Universidade Federal de Pernambuco
Centro de Tecnologia e Geociências
Departamento de Oceanografia
Programa de Pós-Graduação em Oceanografia

Contaminação ambiental por microplásticos em Fernando de Noronha, Abrolhos e Trindade

Juliana Assunção Ivar do Sul

Recife - PE

2014

Juliana Assunção Ivar do Sul

Contaminação ambiental por microplásticos em Fernando de Noronha, Abrolhos e Trindade

Tese apresentada ao programa de Pós-Graduação em Oceanografia como requisito parcial à obtenção do título de Doutora em Oceanografia. Área de concentração em Oceanografia Abiótica.

Orientadora: Dra. Monica F. Costa
Co-orientador: Dr. Gilberto Fillmann (IO-FURG)

Recife - PE
2014

Catalogação na fonte
Bibliotecária Maria Luiza de Moura Ferreira, CRB-4 / 1469

I93c Ivar do Sul, Juliana Assunção.
Contaminação ambiental por microplásticos em Fernando de Noronha, Abrolhos e Trindade / Juliana Assunção Ivar do Sul. - Recife: O Autor, 2014.
vi, 24 folhas + anexos; il., tabs.

Orientadora: Dra. Monica F. Costa.
Tese (Doutorado) – Universidade Federal de Pernambuco. CTG. Programa de Pós-Graduação em Oceanografia, 2014.

Inclui Referências.

1. Oceanografia. 2. Amazônia Azul. 3. Ilhas oceânicas brasileiras. 4. Lixo marinho. 5. *Pellets*. 6. Transporte por longa distância I. Costa, Monica F.. (Orientadora). II. Título.

551.46 CDD (22. ed.) UFPE/BCTG/2014-201

Juliana Assunção Ivar do Sul

Contaminação ambiental por microplásticos
em Fernando de Noronha, Abrolhos e Trindade

Tese aprovada em 16 de maio de 2014 pelo Programa de Pós-Graduação em Oceanografia como requisito parcial à obtenção do título de Doutora em Oceanografia.

Banca examinadora

____

Prof. Dra. Monica F. Costa (Orientador - UFPE)

____

Prof. Dr. Ruy José Válka Alves (Membro externo - UFRJ)

____

Prof. Dra. Vanessa Hadje (Membro externo - UFBA)

____

Prof. Dr. José Henrique Muelbert (Membro externo - FURG)

____

Prof. Dr. Moacyr Cunho de Araújo Filho (Membro interno- UFPE)

Existe uma mulher forte mas sensível,
decidida e serena,
experiente e inspiradora.
Esta mulher é minha mãe,
a quem dedico esta Tese e a minha vitória.

AGRADECIMENTOS

Ao CNPq pela concessão da bolsa de Doutorado e taxa de banca (Processo 551944/2010-2), que foram essenciais nestes 4 anos de doutoramento.

Ao CNPq, Secretaria da Comissão Interministerial para os Recursos do Mar (SECIRM) e Marinha do Brasil pelo apoio financeiro e logístico do Projeto "Contaminação ambiental por poluentes orgânicos persistentes, fragmentos plásticos e pellets ao redor da Ilha da Trindade" (557184/2009-6).

Ao Instituto Chico Mendes de Proteção à Biodiversidade (ICMBio) pelo apoio ao desenvolvimento deste projeto no Parque Nacional Marinho de Fernando de Noronha e no Parque Nacional Marinho dos Abrolhos. Á Fundação Pró-Tamar pela assintência fundamental nas coletas de plâncton em Noronha.

Ao Departamento de Oceanografia da UFPE, que me acolheu durante 8 anos, pelo apoio financeiro e logístico. Agradeço em especial aos Coordenadores do PPGO, secretários e funcionários que sempre estão disponíveis a nos ajudar. Aos colegas do doutorado, do mestrado e da graduação que enchem nosso departamento de alegria. Obrigada pela amizade e pelos momentos de descontração.

Agradeço ao LECEGE pelo opoio logístico, financeiro e intelectual durante os anos de doutorado.

Esta Tese é o resultado dos esforços de muitas pessoas, sem as quais não seria possível chegar à etapa tão esperada da defesa. Agradeço, em primeiro lugar, à minha orientadora Dra. Monica Costa, que me conduziu até aqui. Nunca estive sozinha nesta caminhada. Da nossa convivência de 8 anos eu levo ensinamentos que sempre nortearão minha vida pessoal e profissional. Meus sinceros e eternos agradecimentos.

Aos co-autores do artigo de Qualificação exigido pelo PPGO para a obteção deste título, Dr. Mário Barletta e Dr. Francisco Cysneiros.

Ao Dr. Gilberto Fillmann, meu primeiro orientador e que acompanha a minha caminhada há pelo menos 10 anos, agradeço pela co-autoria de 2 capítulos desta tese, e pelo apoio de todo seu laboratório (CONECO/FURG) durante o desenvolvimento do projeto em Trindade.

Agradecimentos especiais ao Oc. Luís Henrique B. Alves por ser um oceanógrafo tão dedicado e apaixonado pela profissão e à Oc. Raíra Tavares pelos ensinamentos trocados no LEGECE.

Durante os trabalhos de campo, sempre contei com o apoio irrestrito de pessoas que muitas vezes desconheciam o tema, mas encaravam as coletas com alegria e disposição. Sou imensamente grata por todos que me ajudaram, muitos que agora são amigos que levarei para toda a vida.

Em Trindade, o apoio da Marinha do Brasil (I Distrito Naval) foi essencial ao desenvolvimento deste trabalho. Agradeço ao CF Otoch, coordenador do PROTRINDADE/SECIRM, pelo carinho e dedicação, não só comigo, mas com a querida Ilha da Trindade. Agradeço a toda tripulação dos Navios NDD Rio de Janeiro, NDCC Almirante Saboía, Fragata Bosísio e NHi Sirius pelas travessias sempre alegres entre o Rio de Janeiro e a Ilha da Trindade. No POIT, foram pelo menos 150 dias de convivência com uma tripulação dedicada e unida da qual tenho muito orgulho em fazer parte. Agradecimentos especias aos tripulantes da cabritada de 2011/2012: CC Leonardo Amaral, CT Fernando, 1T Crespo; equipe Delta, “a equipe que Decide” (Sg. Anderson, Cb. Duarte, Cb. M-Silva, Cb. Conteiras); ao trilheiro mais experiente da ilha, Sg. Alberto; aos demais amigos, cada um na sua profissão, que fazem possível o dia-a- dia na ilha. Aos biólogos Lidiane Bahls e Fernando C. de Sales Junior, que me ajudaram nas coletas e se tornaram grandes amigos.

Em Noronha, agradecimentos a Admistração da Ilha, EcoNoronha e Parque Nacional Marinho de Fernando de Noronha pela liberação das taxas de permanência e visitação do ParNaMar. Em Noronha, tivemos apoio do amigo Joãozinho, que nos conduzou com segurança durante os arrastos de plâncton.

Em Abrolhos, agradeço ao II Distrito Naval (Marinha do Brasil) pela liberação da permanência na Ilha e os militares pela convivência no Arquipélago. Agradeço principalmente ao Edinho, dedicado guarda-parque, e à Dra. Keyla Travassos, pelo auxílio nas coletas de campo.

Aos membros da Associação de Pesquisadores em Início de Carreira para o Mar e os Pólos (APECS-Brasil), da qual faço parte desde 2010, por integrar com hamonia e eficiência Pesquisadores e Educadores em práticas constantes de divulgação da ciência no Brasil.

Ao Projeto Pinguins e Skuas (PROANTAR/UFRJ) pela oportunidade de colaborar com a preservação do ecossistema Antártico, em especial a Dra. Erli Costa, grande pesquisadora, inspiradora e amiga.

Aos meus companheiros Fabiano, Antonio e Larissa, por dividirem a mesma casa e as mesmas alegrias durante os anos de doutorado.

A minha grande amiga Júlia, que sempre tem uma palavra de incentivo, obrigada pela companhia em muitos momentos de diversão.

Finalmente, agradeço àqueles que me proporcionaram tudo isso, com uma vida alegre e saudável: meu pai, Sérgio Luiz e minha mãe Maria Eugênia, que vibravam a cada pequena vitória minha, e para quem os obstáculos nunca foram um problema. Me enchi de alegria ao meu pai comentar que “seria eu a primeira Doutora numa família de muitos médicos doutores...”.

À minha família, peço desculpas pelas muitas ausências. Agradeço à minha irmã Raquel, minhas primas, tios e tias por torcerem por mim mesmo depois de 12 anos longe da nossa convivência diária.

SUMÁRIO

RESUMO

Recentemente, a comunidade científica especializada vem concentrando seus esforços na identificação, caracterização e quantificação dos microplásticos, definidos pela literatura como partículas plásticas menores que 5 milímetros. Microplásticos então presentes na superfície dos oceanos, em praias arenosas e ambientes lamosos, desde o Equador até os Pólos, em praias urbanas e regiões remotas do globo, e ainda depositados em sedimentos profundos (>2.000m). Experimentos de laboratório indicam que estas partículas plásticas podem ser ingeridas por organismos de todos os níveis da teia trófica marinha. Poluentes orgânicos, como DDTs e PCBs, e inorgânicos presentes na água do mar podem estar adsorvidos a estes plásticos, transportando contaminantes químicos para diversas regiões do globo, ou sendo liberados quando no trato gastrointestinal de vertebrados e invertebrados se ingeridos, podendo ainda ser transportados ao longo da teia trófica marinha. Há mais de 10 anos relata-se que no Oceano Pacífico Norte microplásticos estão presentes principalmente no centro do giro subtropical, aparentemente influenciados por variáveis oceanográficas. Para o Oceano Atlântico tropical, evidências sobre a presença de microplásticos existiam apenas para as praias arenosas do Arquipélago de Fernando de Noronha (3°S, 32°W), e para as águas adjacentes ao Arquipélago de São Pedro e São Paulo. Para preencher esta lacuna, microplásticos foram o foco da amostragem em três importantes ambientes insulares no oeste do Oceano Atlântico tropical: Arquipélago de Fernando de Noronha, Arquipélago de Abrolhos (17°S, 38°W) e a Ilha da Trindade (20°S, 29°W) em 4 expedições científicas realizadas entre dezembro de 2011 e março de 2013. Plásticos flutuantes foram amostrados através de arrastos planctônicos (neuston) nas áreas marinhas adjacentes a estes ambientes. Um total de 160 arrastos foi realizado. Em Trindade, mais de 90% dos arrastos estavam contaminados por microplásticos, identificados como fragmentos duros, fragmentos moles, *paint chips,* linhas e fibras. Em Noronha e Abrolhos aproximadamente metade dos arrastos estava contaminada. Fragmentos plásticos duros foram os tipos de itens mais amostrados assim como em outros estudos de microplásticos em amostras de plâncton. Entre os fragmentos, >75% tinham 5mm ou menos. A contaminação média foi de 0,03 partículas por m³, inferior às quantidades previamente conhecidas no Oceano Pacífico. As amostras de microplásticos depositados na superfície do sedimento foram coletadas nas praias arenosas em cada uma das ilhas através de quadrantes. As amostras coletadas também foram analisadas quanto a granulometria predominante, já que estas informações ainda eram inexistentes para as ilhas estudadas. Em Abrolhos nenhuma partícula plástica foi amostrada. Fragmentos plásticos duros e esférulas plásticas foram identificados somente em Fernando de Noronha e Trindade, sendo que o lado mais exposto à ação de ventos e corrente superficias predominantes estava mais contaminado, quando comparado ao lado relativamente mais protegido nas ilhas estudadas. Estes resultados são os primeiros indícios da contaminação do oeste do Oceano Atlântico tropical em relação à contaminação por microplásticos. A presença destes microplásticos alerta para a vulnerabilidade destas ilhas e sua biota em relação á contaminação por plásticos.

Palavras-chave: Amazônia Azul, ilhas oceânicas brasileiras, lixo marinho, pellets, transporte por longa distância.

