.

Among the subsets of macro ocean litter items, the majority of plastic bottles collected on Dongsha Island in this study came from China and Vietnam, which were responsible for approximately 47.5%–63.7% of the plastic bottles entering the waters surrounding the island each month (figure 5). The macro ocean litter that was contributed from China in the winter (December–February) increased sharply in the most recent two years, up to 66.4%–80.6% per month, and there was an increasing trend of plastic bottles originating from Vietnam in the summer, especially in August, when there was more macro ocean litter from Vietnam (29.2%) than from China (24.3%). Taiwan, Japan and Korea were tied for third in terms of being the source of plastic bottles, which ranged from 2.9%–22.1% of the monthly total. Of the plastic bottle source countries, opposite seasonal patterns were manifested between Vietnam and Taiwan, Japan and Korea, with the highest proportion in summer coming from Vietnam and that in winter from the other three countries. Countries in Southeast Asia, including Singapore, the Philippines, Thailand, Malaysia, and Indonesia, contributed approximately 1.3%–6.2% of the monthly accumulation of macro ocean litter on Dongsha Island. Finally, a small portion (0%–1.1% per month) of the plastic bottles floating across the Pacific Ocean were identified as coming from the USA, Australia, Fiji and Canada.

Model simulation

Based on the backward-tracking model simulation, current advection effect at different depths and low windage at the surface, i.e. $C_w = 0$ and 0.01 and at depths of 0.5 m and 1 m, showed similar patterns, while medium to high windage experiments, i.e. $C_w = 0.03$, 0.05 and 0.1, exhibited comparable expression patterns in response to potential source regions and drifting time (table 1; figure 6). The Western Philippine Sea, i.e. through the Luzon Strait between Taiwan and the Philippines, and the southwestern SCS were predicted to be the two main external sources of macro ocean litter on Dongsha Island, showing monthly variations and a general pattern at either the surface with low windage or at depths of 0.5 m or 1 m, whereas with increasing windage, the Taiwan Strait was an additional major potential source of macro ocean litter (figure 6). Of the macro ocean litter buoyant in shallow surface layer with effects of current velocity and low windage, i.e. $C_w = 0$ and 0.01 and at depths of 0.5 m and 1 m, the Western Philippine Sea made a considerable contribution from October to March, especially in December, when it was responsible for up to 92.2% of the litter, but from April to September, approximately 62.9% of the ocean litter was predicted to originate from the southwestern SCS. In addition, the Gulf of Tonkin waters accounted for an average of 16.8% of the macro ocean litter in July, August and September but only 0.61% in the other months. When carrying out the medium to high windage simulation of litter motion, a wide proportion of macro ocean litter (7.2%–80.5%, an average of 47.6%) that originated from the Taiwan Strait was instead transported into Dongsha Island and the surrounding waters from October to March, implying a strong influence of the winter monsoon blowing from the northeast. There was consistently almost no macro ocean litter drifting from the southeastern SCS.

Table 1. Drifting time (unit: days) of ocean litter accumulated on Dongsha Island and in the surrounding waters as simulated by the backward-tracking method. Both the effects of current velocity at the depths from the surface to 1 m and of windage at the sea surface are considered. The sections classified as possible pathways of macro ocean litter are shown in figure 6. In a month, the bold value denotes the shortest drifting time among the sections for each experiment.

Section	Western Philippine Sea							Southwestern South China Sea							Gulf of Tonkin							Taiwan Strait						
	Surface and windage setting (C_w)					Depth (m)		Surface and windage setting (C_w)					Depth (m)		Surface and windage setting (C_w)					Depth (m)		Surface and windage setting (C_w)					Depth (m)	
Month	0	0.01	0.03	0.05	0.1	0.5	1	0	0.01	0.03	0.05	0.1	0.5	1	0	0.01	0.03	0.05	0.1	0.5	1	0	0.01	0.03	0.05	0.1	0.5	1
January	**28**	25	63	112	69	**27**	**30**	242	316	355	333	300	277	223	235	217	227	192	198	224	218	84	45	**19**	**12**	**9**	82	83
February	**31**	24	40	62	73	**29**	**42**	222	341	359	336	318	243	236	253	232	245	239	285	255	256		59	**23**	**14**	**16**		
March	**43**	22	21	42	45	**42**	**66**	174	140	402	392	362	182	180	297		342	256	289	333	280		61	34	**22**	**25**		
April	**50**	27	20	20	22	**48**	**55**	127	404	496	461	398	134	140	448		650	468	329	380	305		82	46	**29**	**37**		
May	**55**	30	22	21	18	**60**	**72**	118	227	366	288	172	115	128	280			632	464	73	294				**33**	**32**		
June	61	44	40	**32**	27	62	99	120	119	167	102	37	111	121	**40**	34	29	36	22	**39**	**79**	257		198	69	**27**	253	
July	59	43	40	**22**	**9**	57	61	81	74	66	37	20	81	88	**44**	37	37	25	20	**44**	**43**	256	208	201	**21**		258	
August	81	80	30	**18**	**11**	89	91	88	87	56	38	21	87	89	**57**	47	27	24	20	**57**	**57**	270	215	255	**183**		335	
September	**55**	34	23	18	**12**	**55**	**64**	119	100	61	45	31	119	118	65	48	41	42	43	66	69	301	**16**	22	16			
October	**36**	27	28	36	41	**36**	**38**	154	128	130	134	147	154	153	109	103	79	95	134	109	113		43	**22**	**15**	**15**		
November	**25**	23	71	86	73	**26**	**29**	217	183	234	207	182	208	183	128	145	114	186	111	123	127		44	**20**	**12**	**11**		
December	**23**	28	107	113	87	**23**	**25**	362	261	326	259	243	363	263	182	178	121	487	382	165	195	467	42	**18**	**12**	**8**	187	78

Figure 3. (*a*) A wide variety of macro ocean litter found on the coasts of Dongsha Island, such as (*b*) fishing-related instruments, (*c*) shoes and toys, (*d*) Styrofoam, (*e*) plastic bottles (barcode systems representing source countries are shown by black boxes) and metal. Human stewardship of coastal environments by the Coast Guard Administration on Dongsha Island as well as the source country marked on a life buoy are also represented in the figure.

Notably, the modeled results indicated that some litter remained in the northern SCS throughout the year (from 0.5%–36.2% per month) and were never drifted back to land or to the surrounding seas, i.e. the 'Inner' Section showed on the figure 6.

The estimated drifting time of the macro ocean litter in the shallow sea surface layer showed monthly and directional variability ranging from 8–496 days (table 1). When modeling effects of low windage at the surface and current velocity at different depths, most of the macro ocean litter drifting in the Western Philippine Sea, i.e. the Luzon Strait, was predicted to reach Dongsha Island merely in approximately 1–2 month(s). From June to August, the path of macro ocean litter from the Gulf of Tonkin to Dongsha Island instead took the shortest time, approximately 1–2 months; in contrast, the macro ocean litter drifting from the southwestern SCS and the Gulf of Tonkin to Dongsha Island required more time (103–448 days) from October to April. In terms of drifting days of the accumulated ocean litter released at the surface with medium to high windage assumptions on Dongsha Island and in the surrounding waters, the patterns changed. The litter was predicted to have the fastest drift trajectory in the Taiwan Strait from October to March, with average of 17 d; during this period, the litter took more than two months and even one year to travel from the

Gulf of Tonkin or the southwestern SCS to Dongsha Island. The Western Philippine Sea origin was consistently predicted to greatly contribute litter around Dongsha Island, especially in April and May, showing 18–22 days of modeled arrival, which was more frequent in the cases of windage ranging between 0.03 and 0.1 than those of current advection at the near-surface depths and low windage at the sea surface on macro ocean litter source sections.