ABSTRACT

Recently, the scientific community is focussed on the identification, characterization e quantification of microplastics, defined in the literature as those plastic particles with less than 5 millimetres. Microplastics are widespread on the ocean's surface, on sand beaches and mud sediments, from the equator to the poles, on urban beaches and remote regions in the globe, and even deposited on deep sediments (>2,000m). Laboratory experiments indicate that organisms from every level of the marine food web potentially ingest microplastic particles. Organic, such as DDTs and PCBs, and inorganic pollutants available in seawater may adsorbed onto microplastics, transporting chemical contaminants to diverse regions in the globe, or being released in the gastrointestinal tract of vertebrates and invertebrates if ingested, when they are even transported along the marine food web. For more than 10 years, there were reports on the occurrence of microplastics in the North Pacific Ocean, mainly in the centre of the subtropical gyre, probably influenced by oceanographic variables. To the tropical Atlantic Ocean, however, evidences on the presence of microplastics were available only to sandy beaches in the Fernando de Noronha Archipelago (3°S, 32°W), and to waters around the São Pedro e São Paulo Archipelago. To fulfil this gap, microplastics were studied in three important insular environments in the western Atlantic Ocean: the Fernando de Noronha Archipelago, the Abrolhos Archipelago (17°S, 38°W) and the Trindade island (20°S, 29°W), during four scientific expeditions between December 2011 and March 2103. Floating plastics were collected by plankton tows (neuston) on the sea surface in the adjacent region to these environments. A total of 160 tows were conducted. In Trindade Island, more than 90% of the tows were contaminated with microplastics, identified as hard plastic fragments, soft fragments, paint chips, lines and fibres. In Fernando de Noronha and Abrolhos, approximately half of the tows were contaminated. Hard plastic fragments were the majority of the sampled items, as well as reported in other studies with plankton samples. Among plastic fragments, >75% had 5mm or less. The mean contamination pattern was 0.03 particles/m^3, less than previously reported on the Pacific Ocean. Microplastics sampled on sediments were collected on sandy beaches in each island by quadrants dispoded in the strandline. Samples were also analysed in the relation to the main grain size of sediments because these information was still non-existent to the studied islands. In Abrolhos, no plastic particle was sampled. Hard plastic fragments and plastic pellets were identified in Fernando de Noronha and Trindade, where the windward side of the islans were significantly more contaminated when compared to the leeward side. These results are the first results indicating the occurrence of microplastic debris particles in the Western tropical Atlantic Ocean. The occurrence of microplastics highlights the vulnerability of these islands and their biota in relation to microplastic pollution.

Keywords: Blue Amazon, Brazilian oceanic islands, marine debris, pellets, long-range transport.

INTRODUÇÃO

O termo plástico significa “maleável” ou “flexível”. As primeiras pesquisas que deram origem à descoberta dos plásticos que conhecemos atualmente datam de meados do Século XIX (Moore e Phillips 2010). Cem anos depois, impulsionada pelas crescentes necessidades de uma sociedade de consumo e pelos advindos da II Guerra Mundial, a já bem estabelecida indústria dos plásticos começa então a produzi-los em grandes quantidades. Até hoje novos materiais (polímeros) - que como os primeiros plásticos são obtidos do petróleo, gás natural e carvão - são descobertos e comercializados, alimentando uma indústria que produz mais de duzentas milhões de toneladas por ano. Entre os plásticos ou polímeros mais utilizados, e consequentemente, mais descartados pela sociedade moderna, estão o polietileno (PE) de alta e baixa densidades, polipropileno (PP), cloreto de polivinila (PVC), poliestireno (PS) e tereftalato de polietileno (PET) (Thompson et al. 2009). Juntos, eles representam cerca de 90% da produção global de plásticos (Andrady 2011). As possibilidades tecnológicas oferecidas pelos polímeros nunca foram tão grandes; nenhum material utilizado pela sociedade jamais foi tão flexível e moldável às nossas necessidades.

Duas das características que fazem do plástico um material tão útil à sociedade – seu baixo peso e durabilidade – também fazem com que os plásticos descartados de forma inapropriada causem danos significativos ao meio ambiente (Ryan et al. 2009). A presença de resíduos plásticos >5 mm, denominados macroplásticos, em ambientes marinhos e costeiros foi extensivamente documentada pela literatura científica especializada nos últimos 40 anos (Moore 2008), inclusive no litoral do Brasil (Ivar do Sul e Costa 2007, Santos et al. 2009, Ivar do Sul et al. 2011). Entre os danos mais visíveis à biota estão o enredamento, a ingestão e o possível transporte marinho de invertebrados incrustantes que se fixam à superfície dos plásticos (Moore 2008, Barnes et al. 2009).

Nos ambientes costeiros e marinhos, os macroplásticos começam a sofrer sucessivos processos de degradação, induzidos principalmente pela luz do sol (processos foto-oxidativos). Com sua estrutura molecular fragilizada, os plásticos começam então a se fragmentar em pedaços cada vez menores, em um processo lento mas significativo (Barnes et al. 2009, Costa et al. 2009, Ivar do Sul et al. 2009, Ivar do Sul e Costa 2014), que ocorre provavelmente até atingir o nível molecular, quando estes já se encontram descaracterizados em relação ao polímero inicial/precursor.

Recentemente (~5 anos) a comunidade científica especializada vem concentrando seus esforços na identificação, caracterização e quantificação, em escala global, de fragmentos plásticos de pequenas dimensões (<5 mm), denominados microplásticos (por exemplo, Browne et al. 2011). Algumas definições já foram amplamente aceitas por esta comunidade, destacando-se a classificação dos microplásticos pela sua fonte ou origem (Arthur et al. 2009). Esférulas de plástico virgens e outras partículas que chegam aos ambientes costeiros e marinhos por derramamentos acidentais durante o manuseio e transporte e/ou sistemas de drenagens de esgotos (Moore 2008, Fendal e Sewell 2009), já com forma e tamanho definidos, foram classificadas como primárias (fontes primárias). Já as partículas plásticas, formadas no ambiente por contínuos processos de degradação e fragmentação, foram classificadas como secundárias (fontes secundárias).

Dezenas de estudos confirmam a presença de microplásticos flutuantes nos Oceanos Pacífico Norte, Pacífico Sul, Mediterrâneo e Atlântico Norte (Cole et al. 2011, Ivar do Sul e Costa 2014). É possível que, por fatores oceanográficos, estes microplásticos se concentrem principalmente no centro dos giros subtropicais (Moore et al. 2001). Nos sedimentos de praias arenosas, microplásticos foram amostrados em pelo menos seis continentes. Aparentemente, regiões próximas às aglomerações urbanas apresentaram maiores concentrações, indicando a possível influência dos sistemas de drenagem de esgotos (Browne et al. 2011).

Os microplásticos são ainda mais pervasivos que os resíduos plásticos grandes quando estão no ambiente marinho, atingindo praticamente todos os níveis da teia trófica através de sua ingestão (Wright et al. 2013, Ivar do Sul e Costa 2014). Poluentes orgânicos, como DDTs e PCBs, e inorgânicos presentes na água do mar podem adsorver-se a estes microplásticos (Mato et al. 2001), transportando contaminantes químicos para diversas regiões do globo incluindo os polos (Zarfl e Matthies 2010), ou sendo liberados no trato gastrointestinal de vertebrados e invertebrados quando ingeridos (Tanaka et al. 2013), sendo então transferidos ao longo da teia trófica marinha.

No Brasil, estudos com resíduos plásticos em ambientes costeiros são realizados desde o final da década de 1990 (Ivar do Sul e Costa 2007). Porém, estudos sistemáticos relacionados à presença de microplásticos em praias arenosas começaram somente no final da década de 2000 (Ivar do Sul et al. 2009, Costa et al. 2009). Nestes estudos foi identificada, pela primeira vez, a presença de esférulas plásticas no Arquipélago de Fernando de Noronha, oeste do Oceano Atlântico tropical, e na Praia da Boa Viagem, um dos principais destinos turísticos do estado de Pernambuco, NE do Brasil. Registros de esférulas plásticas e fragmentos plásticos de pequenas dimensões em Fernando de Noronha são um indicativo de que micro partículas de plástico estariam não só depositadas em praias arenosas nesta ilha, mas distribuídas em todo oeste do Oceano Atlântico tropical, incluindo outros ambientes insulares inseridos no contexto da Amazônia Azul. Entretanto aspectos relacionados à poluição destes ambientes por microplásticos eram, até o momento, desconhecidos apesar de serem prioritários devido a sua grande importância ecológica e conservacional.

Seguindo as tendências da comunidade científica internacional para estudos sobre microplásticos em ambientes insulares e devido à ausência de estudos na Zona Econômica Exclusiva Brasileira, a principal hipótese desta tese de doutorado foi de que microplásticos pelágicos estão presentes na superfície do mar, em regiões adjacentes às ilhas oceânicas brasileiras, bem como depositados em suas praias arenosas. As amostragens foram concentradas em três importantes ambientes insulares: o Arquipélago de Fernando de Noronha (3°S, 32°W), o Arquipélago de Abrolhos (17°S, 38°W) e a Ilha da Trindade (20°S, 29°W). Plásticos flutuantes foram amostrados, pela primeira vez, através de arrastos planctônicos (neuston) nas áreas marinhas adjacentes a estes ambientes. As amostras de microplásticos depositados no sedimento foram coletadas nas praias arenosas em cada uma das ilhas, seguindo metodologia previamente estabelecida (Ivar do Sul et al. 2009).

Objetivo geral: identificar e caracterizar a poluição por microplásticos em Fernando de Noronha, Abrolhos e Trindade, oeste do Oceano Atlântico tropical.

Objetivos específicos:

- Identificar e caracterizar a poluição por microplásticos na superfície do mar adjacente aos Arquipélagos de Fernando de Noronha, Abrolhos e à Ilha da Trindade
- Identificar e caracterizar a poluição por microplásticos nas praias arenosas dos Arquipélagos de Fernando de Noronha, Abrolhos e da Ilha da Trindade

Durante todo o curso de Doutorado foi realizada uma extensa revisão da literatura científica sobre o tema, sendo acessados mais de centenas de artigos científicos, todos publicados em revistas indexadas com revisão por pares. Esta revisão representa o **Capítulo I** desta tese de Doutorado, intitulado "***The present and future of microplastic pollution in the marine environment***". De modo geral, estudos relacionados à poluição por microplásticos têm seu principal foco nos ambientes costeiros e oceânicos onde eles ocorrem, principalmente (1) na superfície do mar; (2) em sedimentos arenosos e lamosos; (3) na sua ingestão por organismos invertebrados e vertebrados; (4) nas interações com poluentes químicos e, consequentemente, no seu papel na dispersão destes dentro das teias tróficas e ao redor do globo. A cada dia novas evidências reiteram a onipresença das micropartículas plásticas e, até onde se sabe, não existem barreiras físicas ou biológicas para estes poluentes (Ivar do Sul e Costa 2014). Entretanto, muitas outras lacunas ainda precisam ser preenchidas no que se refere à poluição marinha por microplásticos (Cole et al. 2011, Ivar do Sul e Costa 2014). O **Capítulo I** deste documento começa na página 6, sendo numerado de acordo com a paginação da revista *Environmental Pollution* (ISSN: 0269-7491), onde encontra-se publicado. (*Environmental Pollution,* volume 185, páginas 352-364, 2014).

Um dos aspectos em evidência na literatura especializada consiste na utilização de amostra de plâncton já existentes para a caracterização da poluição por microplásticos, principalmente em áreas oceânicas onde o acesso é restrito e as amostragens são dispendiosas (Arthur et al. 2009). O uso destes "bancos de amostras" preexistentes já tinha sido realizado com sucesso em estudos de larga escala no oceano Atlântico Norte (Thompson et al. 2004; Law et al. 2010; Morét-Ferguson et al. 2010) e foi novamente utilizado nesta tese de Doutorado. Amostras de plâncton coletadas no Arquipélago de São Pedro e São Paulo (0°55'N, 29°20'W) foram reanalisadas para identificar e caracterizar a poluição por microplásticos neste arquipélago que é um dos mais remotos do Oceano Atlântico. Os resultados destes esforços representam o **Capítulo II** desta tese, intitulado "***Pelagic microplastics around an archipelago of the Equatorial Atlantic***". O uso de amostras preexistentes mostrou-se novamente eficiente na identificação de microplásticos, além de representar uma importante oportunidade para acertar os passos metodológicos para a coleta, manipulação e análise das amostras da tese. Este artigo foi apresentado e aprovado em agosto de 2012 como exame de Qualificação, um dos pré-requisitos para a obtenção do título de Doutor em Oceanografia. O **Capítulo II** deste documento começa na página 7, sendo numerado de acordo com a paginação da revista *Marine Pollution Bulletin* (ISSN: 0025-326X), onde encontra-se publicado (*Marine Pollution Bulletin*, volume 75, páginas 305-309, 2013).

A revisão da literatura (Ivar do Sul e Costa 2014) também guiou a composição dos demais capítulos desta tese de Doutorado e os assuntos encontram-se abordados na ordem histórica; primeiramente os resultados dos arrastos de plâncton, cujos registros datam do início da década de 1970 (por exemplo, Buchanan 1971, Carpenter e Smith 1972), seguidos pelos resultados da amostragem de sedimentos nas praias arenosas (por exemplo, Gregory 1977).