Discussion

This study documented all the macro ocean litter items arriving on shore through a consistently frequent and multi-year sampling effort. The highest monthly and annual weight and quantity of macro ocean litter items virtually loaded on Dongsha Island, which is impacted by a limited range of land and water, implies that oceanic pollution is more severe than expected both regionally and globally. The major types of macro ocean litter materials were plastic products and Styrofoam, and their very slow degradation rates illustrate that inventions for human convenience can pose an unexpected threat to the environment (Derraik 2002, Gall and Thompson 2015). In addition, although Eriksen *et al* (2014) proposed that ocean margins are areas
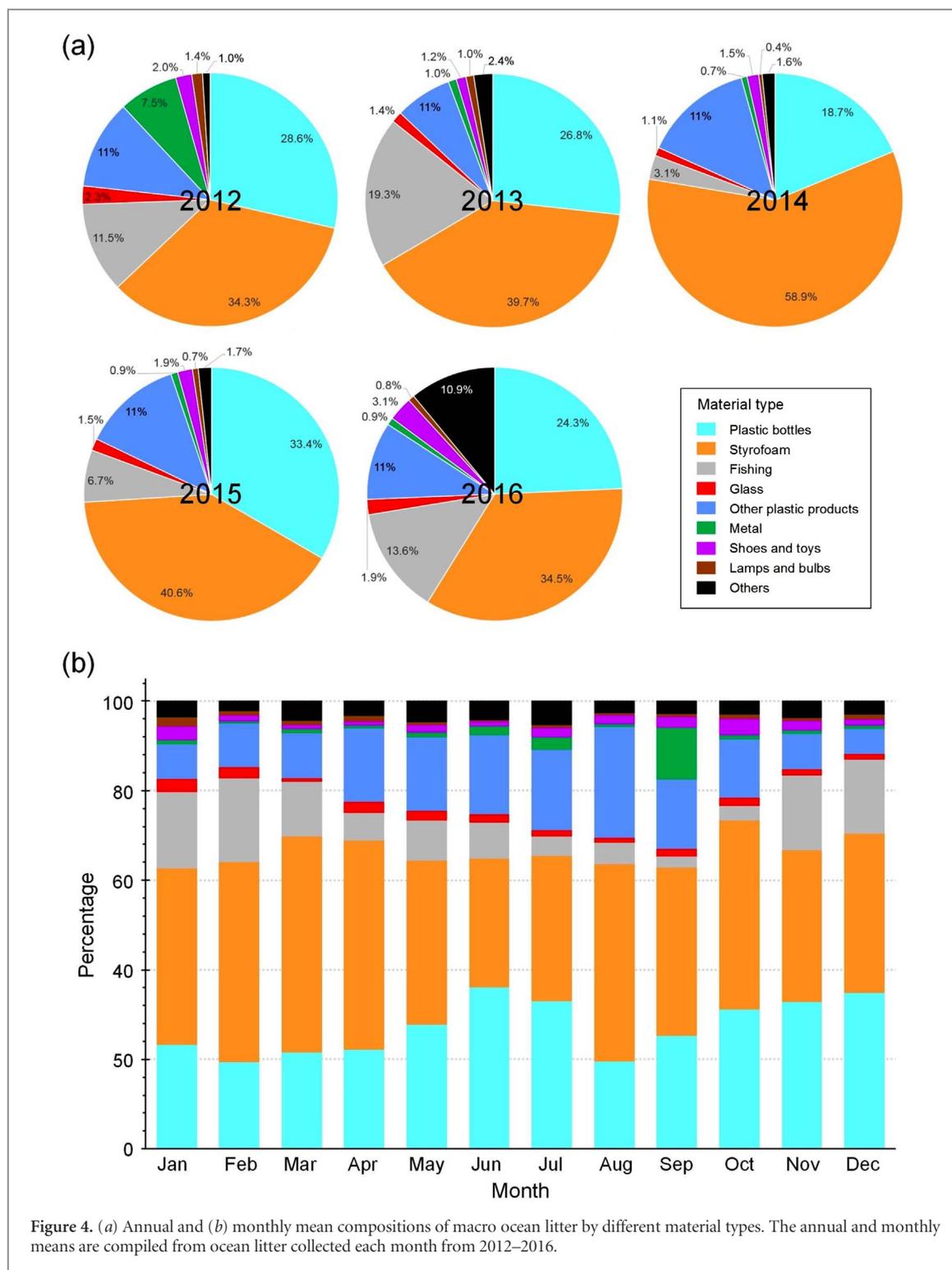
Figure 4. (*a*) Annual and (*b*) monthly mean compositions of macro ocean litter by different material types. The annual and monthly means are compiled from ocean litter collected each month from 2012–2016.