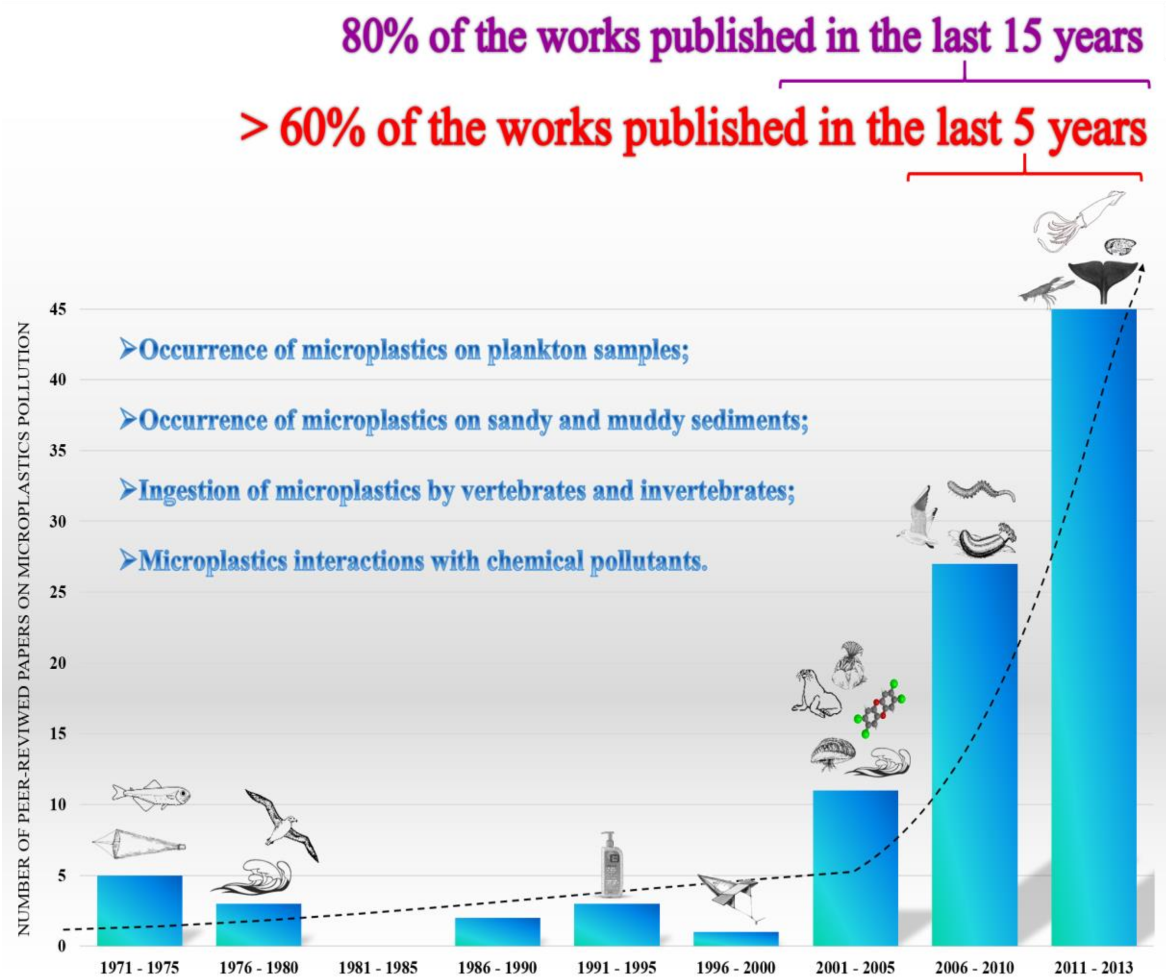
O **Capítulo III** apresenta os resultados dos arrastos de plâncton realizados na superfície do mar, em áreas adjacentes às ilhas estudadas, sob o título **"*Microplastics in the pelagic environment around oceanic islands of the Western Tropical Atlantic Ocean*".** Nos arrastos de plâncton, optou-se pela rede neustônica, que amostra os primeiros centímetros da coluna d'água, onde estão maioria dos plásticos flutuantes. A estrutura da rede foi inspirada em um modelo já existente e amplamente utilizado pela comunidade científica internacional, buscando-se garantir a melhor eficiência nas coletas. Este modelo foi inicialmente desenvolvido pelo Capitão Charles Moore, fundador da Fundação Algalita (Califórnia, EUA). Foram feitas algumas modificações para que a rede fosse desmontável, facilitando o manuseio e transporte entre as ilhas pesquisadas. Atualmente, novas tecnologias foram desenvolvidas e aplicadas às redes neustônicas, inclusive pelo Cap. Charles Moore, e encontram-se disponíveis no mercado. Adicionalmente, sabe-se que os plásticos podem estar também distribuídos ao longo da coluna d'água, sendo necessário o desenvolvimento de técnicas que permitam a amostragem em diferentes camadas de profundidade. Outra questão que vem sendo amplamente discutida pela comunidade internacional é a proporção relativa da poluição por plásticos em distintas categorias de tamanho, destacando-se os nanoplásticos (1000X menores que os microplásticos). A utilização de uma rede tipo bongo, com diferentes tamanhos de malha (ex. 200µm, 64µm) poderia contribuir para o esclarecimento desta questão. Estes novos resultados demandariam novos procedimentos de coleta e de laboratório para a identificação e manuseio dos microplásticos amostrados. Quanto menor o tamanho dos plásticos estudados, maior a necessidade de cuidados com a possível contaminação das amostras, tanto em campo (fragmentos da rede utilizada durante as coletas, por exemplo) quanto em laboratório, através do ar, das roupas e instrumentos de laboratório, durante os procedimentos analíticos. O **Capítulo III** deste documento começa na página 8, recebendo a numeração de acordo com a paginação da revista *Water, Air and Soil Pollution* (ISSN: 0049-6979), onde encontra-se publicado (*Water, Air and Soil Pollution*, volume 225, páginas 1-13, 2013).

O **Capítulo IV** apresenta os resultados da amostragem de sedimento nas praias arenosas de cada uma das ilhas estudadas, sob o título ***"Ocurrence and characteristics of microplastics on insular beaches in the western tropical Atlantic Ocean".*** Na amostragem do sedimento, a literatura apresenta diversos métodos de coleta e tratamentos de dados, havendo assim, a urgente necessidade de padronização destas metodologias. Em geral, a amostragem de quadrantes que foi utilizada neste estudo vem sendo empregada em praias arenosas na determinação da poluição por microplásticos em escala de mm (1-5mm). Nestas amostras, *pellets* e fragmentos plásticos são a maioria, sendo possível a presença de filamentos (µm) que não foram detectados. O **Capítulo IV** começa na página 9 e termina na página 20.

Todas as atividades de campo realizadas durante este estudo foram realizadas com licença ambiental concedida pelo SISBIO/ICMBio sob o registro N° 21934-1.

CAPÍTULO I

The present and future of microplastic pollution in the marine environment



Number of peer-reviewed articles on microplastic pollution published since the 1970s.

Research highlights:

- >100 works on microplastic marine pollution were reviewed and discussed;
- Microplastics (fibres, fragments, pellets) are widespread in oceans and sediments;
- Microplastics interact with POPs and contaminate the marine biota when ingested;
- The whole marine food web may be affected by microplastic biomagnification;
- Urgently needed integrated approaches are suggested to different stakeholders.

Environmental Pollution 185 (2014) 352–364

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Review

The present and future of microplastic pollution in the marine environment

Juliana A. Ivar do Sul*, Monica F. Costa

Laboratório de Gerenciamento de Ecossistemas Costeiros e Estuarinos, Departamento de Oceanografia, Universidade Federal de Pernambuco, CEP 50740-550 Recife, Brazil

ARTICLE INFO

Article history:
Received 31 July 2013
Received in revised form
28 October 2013
Accepted 30 October 2013

Keywords:
Marine debris
Risk to marine life
Priority pollutants
Coastal environments
POPs
Literature review

ABSTRACT

Recently, research examining the occurrence of microplastics in the marine environment has substantially increased. Field and laboratory work regularly provide new evidence on the fate of microplastic debris. This debris has been observed within every marine habitat. In this study, at least 101 peer-reviewed papers investigating microplastic pollution were critically analysed (Supplementary material). Microplastics are commonly studied in relation to (1) plankton samples, (2) sandy and muddy sediments, (3) vertebrate and invertebrate ingestion, and (4) chemical pollutant interactions. All of the marine organism groups are at an eminent risk of interacting with microplastics according to the available literature. Dozens of works on other relevant issues (i.e., polymer decay at sea, new sampling and laboratory methods, emerging sources, externalities) were also analysed and discussed. This paper provides the first in-depth exploration of the effects of microplastics on the marine environment and biota. The number of scientific publications will increase in response to present and projected plastic uses and discard patterns. Therefore, new themes and important approaches for future work are proposed.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

In 1972, E. J. Carpenter and K. L. Smith became the first researchers to sound the alarm on the presence of plastic pellets on the surface of the North Atlantic Ocean. In their publication in *Science*, they stated: "*The increasing production of plastic, combined with present waste-disposal practices, will probably lead to greater concentrations on the sea surface… At present, the only known biological effect of these particles is that they act as a surface for the growth of hydroids, diatoms, and probably bacteria*". Not surprisingly, only months later, the ingestion of those same polyethylene pellets by fish was reported (Carpenter et al., 1972). The prediction by Carpenter and Smith (1972) is the focus of the scientific community that is studying the smallest plastic debris pollution sizes (Moore, 2008; Barnes et al., 2009; Thompson et al., 2009; Ryan et al., 2009; Andrady, 2011). Several million tonnes of plastics have been produced since the middle of the last century (more than two hundred million tonnes annually) (Barnes et al., 2009; Thompson et al., 2009; Andrady, 2011). Speculation exists over how much of this plastic will end up in the ocean, where it suffers degradation and fragmentation (Barnes et al., 2009; Andrady, 2011). In the environment, microplastic debris (<5 mm) proliferates, migrates and accumulates in natural habitats from pole to pole and from the ocean surface to the seabed; the debris is also deposited on urban beaches and pristine sediments (Moore, 2008; Barnes et al., 2009; Thompson et al., 2009; Ryan et al., 2009). This type of pollution is ubiquitous and persistent in the world's oceans and openly threatens marine biota.

Plastic means "malleable" or "flexible". Indeed, these synthetic materials can be moulded into virtually any shape (Moore, 2008). Plastics are versatile materials that are inexpensive, lightweight, strong, durable and corrosion-resistant. They have high thermal and electrical insulation values (Thompson et al., 2009) and are incredibly practical. Plastics are formed by long chains of polymeric molecules that are created from organic and inorganic raw materials, such as carbon, silicon, hydrogen, oxygen and chloride; these materials are usually obtained from oil, coal and natural gas (Shah et al., 2008). Currently, the most widely used synthetic plastics are low- and high-density polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET). Altogether, these plastics represent ~90% of the total world production (Andrady and Neal, 2009). Thus, it is widely

* Corresponding author.
E-mail address: julianasul@gmail.com (J.A. Ivar do Sul).

0269-7491/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envpol.2013.10.036

accepted that the majority of the items polluting coastal and marine environments are comprised of these materials (Andrady, 2011; Engler, 2012).

Most synthetic polymers are buoyant in water (e.g., PE and PP). Consequently, substantial quantities of plastic debris that are buoyant enough to float in seawater are transported and eventually washed ashore (Thompson et al., 2009; Andrady, 2011; Engler, 2012). The polymers that are denser than seawater (e.g., PVC) tend to settle near the point where they entered the environment; however, they can still be transported by underlying currents (Engler, 2012). Additionally, microbial films rapidly develop on submerged plastics and change their physicochemical properties (i.e., surface hydrophobicity and buoyancy) (Lobelle and Cunliffe, 2011). If these fragments sink, then the seabed becomes the ultimate repository for the plastics (including those that were initially buoyant) (Barnes et al., 2009).

Polymers are rarely used as pure substances. Typically, resins are mixed with additives to enhance their performance (Andrady and Neal, 2009; Teuten et al., 2009). Considerable controversy exists over the extent to which additives that are released from plastic products (e.g., phthalates and bisphenol A) adversely affect animals and humans (Andrady and Neal, 2009; Thompson et al., 2009; Teuten et al., 2009; Lithner et al., 2009, 2011). More information is available from Thompson et al. (2009) and Cole et al. (2011), among others.

Additionally, the hydrophobic pollutants available in seawater may adsorb onto plastic debris in ordinary environmental conditions (Thompson et al., 2009; Cole et al., 2011). The majority of these pollutants are persistent, bioaccumulative and toxic; thus, they are of particular concern for human and environmental health (Engler, 2012). Plastics not only have the potential to transport contaminants, but they can also increase their environmental persistence (Teuten et al., 2009). This highlights the importance of plastic as vehicles of pollutants to marine biota and humans (Teuten et al., 2009; Tanaka et al., 2013).

Small plastics enter the environment directly, whereas larger items are continuously fragmenting (Barnes et al., 2009). Primary-sourced microplastics (Arthur et al., 2009) are directly released to the environment in the form of small (μm) pellets that are used as abrasives in industrial (shot blasting) (Gregory, 1996) and domestic applications (e.g., Fendall and Sewell, 2009); they can also be released by spilling virgin plastic pellets (mm) (Thompson et al., 2009). Facial cleansers that are used by millions of people, especially in developed countries, contain PS particles (μm) that directly enter sewage systems and adjacent coastal environments (Zitko and Hanlon, 1991; Gregory, 1996; Fendall and Sewell, 2009). Moreover, laboratory experiments using *Sphaeroma quoianun* indicated that isopods can produce millions of PS fragments, which resemble plastic pellets, when incrusted in buoys in the Pacific Ocean (Davidson, 2012).

Larger plastics eventually undergo some form of degradation and subsequent fragmentation, which leads to the formation of small pieces (Shah et al., 2008; Costa et al., 2010; Andrady, 2011). Degradation is a chemical change that reduces the average molecular weight of polymers (Andrady, 2011). The most-used polymer types (i.e., PE and PP) have high molecular weights and are non-biodegradable (Shah et al., 2008). However, once in the marine environment, they start to suffer photo-oxidative degradation by UV solar radiation, followed by thermal and/or chemical degradation. This renders plastics susceptible to further microbial action (i.e., biodegradation) (Shah et al., 2008; Andrady, 2011). The light-induced oxidation is orders of magnitude higher than other types of degradation (Andrady, 2011). Any significant extent of degradation inevitably weakens the plastic, and the material become brittle enough to fall apart into powdery fragments (Andrady, 2011) when subjected to sea motion. This process essentially occurs forever (Barnes et al., 2009), including on the molecular level (Andrady, 2011).

Reports of plastics have spread rapidly in terms of geography, marine habitat and biota influenced (Barnes et al., 2009; Ryan et al., 2009). It was hypothesised that microplastics accumulate in the centres of subtropical gyres, but their means of movement and transport in the sea are largely unknown (Hidalgo-Ruz et al., 2012), especially along the vertical axis. Environmental microplastics are available to every level of the food web, from primary producers (Oliveira et al., 2012) to higher trophic-level organisms (Wright et al., 2013). Individuals who ingest microplastics may suffer physical harm, such as internal abrasion and blockage. Impacts at the population-level are also possible, but largely unknown (Wright et al., 2013). Plastic pellets are also used as oviposition sites by insects, such as *Halobates micans* and *H. sericeus*, which can affect their abundance and dispersion (Majer et al., 2012; Goldstein et al., 2012). In the western Atlantic, 24% of the pellets ($N > 1000$) had eggs attached to their surface, most with viable embryos. In the North Pacific Ocean, the numbers of adults, juveniles and eggs (*H. sericeus*) were significantly correlated with microplastic abundance. Although it is still risky to conclude the magnitude of this problem (i.e., transport of fouling species), it is fair to consider plastics as potential vectors that transport species to previously unknown mobility levels (Barnes et al., 2009).

As predicted (e.g., Carpenter et al., 1972), microplastic pollution became widespread with significant implications for ecosystems and organisms in a variety of forms. Supporting evidence has been published in peer-reviewed journals from the 1971 benchmark paper by Buchanan (1971) to the present. In this context, the present work aims to sort, critically analyse, and synthesise the recent literature regarding microplastics at sea, as well as highlight the risks to and effects on the marine biota. The Arthur et al. (2009) definition of microplastics was adopted (fragments and primary-sourced plastics that are smaller than 5 mm) as the main criteria for discerning a specific size class of plastic pollution. A periodic critical assessment of this issue is essential, especially because the problem is mounting and will persist for centuries, even if pollution is immediately stopped (Barnes et al., 2009).

2. Results

Results from the scientific literature were classified according to the main focus of each work: (1) the presence of microplastics in plankton samples; (2) the presence of microplastics in sandy and muddy sediments; (3) the ingestion of microplastics by vertebrates and invertebrates; (4) microplastics' interactions with chemical pollutants (see the supplementary content in Tables S1, S2, S3, S4 and S5). Papers in each category were analysed for their most relevant findings to improve and advance discussions on microplastics at sea.

One hundred and one documents from various sources fulfilled the review criteria (Table 1). Two works were included in more than one category: Carpenter et al. (1972) and Thompson et al. (2004). Fourteen literature reviews, from 2008 to 2013, on microplastics in the marine environment were also consulted. Research related to the development of new sampling or laboratory methods and/or analytical procedures, the (bio)degradation of plastics and other relevant issues were used when appropriated. Approximately 80% of the articles were published in the last 15 years, and more than 60% of the articles were published in the last 5 years.

2.1. Plankton samples and floating microplastics

The notion of using surface plankton samples to diagnose pelagic areas in relation to the presence and amount of floating

Table 1
The main focuses of the publications, the number of reviewed papers and the peer-reviewed journal with the most publications in each category. [dotted box] = works deal with the ingestion of microplastics by marine biota. See the Supplementary content for details.

Main focus	Number of papers	Journal with the most contributions
Microplastics on plankton samples	25	*Marine Pollution Bulletin*
Microplastics in sediments	22	*Marine Pollution Bulletin*
Ingestion of microplastics by vertebrates	26	*Marine Pollution Bulletin*
Ingestion of microplastics by invertebrates	11	*Environmental Science and Technology*
Interactions of microplastics with pollutants	17	*Marine Pollution Bulletin*

plastics is well-established (Carpenter and Smith, 1972; Carpenter et al., 1972; Morris and Hamilton, 1974; Wilber, 1987; Ryan, 1988) (Table S1). While sampling the pelagic sargassum community in the early 1970s, Carpenter and his team observed high quantities of polystyrene plastic pellets (1–2 mm) on the sea surface of the western North Atlantic Ocean. Most pellets had hydroids and diatoms attached to their surfaces (Carpenter and Smith, 1972). Previously, the only evidence of synthetic microplastic fibres were reported in membrane-filtered water samples from the North Sea (Buchanan, 1971). Archived plankton samples from the North Atlantic Ocean, which are regularly obtained with a continuous plankton recorder (CPR) between Aberdeen and the Shetlands and from Sule Skerry to Iceland, also revealed the presence of microplastics in the 1960s (Thompson et al., 2004). Furthermore, these samples indicated a significant increase in the abundance of microplastics (mainly fibrous and 20 μm in length) during the 1960–1970s and 1980–1990s (Thompson et al., 2004).

In the western North Atlantic Ocean and Caribbean Sea, a wide-range ship-survey dataset (~6100 tows) also reported the quantities and characteristics of pelagic plastics (Law et al., 2010). Plastic fragments, 88% of which were smaller than 10 mm, were sampled between 22 and 38°N. This finding reflects the presence of a large-scale subtropical convergence zone. Chemical analysis revealed that 99% of the particles were less dense than seawater: high- and low-density PE, PP (Law et al., 2010) and plastic pellets. Using a subset of these samples (Law et al., 2010), Kukulka et al. (2012) developed a theoretical model that indicates that the plastics obtained from surface tows are dependent on wind speed (i.e., tows in high wind conditions tend to capture fewer plastic pieces) because plastics are vertically distributed in the mixed layer due to wind (Kukulka et al., 2012). Around the Saint Peter and Saint Paul archipelago in the equatorial Atlantic Ocean, plastic fragments ($N = 71$; ~85% smaller than 5 mm) were retained near the seamount, as well as reef fish and semi-terrestrial decapod larvae (Ivar do Sul et al., 2013). Despite its isolation, the archipelago is not free of autochthonous and allochthonous sources of plastics, which may be ingested by the biota.

In the North Atlantic Ocean (11–44°N, 55–71°W), more than 18,000 archived surface net tows were analysed, which allowed researchers to investigate the spatial and temporal trends (1991–2007), as well as the visual characteristics, of pelagic microplastics (Morét-Ferguson et al., 2010). Sixty per cent of the fragments were 2–6 mm. Apparently, the densities (g ml^{-1}) of the plastic pellets decreased, but the quantities of the fragments increased 18% over the time period (Morét-Ferguson et al., 2010). The microplastics were sampled significantly higher at 30°N, the subtropical convergence zone. Furthermore, neustonic samples collected in the Mediterranean Sea indicated that the closed basin is also threatened by microplastic pollution (Collignon et al., 2012). Ninety per cent ($N = 40$) of the samples contained plastics (0.3–5 mm), which were mostly fibres, PS fragments and films. The microplastic concentrations were 5 times higher before a strong wind event than after the event. Researchers suggested that wind stress might redistribute plastics in the upper layers of the water column and prevent them from being sampled by the surface tows (Collignon et al., 2012). Recently, the occurrence of suspended plastic pellets and fibres was reported in the Jade System of the southern North Sea. The pellets were associated with a paper recycling plant, whereas the fibres were most likely sewage-related (Dubaish and Liebezeit, 2013).

In the Pacific Ocean, plankton tows performed in the 1980s revealed high amounts of coloured microplastic fragments (Shaw and Day, 1994). The North Pacific Central Gyre (NPCG) was sampled for the first time at the turn of the XXIst Century (Moore et al., 2001). The surface tows collected plastic fragments, thin films and monofilament lines, the majority of which were smaller than 5 mm. A large plastic to plankton ratio was reported. However, the NPCG is not an area of high biological productivity, and the extrapolation of these findings to other oceanic areas is somewhat limited.

Surface plankton tows were carried out in southern California's coastal waters (Moore et al., 2002). Higher quantities of plastics (mainly small fragments) were sampled after a storm event, which resulted in a high plastic to plankton ratio (Moore et al., 2002). Plastics were also sampled throughout the water column (surface, middle and bottom) in Santa Monica Bay, California, before and after a storm (Lattin et al., 2004). Unexpectedly, the densities of the plastics were not the highest at the surface, but instead were the highest near the bottom. Higher amounts were sampled after a storm, especially close to the shore, which reflects the inputs from land-based runoff and re-suspended sediments (Lattin et al., 2004). In another study, microplastics were collected on the surface, rather than at subsurface layers, of the North Pacific Ocean (the Bering Sea and off the coast of southern California). The authors emphasise that microplastics (fragments, fishing lines/fibres and virgin plastic pellets) were concentrated near the surface due to their buoyancy in seawater (Doyle et al., 2011).

In the western Pacific Ocean, particularly in the Kuroshio Current (30–34°N, 133–139°W), plastic and PS fragments were identified in surface plankton tows (Yamashita and Tanimura, 2007). Seventy-two per cent of the sampled stations contained fragments, many of which measured ~3 mm. Plastic pellets represented <1% of the total sampled items. The surface microlayers (50–60 μm) and subsurface layers (1 m) around Singapore were also reported to be contaminated by PE, PP and PS microplastics (Ng and Obbard, 2006).

The Southern Hemisphere is likely contaminated by floating plastic debris, as predicted by a recent mathematical computational model (Maximenko et al., 2012). Based on these findings, Eriksen et al. (2013) conducted a specific surface survey in the South Pacific Subtropical Gyre (SPSG), where 96% of the samples revealed the presence of plastics. The majority of the plastics (88.8% of the total weight) were microplastic fragments (1–5 mm) that were collected between 97 and 111°W. The total amount of sampled plastics was lower than that in the NPCG (Moore et al., 2001), but both gyres contained similar sized fragments. A possible inverse relationship exists between plastic counts (or weight) and the sea conditions (Kukulka et al., 2012; Collignon et al., 2012).

2.2. Sandy and muddy sediments

Microplastics on sandy beaches were first reported in the form of plastic pellets in New Zealand, Canada, Bermuda and Lebanon (Gregory, 1977, 1978, 1983; Shiber, 1979) (Table S2). In New Zealand, the pellets were translucent, 2–5 mm in size and related to accidental spillages at the major ports (Gregory, 1977, 1978). These characteristics were also observed for PE pellets sampled on beaches in Canada, Bermuda and Lebanon. Many of the pellets showed deterioration due to weathering (Gregory, 1983). Plastic pellets have also been reported on beaches at the Gulf of Oman, the Arabian Gulf (Khordagui and Abu-Hilal, 1994) and the Maltese coast of the Central Mediterranean (Turner and Holmes, 2011). On the Arabian coast, large numbers of stranded pellets and the presence of entire bags indicated that a massive spill most likely occurred during shipping. Some of the PE pellets observed in the Mediterranean were embedded in tar. Recently, Fotopoulou and Karapanagioti (2012) investigated the superficial characteristics of plastic pellets; they revealed that the surfaces of virgin pellets are smooth and uniform, whereas the surfaces of stranded and eroded PS and PP pellets are rough and uneven. The PS pellets found in the environment had enlarged surface areas and were more polar, which indicates that they more efficiently interact with a variety chemical compounds compared with virgin pellets (Fotopoulou and Karapanagioti, 2012).

It seems that plastic resin pellets were already distributed worldwide in the 1970s (Hidalgo-Ruz et al., 2012). Nowadays, other types of microplastics are also reported globally (Browne et al., 2011). Microplastics are reportedly present on six continents, and higher amounts are commonly related to densely populated areas. In a study of the types (mostly fibres) and materials (frequently polyester and acrylic) of microplastics, Browne et al. (2011) suggested that the plastics were produced by sewage effluents, including wastewater from washing machines.

By analysing sediments from 18 beaches around the UK, Thompson et al. (2004) most often observed polymers in the form of fibres. Microplastics (<1 mm) were also present in sediment samples from the Tamar Estuary, UK (Browne et al., 2010). PVC, polyester and polyamide comprised ~80% of the total sampled fragments and were generally more common at downwind sites.

On the Belgium coast, the sediment from beaches, harbours and sub-littoral habitats were found to be contaminated with microplastics (38 μm–1 mm). In general, plastic fibres were more common than pellets, except in harbour areas (Claessens et al., 2011). The sediment cores from sandy beaches revealed that microplastic deposition tripled over the last 20 years (Claessens et al., 2011). In the North Sea, microplastics were quantified on beach and tidal flat habitats on the East Frisian Islands (Liebezeit and Dubaish, 2012). Pellets (<100 μm) and fibres were present, but plastic fragments and PS pellets were completely absent. The tidal flats were more contaminated, mostly by pellets, than the sandy beaches.