of plastic migration while subtropical gyres are areas of accumulation, our simulation results suggest that a minimum of 0.5% and up to 36.2% of the ocean litter would be continually present in the ocean cycle and may either stay afloat or break down into meso and micro litter, further affecting ocean ecosystems (Thompson *et al* 2004). Several previous studies also support the hypothesis that the sea surface is likely not the ultimate sink for ocean litter (Cózar *et al* 2014, Eriksen *et al* 2014, Woodall *et al* 2014, Gross 2015). Since an increasing load of ocean litter is being dispersed over

long distances (Ryan *et al* 2009, Eriksen *et al* 2014, van Sebille 2015), the eventual settling of litter into oceanic sediments, where it may persist for centuries, and how this affects organisms at various trophic levels require further exploration.

The density, estimated as the monthly average of 0.2 kg or 4.4 items per a linear meter of the Dongsha beach in this study, was similar to that of studies in remote islands of South Australia (Taffs and Cullen 2005) and the Seychelles (Duhec *et al* 2015) and an unpopulated beach in Brazil (Santos *et al* 2008) and
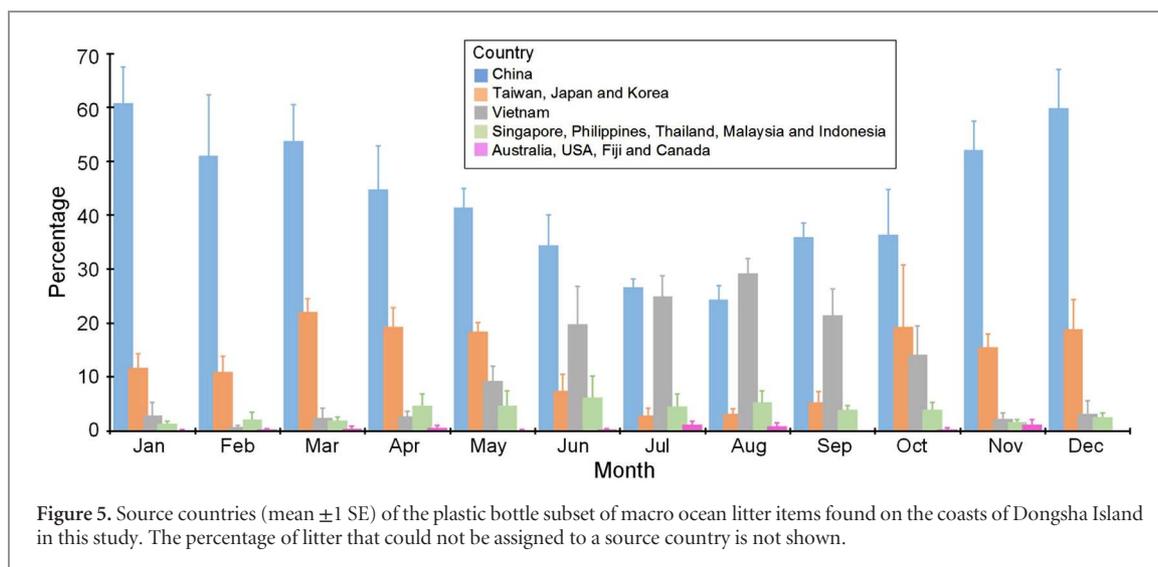
Figure 5. Source countries (mean ±1 SE) of the plastic bottle subset of macro ocean litter items found on the coasts of Dongsha Island in this study. The percentage of litter that could not be assigned to a source country is not shown.

much lower than that of coastal ecosystems in relation to specific human activities (Madzena and Lasiak 1997, Williams and Tudor 2001), all again indicating ocean litter pollution has become global, with both land and ocean loads, in this century, regardless of regions and demographic levels. Although intrinsic differences in litter collection frequencies and size-dependent analyses are likely to confound comparisons and answers for adaptive management (Thompson *et al* 2004, Ryan *et al* 2009, Moreira *et al* 2016), it can be expected that the various threats resulting from poorly managed activities could be highly introduced to coastal and ocean ecosystems, and much work remains to be done to understand litter deposition and movement to address this pressing environmental issue.