At the Lagoon of Venice, Italy (Vianello et al., 2013), 10 different polymers that measured 30–500 μm were successfully identified by μFT-IR (Harrison et al., 2012). PS and PP were prevalent. Spatially, microplastic particles tend to accumulate in low hydrodynamism sites (such as the inner lagoon) in a similar manner to fine sediment fractions (Vianello et al., 2013).

The presence of small-sized plastics on Hawaiian beaches is expected because the archipelago is located in the NPCG. All of the sediment samples from the islands were contaminated, primarily by plastic fragments (87%) but also by resin pellets (11%) (McDermid and McMullen, 2004). The strand line was significantly more contaminated when compared to the berm. The samples measured 2.8–5 mm; however, on remote beaches, such as Cargo Beach in the Midway Atoll, the majority of the sampled plastics were even smaller. Another heavily polluted beach in the Hawaiian Archipelago is Kamilo Beach, where plastic fragments mostly occur (95%) in the top 15 cm of the sediment cores (Carson et al., 2011). Artificial sediment cores were constructed, and they indicated that higher amounts of fragments increase the permeability of the sediment and change its maximum temperature, which causes the sediments to warm more slowly. This can affect the sex of temperature-determinant organisms, such as sea turtles (e.g., a reduction in the number of females) (Carson et al., 2011).

In the Pacific Ocean (Chile), a volunteer survey revealed that microplastic fragments (1–4.75 mm) occurred in 90% of the beach samples ($N = 39$), including those from Easter Island. There, higher abundances of smaller fragments were registered (Hidalgo-Ruz and Thiel, 2013).

Near the Sea of Japan (Kusui and Noda, 2003), plastic fragments and pellets were reported on Japanese beaches. However, plastic resin pellets were absent from Russian beaches. The presence of buried fragments indicates that surveys might underestimate the quantities of stranded microplastics on sandy beaches (Kusui and Noda, 2003). In the Indian Ocean, the presence of microplastics and other materials in coastal sediments were reported in India (Reddy et al., 2006) and Singapore (Ng and Obbard, 2006). Polyurethane, Nylon, PS and polyester were identified in inter-tidal environments on the western coast of India (Reddy et al., 2006). In Singapore, microplastics, mostly with secondary sources, were prevalent on tourist beaches (east coast) (Ng and Obbard, 2006) (Table S2).

In the western South Atlantic Ocean, plastic pellets have been present on the continental shores for many years (e.g., Ivar do Sul and Costa, 2007). The occurrence of plastic fragments was documented over the last three decades, but not systematically. The studies were usually related to macro categories of plastic debris. Currently, the research focuses on microplastic debris (Ivar do Sul et al., 2009; Costa et al., 2010; Fisner et al., 2013). Microplastics (mostly hard fragments) were reported on the beaches of Fernando de Noronha Archipelago (3°S, 32°W). Virgin plastic pellets have only been spotted on windward beaches, which highlights their oceanic origins. Microplastics pose a serious risk to the resident and migrant biota, especially endemic species (Ivar do Sul et al., 2009). At Boa Viagem Beach (8°S), an important tourist destination in the region, primary- and secondary-sourced microplastics were present (Costa et al., 2010). The authors emphasised that beach cleaning services cannot target this size category. Thus, the only abatement method is to reduce the amount of microplastics that enter the marine and coastal environments. New methods and techniques aimed at improving microplastic research and the standardisation of sampling protocols are continually being developed (e.g., Imhof et al., 2012; Claessens et al., 2011; Harrison et al., 2012).

2.3. Ingestion of microplastics

The ingestion of microplastics has been documented for vertebrate and invertebrate marine species (Tables S3 and S4). The interactions between microplastics and marine vertebrates were discovered and primarily reported from opportunistic sampling. However, for invertebrates, the research is somewhat restricted to controlled laboratory experiments (Table 2).

2.4. Vertebrates

The ingestion of microplastics by teleost fish was discovered many years ago (Carpenter et al., 1972; Hoss and Settle, 1990). In the early 1970s, Carpenter et al. (1972) reported the presence of plastics (<5 mm) in larvae and juvenile *Pseudopleuronects flounder* in the North Atlantic Ocean. Adults (*Morone america* and *Pronotus evolans*) were also found to ingest plastic pellets. Furthermore, controlled laboratory experiments were performed (Hoss and Settle, 1990) in which six different species of fish in early life stages were fed 100–500 μm pellets; all of the fish ingested the microplastics. These early works were the first to detect and report this level of interaction between microplastics and the marine biota.

Recently, concerns over the ingestion of microplastics emerged when synthetic fragments were found in the gastrointestinal content from 35% ($N = 670$) of the planktivorous fish in the NPCG (Boerger et al., 2010; Table S3). Quantitatively, the average number of plastic pieces ingested (1–2.79 mm) increased with the fish size. The colours of the plastics collected in the marine environment during sampling revealed similar percentages to those of the ingested plastics (Boerger et al., 2010). This similarity may indicate that there is no colour-based selectivity by lantern fish (Myctophidae) during feeding. Pelagic and demersal fish inhabiting the coastal waters around the UK were also found with synthetic and semi-synthetic plastics from sewage sources in their digestive tracts. Thirty-six percent ($N = 504$) mostly ingested fibres (68%) and microplastic fragments (Lusher et al., 2013).

In the North Pacific, mesopelagic fish (9%; $N = 141$), including Myctophidae, were also contaminated with microplastic fragments (~2.2 mm) and fibres (Davison and Asch, 2011). Lantern fish were also found with plastics in their stomach contents (~40%) at the Mariana Islands (Philippines Sea). Unlike the NPCG, the Marianna Islands are not a hotspot of microplastic debris, which illustrates the magnitude of the problem (Van Noord, 2013).

It is well-established that estuarine environments around the world are affected by microplastic pollution (Browne et al., 2011), and their resident fish are at risk of interacting with this pollutant. In a small estuary in the western South Atlantic Ocean, catfishes (Ariidae), estuarine drums (Sciaenidae) and mojarras (Gerreidae) have been reported to have synthetic polymers in their digestive tracts (Possatto et al., 2011; Dantas et al., 2012; Ramos et al., 2012; Table S3). All of the studied species are benthophagous, which feed on or just below the sediment surface. These species most frequently ingest blue nylon threads. For catfishes ($N = 182$), the ingestion of plastic debris appeared to vary according to the ontogenetic phase (except for *Cathorops agassizii*) (Possatto et al., 2011). Approximately 8% ($N = 569$) of the estuarine drums (adults) ingested plastic threads during the late rainy season and in the middle estuary, when higher water fluxes and intense fishery activities occurred (Dantas et al., 2012). Among mojarras, 13.4% ($N = 425$) were contaminated with synthetic threads. The sources of microplastics are related to the ingestion of contaminated prey (e.g., polychaetes), the ingestion of threads during normal suction feeding, and the active ingestion of plastics with biofilm. The possible transference of the plastics to the species predators at higher trophic-levels in the estuarine and coastal food webs was highlighted (Ramos et al., 2012).

Table 2
The main differences in the ingestion of microplastics between vertebrate and invertebrate marine species based on the retrieved literature ($N = 37$ works). See the Supplementary content for details.

Group	Type of study	Number of organisms examined	Plastic size range
Vertebrates	Field campaigns	Dozens to hundreds	~1 mm to several cm
Invertebrates	Controlled laboratory experiments	Units to dozens	Few μm to few mm

Seabirds have long been known to interact with marine plastic pollution and have been used to monitor the quantities and composition of plastic ingestion for at least four decades (e.g., Day et al., 1984; Fry et al., 1987; Van Franeker and Bell, 1988; Barnes et al., 2009; Colabuono et al., 2009, 2010). The majority of the ingested fragments were identified by the naked eye, and macroplastics (>5 mm) and microplastics are commonly reported together. Plastic pellets were identified in migratory petrels, shearwaters and prions in the 1980s and 2000s in the Atlantic and south-western Indian oceans (Ryan, 2008). Surprisingly, the proportion of pellets decreased significantly in all five species that were investigated over the last 20 years. However, because the total loads of ingested plastics did not vary significantly between decades, the author attributed this change to the enhancement of secondary-sourced plastics (i.e., fragments) (Ryan, 2008).

Plastic fragments and pellets were identified in two *Fulmarus glacialis* colonies in the Canadian Arctic. More than 80% of the fulmars ingested fragments (Provencher et al., 2009). This species was monitored in several regions in the North Sea and the Netherlands for at least three decades (Table S3). As previously observed by Ryan (2008), the industrial plastic pellets found in stomachs decreased by half over 20 years, but the plastic fragments tripled (Van Franeker et al., 2011). An important finding is that juveniles ate more plastics than adults (Kühn and van Franeker, 2012) and that higher quantities of ingested plastics were reported near highly industrialised areas directly related to fishing and shipping (Van Franeker et al., 2011). Further north in Iceland, *Fulmarus glacialis* were contaminated (Kühn and van Franeker, 2012). Fragmented plastics were much more common than virgin plastic pellets, which illustrates the wide-ranging distribution of these pollutants (Kühn and van Franeker, 2012). However, the percentage of contaminated birds (79%, $N = 58$) was low compared to that of birds inhabiting lower latitudes, most likely because more fragments are available. This hypothesis was previously suggested by Provencher et al. (2010) when they were studying *Uria lomvia* in Nunavut, Canada. There, 11% ($N = 186$) of the murres ingested plastic fragments, some of which were too small to be identified by the naked eye. The authors emphasised that because murres feed below the sea surface, they are not likely to ingest floating plastics. Nonetheless, the magnitude of plastic pollution in the marine environment is still a concern (Provencher et al., 2010). Fulmars throughout the eastern North Pacific Ocean are also highly susceptible to plastics (Avery-Gomm et al., 2012). More than 90% of samples were found to be contaminated by microplastics, mostly fragments.

At the Canary Islands, eastern North Atlantic Ocean, fledgling cory shearwaters (*Calonectris diomedea*) contained plastics (83.5%, $N = 85$) in their guts. Because these chicks never feed in the marine environment, the plastics were certainly regurgitated during parental feeding (Rodríguez et al., 2012). Ingested items (nylon threads) were directly related to commercial fishery activities because the Canary Islands are one of the most important fishery grounds in the world. Along the United States east coast, boluses ($N = 589$) from *Larus glaucescens* were collected from an environmentally protected area to study plastics consumption. Twelve per cent of the boluses were identified as contaminated, mostly by films (<1 cm) derived from supermarket plastic bags (Lindborg et al., 2012). In the North Pacific Ocean, albatrosses obtained as by-catch from fisheries near the Hawaiian Islands were also contaminated. *Phoebastria immutabilis* ($N = 18$; 83.3%) had a higher frequency of ingested plastic than *P. nigripes* ($N = 29$; 52%). Ordinary plastic fragments and fishing lines comprised the majority of the ingested items (Gray et al., 2012). Twenty seabirds and other aquatic bird species that were sampled between British Columbia, Canada, and Washington contained low contamination rates. Among the common murres, for example, only 2.7% were found with ingested plastics. However, many species had small samples, so definitive conclusions could not be drawn (Avery-Gomm et al., 2013).

The transference of organic pollutants adsorbed onto marine plastic fragments to vertebrates via ingestion was detected with *Calonectris leucomelas* and *Puffinus tenuirostris* (Teuten et al., 2009; Tanaka et al., 2013). Streaked shearwater chicks were fed with pellets that were contaminated by significant amounts of PCBs. After 7 days, the identification of lower chlorinated congeners of PCBs, which can be regarded as a sensitive tracer to detect the contribution from plastic-derived PCBs, verified the transference of this contaminant from ingested plastics to the biological tissues of the seabirds (Teuten et al., 2009). Similarly, Tanaka et al. (2013) measured the concentrations of PBDEs from ingested plastic fragments in the natural prey of birds (fish) and in their adipose tissues. Two PBDEs congeners were not found in their prey, but were adsorbed onto the plastics, which indicate the transfer of plastic-derived chemicals to the seabird (Tanaka et al., 2013).

For marine mammals, research related to the ingestion of microplastics is restricted. By analysing fur seal (*Arctocephalus tropicalis* and *A. gazella*) scats collected on Macquaire Island, Eriksson and Burton (2003) identified pellet and plastic fragment (2–5 mm) contamination. The authors related the ingested plastics to the animal's prey, *Electrona subaspera*, which had previously ingested plastics from seawater (Eriksson and Burton, 2003). Recently, scats collected from *Phoca vitulina* in The Netherlands did not contain microplastics. However, 107 stomachs and 100 intestines that were analysed were contaminated (11% and 1%, respectively), mostly by sheets and threads (Rebolledo et al., 2013). To our knowledge, only a single study investigated the impacts of microplastics on cetaceans (Fossi et al., 2012). The authors suggested that fin whales (*Balaenoptera physalus*) ingest microplastics because of the concentration of phthalates in their blubber, which are linked to the pollutants measured on marine microplastics sampled in the same area of the Mediterranean Sea where the whales live and feed (Fossi et al., 2012) (Table S3).

2.5. Invertebrates

After identifying plastics in plankton samples and sedimentary habitats, Thompson et al. (2004) investigated whether invertebrates ingest microplastics in the environment. The authors observed that amphipods (*Orchestia gammarellus*), lugworms (*Arenicola marina*) and barnacles (*Semibalanus balanoides*) ingested microplastics within a few days of exposure. This was the first of a series of works on the ingestion of microplastics by marine invertebrates (mainly molluscs, crustaceans, annelids and echinoderms) using controlled laboratory experiments (Table 2).

Among the well-established model organisms, *Mytilus edulis* is the most commonly studied in terms of microplastic ingestion (Table S4). These mussels ingested and accumulated microplastics (<1 mm) within 12 h of the experiment start time (Browne et al., 2008). High quantities of microplastics (mostly <3 μm) were found in the hemolymph until the 12th day. Recently, the presence of HDPE (≤80 μm) in gills and inside the digestive system of *M. edulis* was also investigated (von Moos et al., 2012). The authors observed microplastics in the gills, that were trapped directly from the water column. Microplastics were also in the intestines, which suggests that particles were ingested via ciliar movements and then transferred to this organ (von Moos et al., 2012). Moreover, mussels ingested even smaller (30 nm) fragments. The experiment results indicated that nanoplastics were also ingested by *M. edulis,* which triggered the production of pseudofeces and reduced their filtering activities (Wegner et al., 2012). The authors emphasised the risks to humans when eating blue mussels. In fact, the transference of microplastics from *M. edulis* to higher trophic levels (*Carcinus maenas*) has already been registered (Farrell and Nelson, 2012). Microplastics can even translocate to the hemolymph and tissues of the crabs. Therefore, the implications are evident for the rest of the food web (Farrell and Nelson, 2012), including for humans (Wegner et al., 2012). Braid et al. (2012) opportunistically found another mollusc, a cephalopod, which has ingested microplastics. Humboldt squids (*Dosidicus gigas*), observed during a mass stranding, ingested pellets and fishing lines (26%; $N = 30$). This exemplifies the growing concern over the accumulation of plastics in the marine environment (Braid et al., 2012).

Another animal group that has been studied in terms of microplastic ingestion is Holothuria (Graham and Thompson, 2009). Deposit-feeding and suspension-feeding sea cucumbers selectively ingest nylon and PVC fragments (0.25–15 mm) over sediment grains. Because plastics concomitantly collected in the study area (USA) were contaminated with organic pollutants, the ingestion of plastics could initiate a new pathway of PCB exposure and cycling within the marine communities (Graham and Thompson, 2009), which could possibly reach human populations.

Studies concerning microplastic ingestion by benthic crustaceans are limited (Thompson et al., 2004; Murray and Cowie, 2011; Ugolini et al., 2013). In the Clyde Sea, eighty-three per cent of the sampled lobsters ($N = 120$) contained microplastics, mainly filaments in the form of balls, in their stomachs (Murray and Cowie, 2011). A visual analysis revealed that the material of these balls is the same (PP) found on the ropes used by the fishing industry for catching *Nephrops*. In the laboratory, lobsters also ingested plastic seeds in the first 24 h after exposure (Murray and Cowie, 2011). *Talitrus saltator* was found to ingest PE and PP microplastics on sandy shores in Pisa (Italy). In the laboratory, experiments confirmed they are able to ingest microplastics when feeding and expel the plastic within one week (Ugolini et al., 2013).

Thirteen zooplankton taxa, mainly crustaceans (Copepoda, Euphausiacea and Decapoda) and Tunicata, Cnidaria and Mollusca, ingested microplastics (1.7–30.6 μm) under laboratory conditions (Cole et al., 2013). Among copepods, the presence of microplastics significantly reduced feeding, which illustrates the negative impacts of microplastics on zooplankton communities (Cole et al., 2013).

Information concerning the uptake of microplastics and its implications for polychaetes also exist (Thompson et al., 2004). In a laboratory experiment, *Arenicola marina* ingested PS microplastics (400–1300 μm); the authors established a positive relationship between the microplastic concentration in the sediment and the ingestion of plastics and the weight loss by the lugworm (Besseling et al., 2013). Feeding activity was also reduced. Despite these physical impacts, the microplastics did not accumulate in their digestive tracts during the experiment (28 days). The ingestion of PS (small doses) by *A. marina* was associated with higher concentrations of PCBs in their tissues (Besseling et al., 2013).

2.6. Adsorption of pollutants onto microplastic particles

PP resin pellets collected along the Japanese coast were enriched with polychlorinated biphenyls (PCBs), organochlorines (DDE) and nonylphenols (NP) absorbed from seawater (Mato et al., 2001; Ogata et al., 2009) (Table S5). The concentrations were comparable to those found in suspended particles and bottom sediments collected in the same area. Plastic additives and/or their degradation products were most likely the major source of NP (Mato et al., 2001). Individual analysis of PCBs revealed that concentrations are highly variable among individual pellets and locations along the Japanese coast (Endo et al., 2005; Ogata et al., 2009). Additionally, discoloured (weathered) pellets generally exhibited higher concentration of PCBs than coloured pellets.

Near Lisbon, along the Portuguese coast, black, white, coloured and aged pellets were analysed separately for PCBs, polycyclic aromatic hydrocarbons (PAHs) and DDTs (Frias et al., 2010). The black pellets exhibited higher concentrations of PCBs than aged pellets, possibly because they have higher adsorption rates (Frias et al., 2010). Latitudinal surveys revealed that organic chemical pollutants were present along the entire Portuguese coastline (Ogata et al., 2009; Mizukawa et al., 2013). The concentrations of PCBs adsorbed onto the pellets were one order of magnitude higher around the major cities of Porto and Lisbon and were directly related to industrial and urban discharges. In less-developed cities, PCBs are most likely airborne from industrialised areas (Mizukawa et al., 2013). Similarly, beaches in the Saronikos Gulf near Athens had higher contamination levels (Karapanagioti et al., 2011) than other beaches around the world (e.g., Ogata et al., 2009). Organic compounds and metals accumulate on PE plastic pellets in the coastal and marine environments (Ashton et al., 2010).

Microplastics and associated pollutants were investigated in the South Atlantic Ocean (Ogata et al., 2009). On South African beaches, long-term surveys of PE pellets indicated that the mean average concentrations of all of the persistent organic pollutants (POPs) decreased from the 1980s to 2000s (Ryan et al., 2012). The concentrations of these contaminants likely decreased in the South African coastal waters as well. In the western Atlantic Ocean, plastic pellets were systematically sampled as deep as 1 m in the sediment of a sandy beach at Santos Bay, which is a long-term and densely industrialised region (Fisner et al., 2013). Higher concentrations of $\sum$-total PAHs were found in the surface layer (0–10 cm), whereas $\sum$-priority PAHs were found in higher concentrations in the 60–70 cm layer. Petrogenic and pyrolytic sources were introduced to the area (Fisner et al., 2013).

Laboratory experiments tested the kinetic distribution of plastic pellets from different materials (PP, PE, polyoxymethylene (POM) and eroded pellets) (Karapanagioti and Klontza, 2008). Phenanthrene adsorption occurs through diffusion onto the plastic pellets for all materials, except for PP. For this material, diffusion is most likely dependent on salinity (more so than for the other materials). For eroded pellets, the distribution coefficient ($Kd_{FW} = 1400$ L kg^{-1}) is higher due to the weathering in the environment, and diffusion occurs more slowly (Karapanagioti and Klontza, 2008).

Near the NPCG and California coast, the presence of PCBs, PAHs from combusted fossil fuels, and DDTs from pesticides was reported in plastic pellets and microplastic fragments (80–90% PP) (Rios et al., 2007). Recently, plankton samples from the same area indicated that PP fragments were still contaminated by organic pollutants. Several samples exhibited high concentration levels (similar to those from marine sediments), which demonstrates that plastics actually adsorb and accumulate pollutants once in the marine environment (Rios et al., 2010).

Using a thermodynamic approach, Gouin et al. (2011) suggested that hydrophobic organic chemicals will adsorb onto PE plastics if the plastics are available in large quantities and the natural organic matter is limited. In addition, the transport of microplastics may enhance the mobility of the hydrophobic compounds that have limited transport potential (Gouin et al., 2011).

To assess the relationships between mass-produced plastic polymers and organic contaminants, Rochman et al. (2013) carried out a controlled experiment that exposed PE, PP, PET and PVC fragments over a 12-month period to environmental concentrations of PCBs and PAHs at San Diego Bay, California, where POPs were already known to contaminate beached plastic debris (Van et al., 2012). The concentrations of PAHs and PCBs that adsorbed onto HDPE, LDPE, and PP were consistently greater than those adsorbed onto PET and PVC fragments (Rochman et al., 2013). The authors suggested that products made from HDPE, LDPE, and PP pose a greater risk to marine animals than those products made from PET and PVC if the fragments are ingested.

The possible differences amongst the most often used and released types of plastics (i.e., PE, PP, PVC) have been tested in sedimentary habitats. PE, which has larger volumes of the internal cavities, adsorbed more phenanthrene than PP and PVC (Teuten et al., 2007). Again, the authors suggested that microplastics would increase the accumulation of PAHs when ingested by lugworms (*A. marina*). However, in the environment, chemical compounds normally occur as mixtures, not single solute systems (Bakir et al., 2012). In the laboratory, in a bi-solute system with phenanthrene and 4,4′-DDT, the DDT did not exhibit significantly different sorption behaviour (using PE and PVC 200–250 μm) than single solute systems. However, the DDT did appear to interfere with the sorption of phenanthrene onto plastics, which indicates an antagonistic effect (Bakir et al., 2012) (Table S5).

3. Discussion

It is well-established that plastics will fragment in the marine environment and form micro and nano pieces (Andrady, 2011); however, no long-term studies have been undertaken to estimate the actual residence time of these fragments (Roy et al., 2011; Hidalgo-Ruz et al., 2012). Moreover, if these fragments are not completely mineralised (i.e., biodegraded) within relatively short periods of time, their potential harmful effects must be addressed (Figs. 1 and 2) (Roy et al., 2011). Scientific evidence of the fate and consequences of microplastics rapidly emerged in the literature, although crucial investigations remain uncompleted or overlooked (Fig. 3).

Microplastics have a larger surface area to volume ratio than macroplastics and are more susceptible to contamination by a number of airborne pollutants (i.e., manufactured POPs and to some extent, metals) (Table S5). Because plastics are made of highly hydrophobic materials, the chemical pollutants are concentrated in and/or onto their surfaces, and microplastics act as reservoirs of toxic chemicals in the environment. Plastic pellets have been successfully studied to assess the worldwide quantities of POPs in a platform called the “International Pellet Watch” (e.g., Ogata et al., 2009). With these data, it was possible to identify geographical ‘hotspots’ (Table S5). More importantly, scientists can continuously and systematically monitor contaminated pellets and determine the temporal patterns of various pollutants, which effectively aids decision-makers (Fig. 3). Recently, laboratory studies showed that weathering significantly changes the superficial characteristics of virgin plastic pellets. Additionally, coloured plastics and different types of polymers (i.e., PP and PE) may adsorb POPs from the