Winds and eddies are the main drivers of ocean surface circulation and help to create a complex system of litter transportation throughout the world's oceans (Cózar *et al* 2014, Maes and Blanke 2015, van Sebille 2015, Cózar *et al* 2017). Our simulation results further confirmed the seasonal variation in macro ocean litter, supporting the idea that ocean litter could arrive at Dongsha Island more rapidly in the dominant months (i.e. October–May for the Western Philippine Sea/the Luzon Strait and the Taiwan Strait and June–August for the Gulf of Tonkin) due to the prevailing seasonal pattern of surface circulation in the SCS. A stronger westward intrusion of the Kuroshio through the Luzon Strait occurs in winter, while a northeastward jet originates from eastern Vietnam in summer (Shaw and Chao 1994, Hu *et al* 2000, Hsin *et al* 2012). Another possible cause for the seasonal variation in sources of ocean litter is the East Asian monsoon, which blows northeastward and southwestward in the summer and winter months, respectively. This study demonstrated that both main drivers may not flow in the same direction, and their different powers would change the circulation or transport of macro ocean litter through the proportion and drifting time of potential geographic origins of litter, which would

further affect ecosystems of different regions that the litter has passed. Given that ocean currents, including a much larger system of overturning currents that circulates all over the world from pole to pole, could collapse if atmospheric carbon dioxide concentration doubles in the future (Liu *et al* 2017), this may lead to a very different picture of the future ocean litter than what we have assumed so far.

In addition to the larger ocean litter patches distributed in the global oceans predicted by van Sebille (2015), there may be countless smaller ocean litter patches scattered outside of the central areas of the subtropical gyres, such as the northern SCS and surrounding water areas in this study, which may threaten unique ecosystems at regional scales. Although previous studies have found that the Ekman convergence and inertial effects explain why plastic litter patches are located roughly in the middle of the subtropical gyres (Lebreton *et al* 2012, Maximenko *et al* 2012, van Sebille *et al* 2012, Beron-Vera *et al* 2016), they cannot explain many other features of litter patches, such as the development of a regional litter path with the predicted specific directions of litter accumulations in the northern SCS area. In addition, the dynamic of the drift greatly depends on shape and buoyancy of the object (Duhec *et al* 2015). According to the observed material types of the compositions of macro ocean litter on Dongsha Island, most belonged to medium to high windage litter, indicating the influence of wind on macro ocean litter travel and accumulation. Thus, we suggest that ocean litter movement is more difficult to predict and more information needs to be considered, including the oceanic flow predicted by the three-dimensional wind-driven ocean circulation model, the force exerted directly by the wind, the shape and density of litter object. Therefore, although the backward-tracking trajectory method allows us to virtually track the movement of litter through the waters, preventing litter from entering the ocean is the ultimate goal.
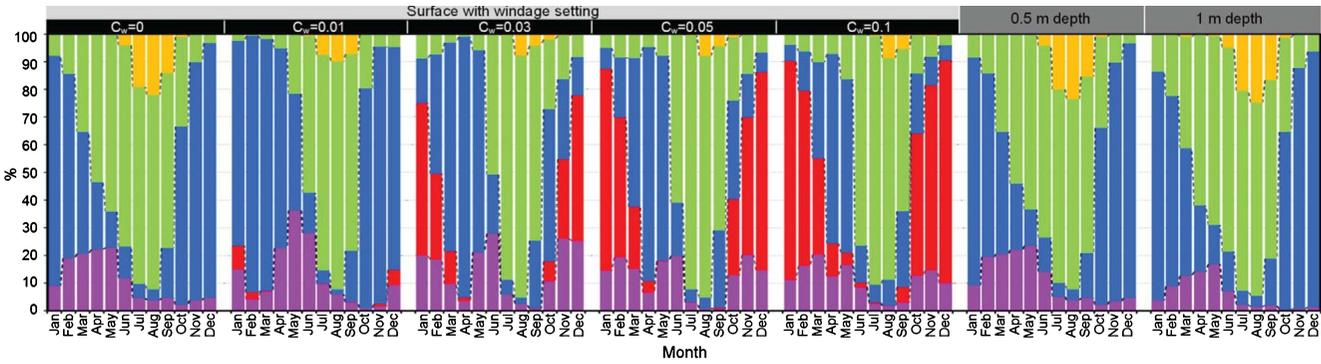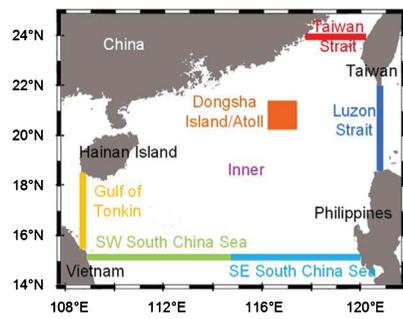
Figure 6. Oceanic pathways of the litter accumulated on Dongsha Island and in the surrounding waters as simulated by the backward-tracking method with both the effects of current velocity at the depths from the surface to 1 m and of windage at the sea surface. Different bar colors represent the litter from different sections, i.e. the Western Philippine Sea (the Luzon Strait), the southwestern South China Sea, the Gulf of Tonkin, and the Taiwan Strait. There is almost no macro ocean litter drifting from the southeastern South China Sea.