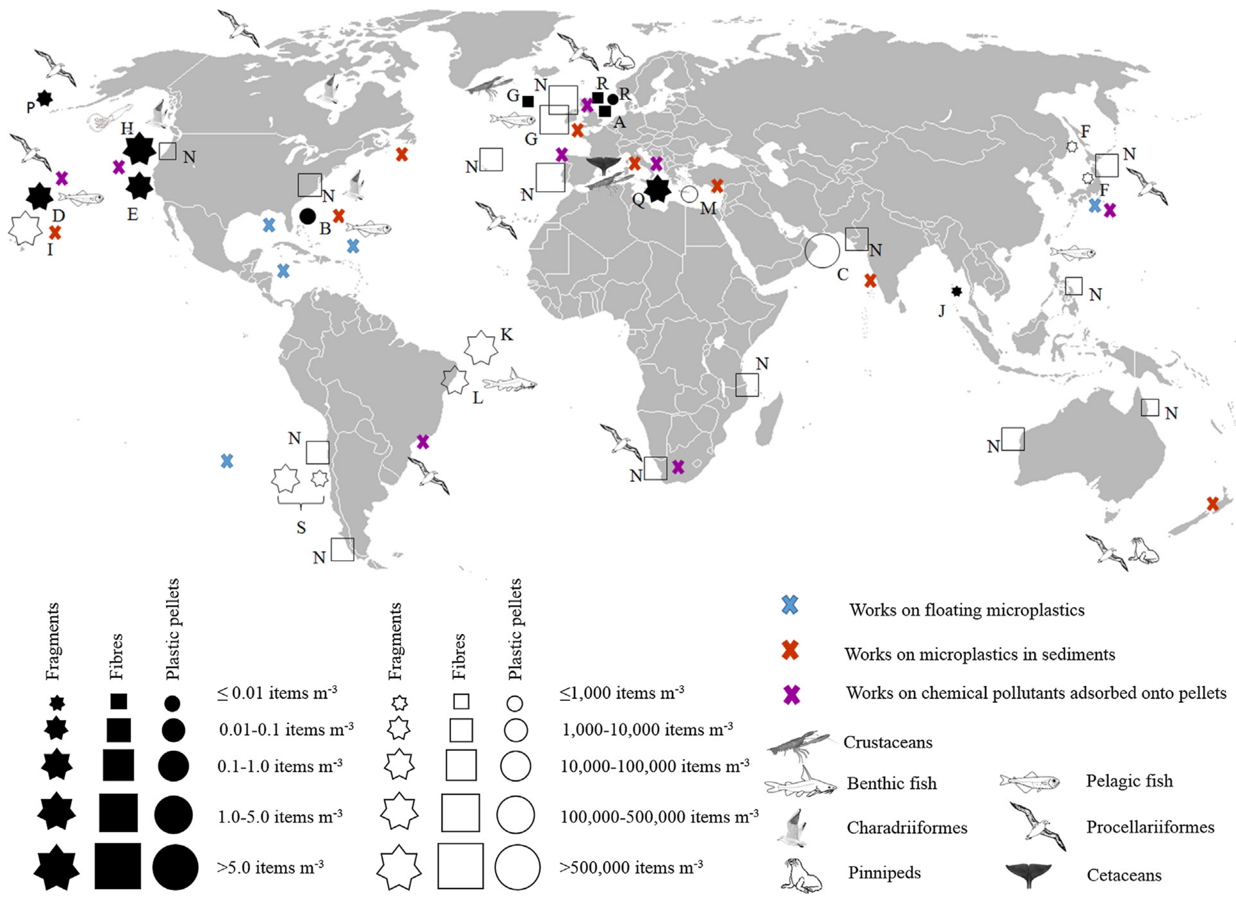


Fig. 1. Reports on the amount and occurrence of microplastics in the marine environment and their interactions with the marine biota in the wild. Stars, squares and circles represent the average number of items per cubic meter of seawater (black symbols) or sediment (open symbols) observed and/or estimated. (A) Buchanan, 1971; (B) Carpenter et al., 1972; (C) Khordagui and Abu-Hilal, 1994; (D) Moore et al., 2001; (E) Moore et al., 2002; (F) Kusui and Noda, 2003; (G) Thompson et al., 2004; (H) Lattin et al., 2004; (I) McDermid and McMullen, 2004; (J) Ng and Obbard, 2006; (K) Ivar do Sul et al., 2009; (L) Costa et al., 2010; (M) Turner and Holmes, 2011; (N) Browne et al., 2011; (P) Doyle et al., 2011; (Q) Collignon et al., 2012; (R) Dubaish and Liebezeit, 2013; (S) Hidalgo-Ruz and Thiel, 2013. The crosses represent works that registered microplastics outside of the scale used here.

environment differently. These findings must be considered and validated in future work and monitoring projects (e.g., Frias et al., 2010), including in the assessment of microplastic fragments (Hirai et al., 2011).

Microplastics transport pollutants over large oceanic areas (Zarfl and Matthies, 2010) and contaminate the marine biota when ingested (Teuten et al., 2007, 2009; Tanaka et al., 2013). By eating the contaminated microplastics, individuals are susceptible to physical damage and to doses of pollutants that were not previously accessible in other tangible matrices, such as seawater and sediments. Organisms at every level of the marine food web ingest microplastics (Fig. 2), but those inhabiting industrialised areas are exposed to higher amounts and may be more contaminated. However, the speculated quantities ($\mu g\ g^{-1}$; $ng\ g^{-1}$) of contaminants vary significantly among fragments within the same area; consequently, the toxicity of pollutants and incorporation into bodily tissues varies for each biological species. Some groups (e.g., holothurians) apparently ingest microplastics with specific colours and shapes; if those polymers adsorb higher quantities of pollutants, the consequences are most likely greater. Therefore, population level effects, including the mechanisms to explain the transference of ingested plastics and their adsorbed contaminants along marine food webs, are merely speculative. Primary producers are known to incorporate microplastics and organic pollutants (Oliveira et al., 2012); therefore, bioaccumulation to top predators, including larger species (Mysticetidae) (Fossi et al., 2012), or among primary and secondary consumers may occur (Eriksson and Burton, 2003; Farrell and Nelson, 2012) (Fig. 2).

Potentially, microplastics with low and high densities are ingested when present in the marine environment (Fig. 2) and tend to float on the sea surface. There, they are available to a wide range of organisms that may ingest microplastics passively or actively. Until recently, only hypotheses and weak evidence for the ingestion process were available (e.g., Day et al., 1984; Boerger et al., 2010; Ramos et al., 2012). If the polymer is denser than the seawater or becomes covered by biological films, then it tends to sink (eventually reaching the seabed) or becomes neutrally buoyant (e.g., Lattin et al., 2004).

Higher amounts of buoyant microplastics were reported in the North Pacific Ocean, particularly the NPCG, than in other ocean basins (Fig. 1). This region is currently referred to as the “eastern garbage path” (Moore et al., 2001, 2002; Lattin et al., 2004; Rios et al., 2010). Microplastics were mainly related to fishing activities (oceanic sources) in the gyre, but on the coast, they were related to continental discharges at highly industrialised low latitudes. In the North Atlantic Ocean, contamination patterns at the sea surface are generally two orders of magnitude lower than in the NPCG (Fig. 1). Fibres were prevalent in the North Sea, whereas hard plastic fragments were more common in the Caribbean Sea; however, the sampling methods varied between the locations (Table S1). The corresponding subtropical gyres in the Southern Hemisphere were less contaminated, most likely because there are

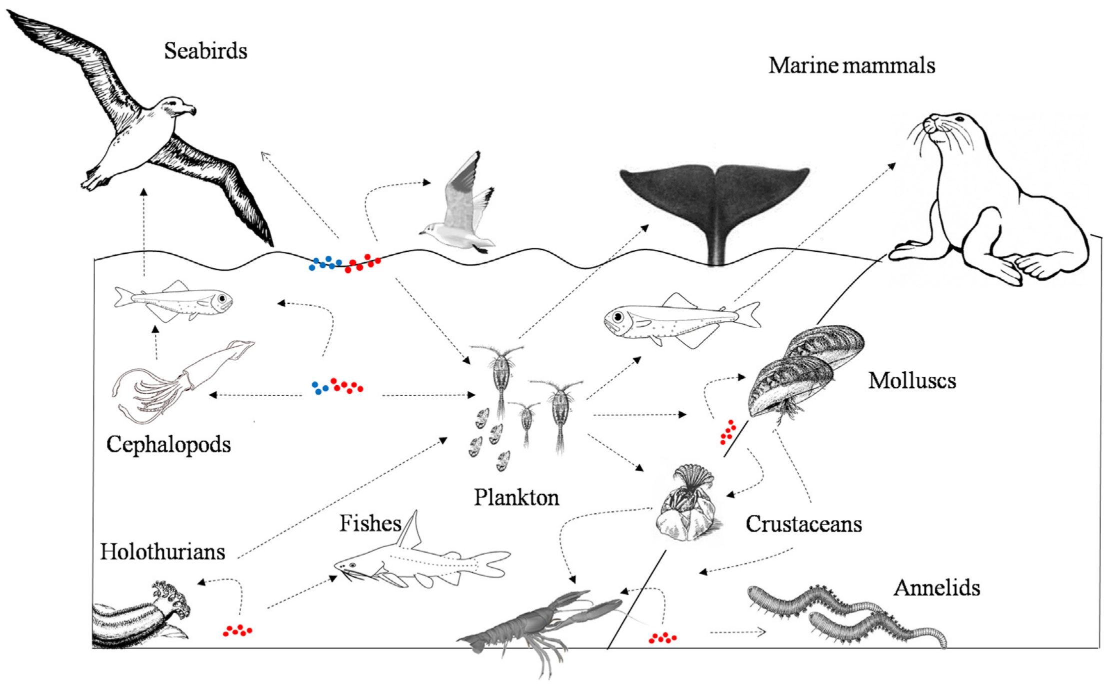


Fig. 2. A conceptual model of the potential trophic routes of microplastics across marine vertebrate and invertebrate groups. The blue dots are polymers that are less dense than seawater (i.e., PE and PP) and the red dots are polymers that are more dense than seawater (i.e., PVC). The dashed arrows represent the hypothesised microplastic transfer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

less land masses and the region is less developed than the highly industrialised Northern Hemisphere. The 300 μm mesh size is most commonly used to sample microplastics at sea (Hidalgo-Ruz et al., 2012). However, additional mesh sizes were also applied, which produce large variations in the quantity of microplastics collected (e.g., Cole et al., 2011).

Surface-feeding petrels, shearwaters and albatrosses, including fledgling chicks, appear to be the most impacted by floating microplastics (up to 90% of samples). Scientific reports are widespread, from the Antarctic to the Canadian Arctic, and throughout all of the ocean basins (Fig. 1 and Table S3). As expected, ingested amounts of plastics decreased towards the high latitudes; plastic

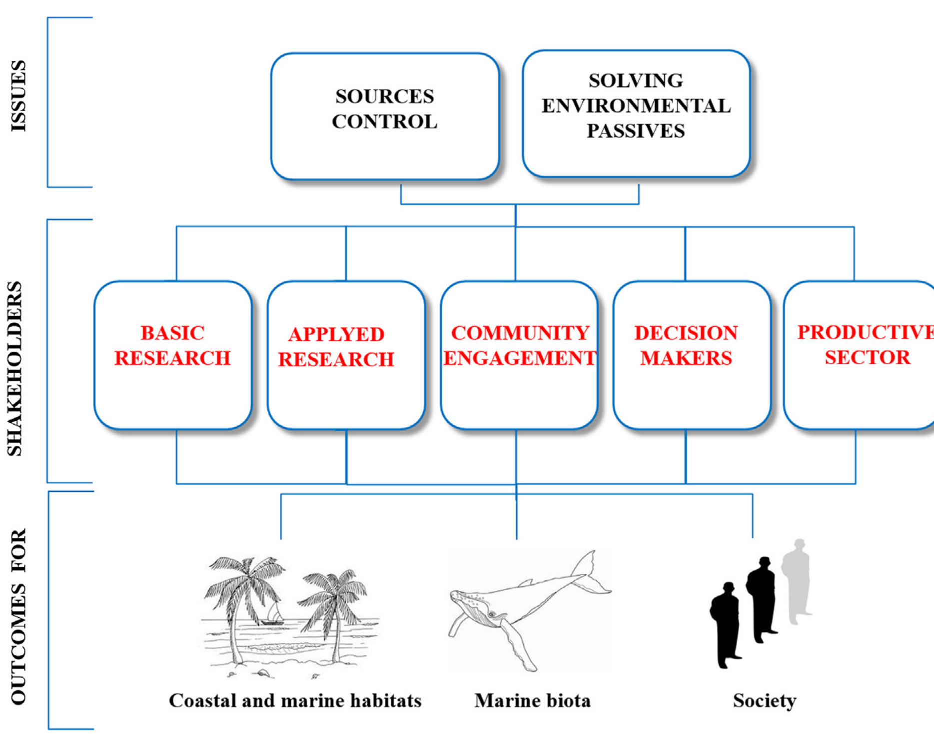


Fig. 3. Various issues regarding microplastic pollution at sea will need the cooperation of different stakeholders. The integration of their actions will encourage positive outcomes for coastal and marine environments, marine biota and society.

fragments are now prevalent over pellets as observed from the long-term field work in the Atlantic Ocean (e.g., Morét-Ferguson et al., 2010). Therefore, seabirds can be considered sensitive monitors of small plastics at sea (Ryan, 2008). Ingested plastics significantly vary in size, and studies now need to quantify the magnitude and characteristics of smaller sizes (<1 mm) of microplastics. Procellariiformes do not regurgitate plastics, which is one explanation for the high amount of plastics observed in their stomachs. However, POPs from the microplastics in their digestive tracts can eventually enter the bloodstream, reach other organs and possibly result in physiologic damage. Seabirds may eat pelagic microplastics when feeding, but they likely also ingest planktivorous fish and squids that had previously ingested microplastics from seawater (similar to the observations of other top predators, such as fur seals) (Table S3). Likewise, pelagic fish and squids may ingest microplastics with plankton or ingest them actively (most of the ingestion processes are largely speculative). The extent of the problem is huge; fish (Myctophidae) reported in various geographic regions with microplastics comprise more than half of the world oceans' total fish biomass. Furthermore, because fish excrete ingested plastics (Hoss and Settle, 1990), sub-lethal effects are a very likely hypothesis.

The shores on six continents are contaminated with microplastics (Fig. 1). Fibres (μm) are prevalent in the eastern North Atlantic and the North Sea due to continental effluent discharges. Microplastic fragments and virgin plastic pellets are more common when the size limitation of their detection is on the order of millimetres (i.e., the eastern and western coasts of South America). However, fibres are most likely also spread throughout these sediments, mostly around urban areas (Browne et al., 2011). Oceanic islands were also reportedly contaminated by microplastic fragments. In estuaries, which are potential sources of these contaminants, studies are nearly non-existent. Moreover, the presence of microplastics in terrestrial ecosystems and the soil are completely absent from the literature (Rillig, 2012). The presence of microplastics in coastal sediments resulted in unexpected consequences, such as changes in the physical proprieties of beaches and associated problems (e.g., Carson et al., 2011).