There was not a high correspondence between the observed source countries and the simulated origins of the macro ocean litter; thus, we suggest that litter may not only originate from the land but also from fishing, shipping and sightseeing vessels, a source that has not been commonly cited or seriously observed in the past. Additional discussion of this topic follows in the section on planning below. However, the modeled results still fairly decoded the seasonal patterns in some areas. For example, there were higher proportions of observed plastic bottles from Taiwan, Japan and Korean from October to May that also was predicted, i.e. litter from the Taiwan Strait section, especially when adding medium to high windage to the models. All assumed simulations, i.e. both including the current velocity at different depths and different levels of windage, showed summer accumulation patterns in the southwestern SCS, which may explain the observation of the motion of plastic bottles from Vietnam.

The gravity of the threat of litter to the oceanic environment has recently been recognized, and marine animals are seriously affected through entanglement in and ingestion of ocean litter (Laist 1987, Gregory 1991, Derraik 2002, Rochman *et al* 2013, Gall and Thompson 2015). Moreover, litter can affect ecosystem functions if its accumulation alters processes such as nutrient cycling, productivity, chemical mobility and decomposition or water flow or quality in oceanic environments (Duan *et al* 2014, Mincer *et al* 2016). Our multi-year observations revealed a large proportion of plastic litter items made of polyethylene with photodegradable but not biodegradable features. The issue that merits particular attention is that plastic fragments may persist in the environment for centuries, and the long-term effects of these synthetic materials on water and sediments are unknown and could pose a potential threat to ecosystems over the long term. Given the persistence of these materials in the environment, the production, distribution, and dispersal of plastic products should be limited and receive greater attention, even in the absence of additional knowledge of the aforementioned issues, to minimize potential future costs and impacts.

Additionally, and crucially, studies have noted that ocean litter patches coincide with 'ocean desert' regions mainly because of low nutrient levels (van Sebille 2015). Again, both theoretical calculations and simulations predict that litter floating in the ocean will roughly end up in the middle of the subtropical gyres, in areas as large as a few thousand kilometers in diameter (Lebreton *et al* 2012, Maximenko *et al* 2012, van Sebille *et al* 2012). However, the greatest risk to marine organisms occurs when litter is nearer to coastlines, where most marine organisms live, and the much higher quantities of nutrients and plankton outside the centers of the gyres support a complex food web. Overall, the impact of marine litter may exceed our expectations; therefore, the capacity and funding for research must be increased to assess the various ocean litter issues that have been identified.

Regional to global management action plans

The root cause of the presence of ocean litter and its associated impacts on the whole biosphere is the massive production of single-use items by humans. This crisis will likely remain a global environmental issue for several decades to come due to a lack of any international regulation and enforcement, especially in remote and low-population regions. Based on our results, neighboring countries greatly impact the oceanic environment of other countries; thus, regional to global management action plans are required for oceanic protection. Suggestions for accomplishing these goals follow.

1. The survey and analytical methods used in this study are time and cost efficient; thus, we suggest incorporating these techniques into existing environmental or wildlife monitoring programs. The benefits of quantifying and monitoring litter are substantial given the potential ecological, economic, and aesthetic costs associated with the accumulation of litter in these areas, especially in protected areas such as Dongsha Island. This points to the need to assess the threats imposed by ocean litter to wildlife species of conservation concern and to promote sufficient resources and better environmental management capacity to naturally restore degraded ecosystems.

2. Current maritime vessel management and specifications for the use of fishing gear are unlikely to be effective unless floating litter-driven alterations to oceanic environments and their profound ecological consequences are considered (Derraik 2002). The inconsistency between the observed and simulated origins of macro ocean litter in this study also implies complex effects of anthropogenic activities. When comparing the paths of vessels passing through waters around the study area based on the vessel monitoring system, strong associations were found between the vessels and the source countries of plastic bottles (data not shown). Therefore, we suggest that the litter onboard vessels should not be dumped at sea, as directed in the past, and should be instead collected, shipped back and processed onshore. Furthermore, encouraging the use of environmentally friendly fishing gear or plastics instead of Styrofoam and establishing recycling areas for fishing gear, fishing nets, and waste in fishing ports should be more broadly implemented as part of adaptive management for ocean conservation, e.g. via the establishment of management plans with pre-established increases in prohibition or restriction strategies or the automatic initiation of monitoring mechanisms for specific oceanic areas when certain litter-related indicators are observed.

3. The current absence of a regional to global, comprehensive, coordinated ocean litter monitoring system is a major obstacle to our understanding of the implications of ocean litter for natural oceanic systems. To better understand and adjust to the distributions of ocean litter, national information exchanges need to be strengthened, and the importance of cooperative oceanic environmental protection plans needs to be acknowledged and fulfilled through trajectory tracking. In addition, the litter disposal provisions for vessels must be strictly co-implemented (Derraik 2002). Further, international non-governmental organizations should be organized to implement inspections and analyses of ocean litter on beaches worldwide so that countries can consider such problems and increase the potential for clean-up funds, which may ameliorate the crisis.

4. Finally, raising public awareness and action to protect the ocean and strengthening the legal system to better regulate ocean litter management are of fundamental importance. Recent studies have stressed that, due to the impacts of ocean litter pollution, considering the litter properties of buoyancy and durability and the hazardous effects of the sorption of toxicants to plastic while it travels through the ocean ecosystem and limiting the use of disposable items as well as enhancing re-use behaviors could substantially reduce our dependence on those products and facilitate ocean litter mitigation measures (Thompson *et al* 2004, Rochman *et al* 2013, Mincer *et al* 2016).

Conclusions

By analyzing continuous and extensive field data and modeling the macro ocean litter load in the SCS, we showed that there is a tremendous quantity of macro ocean litter from the sea surface to a depth of 1 m, including items discarded from the land as well as sea vessels. Furthermore, the modeled results showed that the ocean litter was primarily from neighboring countries. Emphasizing the need to investigate processes that play a role in the dynamics of macro, meso and micro litter in the world's oceans and practically implementing the aforementioned management action plans at regional and global spatial scales are vital for improving and restoring the health and sustainability of the oceanic environment.

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ORCID iDs

Chia-Ying Ko https://orcid.org/0000-0002-2658-2999

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