Additionally, benthic species ingest microplastics in highly developed areas and in small estuarine ecosystems (Fig. 1; Table S3). Threads from fisheries (ropes and nets) were positively identified in the digestive tracts of benthic fish and lobsters. Microplastics, and consequently POPs, are possibly remobilised (bioturbation) in the sediment–water interface (Besseling et al., 2013). Ingestion events were described for several groups of invertebrates through laboratory experiments, but there is still a lack of research on the ingestion of microplastics by invertebrates in the marine environment, possibly because these studies are time-consuming and require more advanced technology (Table S4).

4. Conclusion and suggestions

With knowledge comes greater responsibility. Historical and recent findings regarding microplastic pollution in coastal and marine environments, as described by review papers, need to be coalesced to provide guidelines for all stakeholders concerned with the life cycle of plastic. Two major issues are prevalent: how to proceed with source control and methods to address the enormous environmental passives that were built over the last 60 years (since plastics became largely expendable) (Fig. 3). Source control has been preached by every paper, official and un-official document on marine plastics debris for decades. However, technical evidence and published opinion have failed to effectively introduce it into the DNA of the plastic production, use and re-use industries. Source control has only been a priority for very close and restricted circles where the 3Rs (or the 5Rs: Refuse, Reduce, Reuse, Recycle, Rethink) are the norm rather than the exception. Source control would have to integrate and prioritise Rethink (choose other materials and techniques) and Refuse (reduce the production of all single use plastic items) into society and the production sectors. Specific actions targeted to primary and secondary sources of microplastics are required to control pellets and to stop large items from reaching the sea (where they decay). Unfortunately, based on present trends, animals and humans will continue to be at risk and accidents will occur before these goals are achieved.

Tackling the environmental passives is a different story. Microplastics cannot be sieved from sands or filtered out of seawater. Collecting all of these microparticles would take forever, and even so it would not be effective. Microplastics will continue their slow, intricate paths towards the bottom of the ocean and ultimately become buried in sand and mud for centuries. However, rather than despair, scientists should propose solutions that can be considered by academia, society and industry. Each group of stakeholders (academia, the community, decision-makers and industry) is responsible for various tasks (Fig. 3) including communicating results to other stakeholders. Several knowledge gaps need to filled: standardising size definitions; establishing the relative importance of primary and secondary sources; rescuing information on pelagic plastics that is stored in plankton samples; adding microplastics as a routine survey variable in river basins and oceans; assessing microplastic pollution in the Antarctic and Arctic; creating and continuously improving experimental methods to quantify microplastics.

Applied research, which is performed by many societal sectors, has the potential to introduce new techniques to assess microplastics pollution and new materials, designs and facilities that will ultimately prevent plastics from reaching the environment. Some suggestions include performing laboratory tests on microplastic ingestion and necropsies for verification of physical harm, ingestion of contaminated microplastics (POPs) and confirmation of transference/damage by histology and chemical characterisation of pelagic and benthic microplastics to confirm its composition.

The community, although aware of the problem, must be guided by the public sector to search for local alternatives to excessive packaging, safely deposit their inevitable plastic rubbish and make better and more informed choices as consumers. Additionally, independent world conferences on microplastics would coalesce knowledge and actions, integrate research from countries where primary plastics are produced/exported and help define the temporal patterns of chemical pollutants (e.g., International Pellets Watch).

These suggestions will require implementation of educational programs, the cooperation of urban and rural facilities and, above all, persuasion through practical examples of environments that easily and directly exhibit proper control of waste. Decision-makers, mostly in the public sector, have intelligent and technically sound regulations to issue in the future, in addition to existing issues already enforced. State polices can be formed to direct the control of the sources of primary plastics and calculate environmental value losses (fish stocks, gas exchange, beach erosion) by microplastic pollution. Additionally, a complete cradle-to-grave approach to plastics would reduce the amount that reaches the sea and reduce our carbon footprint. Plastics are a branch of the oil and gas industry (8% of the oil produced is used in plastic production). Therefore, both sectors must meet to collaborate as soon as possible.

In addition to the petrochemical and plastics moulding units, industry as a whole must be prepared for the need to produce and use less plastic. Fiscal incentives for technologies that resolve environmental passives need to be established. The intention is not to face this sector as an arch-enemy, but rather to start a collaborative process that will steadily progress from controlling pellet pollution to effectively and dutifully applying reverse logistics to tackle the environmental passives caused by plastics on land and at sea.

The outcomes of such rationales are expected to be far-reaching. First, coastal and marine habitats will regain their lost aesthetic values, ecological functions and services. Secondly, the risks posed to the marine biota will be reduced. Ultimately, these outcomes would create a less plastic-addicted and more nature-centred society in which the greatest values, based on science and experience, are life and environmental preservation.

Acknowledgements

We are grateful to the National Council for Scientific and Technological Research (CNPq) for the PhD scholarship provided to Juliana A. Ivar do Sul (Process 551944/2010-2). We also thank CNPq (Project 557184/2009-6) and the Brazilian Navy for financial and logistic support for "Environmental contamination by persistent organic compounds, plastic fragments and pellets around the Trindade Island". M.F.C is a CNPq Fellow.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2013.10.036.

References

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605.
Andrady, A.L., Neal, M.A., 2009. Applications and societal benefits of plastic. Phil. Trans. R. Soc. B 364, 1977–1984.
Arthur, C., Baker, J., Bamford, H. (Eds.), 2009. Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris. NOAA Technical Memorandum NOS-OR&R-30.
Ashton, K., Holmes, L., Turner, A., 2010. Association of metals with plastic production pellets in the marine environment. Mar. Pollut. Bull. 60, 2050–2055.
Avery-Gomm, S., O'Hara, P.D., Kleine, L., Bowes, V., Wilson, L.K., Barry, K.L., 2012. Northern fulmars as biological monitors of trends of plastic pollution in the eastern North Pacific. Mar. Pollut. Bull. 64, 1776–1781.
Avery-Gomm, S., Provencher, J.F., Morgan, K.H., Bertram, D.F., 2013. Plastic ingestion in marine-associated bird species from the eastern North Pacific. Mar. Pollut. Bull. 72, 257–259.
Bakir, A., Rowland, S.J., Thompson, R.C., 2012. Competitive sorption of persistent organic pollutants onto microplastics in the marine environment. Mar. Pollut. Bull. 64, 2782–2789.
Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Environmental accumulation and fragmentation of plastic debris in global. Phil. Trans. R. Soc. B 364, 1985–1998.
Besseling, E., Wegner, A., Foekema, E.M., van den Heuvel-Greve, M.J., Koelmans, A.A., 2013. Effects of Microplastic on Fitness and PCB Bioaccumulation by the Lugworm *Arenicola marina* (L.). Environ. Sci. Technol. 47, 593–600.
Boerger, C.M., Lattin, G.L., Moore, S.L., Moore, C.J., 2010. Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Mar. Pollut. Bull. 60, 2275–2278.
Braid, H.E., Deeds, J., DeGrasse, J.L., Wilson, J.J., Osborne, J., Hanner, R.H., 2012. Preying on commercial fisheries and accumulating paralytic shellfish toxins: a dietary analysis of invasive *Dosidicus gigas* (Cephalopoda Ommastrephidae) stranded in Pacific Canada. Mar. Biol. 159, 25–31.
Browne, M.A., Dissanayake, A., Galloway, T.S., Lowe, D.M., Thompson, R.C., 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L. Environ. Sci. Technol. 42, 5026–5031.
Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns of plastic debris along estuarine shorelines. Environ. Sci. Technol. 44, 3404–3409.
Browne, M.A., Crump, P., Niven, S.J., Teuten, E.L., Tonkin, A., Galloway, T., Thompson, R.C., 2011. Accumulations of microplastic on shorelines worldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179.
Buchanan, J.B., 1971. Pollution by synthetic fibres. Mar. Pollut. Bull. 2, 23.
Carpenter, E.J., Smith, K.L., 1972. Plastics on the Sargasso Sea surface. Science 175, 1240–1241.
Carpenter, E.J., Anderson, S.J., Harvey, G.R., Miklas, H.P., Peck, B.B., 1972. Polystyrene spherules in coastal waters. Science 175, 749–750.
Carson, H.S., Colbert, S.L., Kaylor, M.J., McDermid, K.J., 2011. Small plastic debris changes water movement and heat transfer through beach sediments. Mar. Pollut. Bull. 62, 1708–1713.
Claessens, M., Meester, S.D., Landuyt, L.V., Clerck, K.D., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199–2204.
Colabuono, F.I., Barquete, V., Domingues, B.S., Montone, R.C., 2009. Plastic ingestion by Procellariiformes in southern Brazil. Mar. Pollut. Bull. 58, 93–96.
Colabuono, F.I., Taniguchi, S., Montone, R.C., 2010. Polychlorinated biphenyls and organochlorine pesticides in plastics ingested by seabirds. Mar. Pollut. Bull. 60, 630–634.
Cole, M., Lindeque, P., Halsband, C., Galloway, S.C., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597.
Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., Galloway, T.S., 2013. Microplastic ingestion by zooplankton. Environ. Sci. Technol. 47, 6646–6655.
Collignon, A., Hecq, J.H., Galgani, F., Voisin, P., Collard, F., 2012. Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Mar. Pollut. Bull. 64, 861–864.
Costa, M.F., Ivar do Sul, J.A., Santos-Cavalcanti, J.S., Araújo, M.C.B., Spengler, A., Tourinho, T.S., 2010. Small and microplastics on the strandline: snapshot of a Brazilian beach. Environ. Monit. Assess. 168, 299–304.
Dantas, D.V., Barletta, M., Costa, M.F., 2012. The seasonal and spatial patterns of ingestion of polyfilament nylon fragments by estuarine drums (Sciaenidae). Environ. Sci. Poll. Res. 19, 600–606.
Davidson, T.M., 2012. Boring crustaceans damage polystyrene floats under docks polluting marine waters with microplastic. Mar. Pollut. Bull. 64, 1821–1828.
Davison, P., Asch, R.G., 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. Mar. Ecol. Prog. Ser. 432, 173–180.
Day, R.H., Wehle, D.H.S., Coleman, F.C., 1984. Ingestion of plastic pollutants by marine birds. In: Proceedings of the Workshop on the Fate and Impact of Marine Debris. US Department of Commerce, pp. 344–386. NOAA Tech. Mem. NMFS, NOAA-TM-NMFS-SWFC-54.
Doyle, M.J., Watson, W., Bowlin, N.M., Sheavly, S.B., 2011. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific Ocean. Mar. Environ. Res. 71, 41–52.
Dubaish, F., Liebezeit, G., 2013. Suspended microplastics and black carbon particles in the Jade System, Southern North Sea. Water Air Soil Pollut. 224, 1–8.
Endo, S., Takizawa, R., Okuda, K., Takada, H., Chiba, K., Kanehiro, H., Ogi, H., Yamashita, R., Date, T., 2005. Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: variability among individual particles and regional differences. Mar. Pollut. Bull. 50, 1103–1114.
Engler, R.E., 2012. The complex interaction between marine debris and toxic chemicals in the ocean. Environ. Sci. Technol. 46, 12302–12315.
Eriksen, M., Maximenko, N., Thiel, M., Cumminsa, A., Lattin, G., Wilson, S., Hafner, J., Zellers, A., Rifman, S., 2013. Plastic pollution in the South Pacific subtropical gyre. Mar. Pollut. Bull. 68, 71–76.
Eriksson, C., Burton, H., 2003. Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. Ambio 32, 380–384.
Farrell, P., Nelson, K., 2012. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). Environ. Pollut. 177, 1–3.
Fendall, L.S., Sewell, M.A., 2009. Contributing to marine pollution by washing your face: microplastics in facial cleansers. Mar. Pollut. Bull. 58, 1225–1228.
Fisner, M., Taniguchi, S., Moreira, F., Bícego, M.C., Turra, A., 2013. Polycyclic aromatic hydrocarbons (PAHs) in plastic pellets: variability in the concentration and composition at different sediment depths in a sandy beach. Mar. Pollut. Bull. 70, 219–226.
Fotopoulou, K.N., Karapanagioti, H.K., 2012. Surface properties of beached plastic pellets. Mar. Environ. Res. 81, 70–77.
Fossi, M.C., Panti, C., Guerranti, C., Coppola, D., Giannetti, M., Marsili, L., Minutoli, R., 2012. Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (*Balaenoptera physalus*). Mar. Pollut. Bull. 64, 2374–2379.
Frias, J.P.G.L., Sobral, P., Ferreira, A.M., 2010. Organic pollutants in microplastics from two beaches of the Portuguese coast. Mar. Pollut. Bull. 60, 1988–1992.
Fry, D.M., Fefer, S.I., Sileo, L., 1987. Ingestion of plastic debris by Laysan Albatrosses and Wedge-Tailed Shearwaters in the Hawaiian Islands. Mar. Pollut. Bull. 18, 339–343.
Goldstein, M.C., Rosenberg, M., Cheng, L., 2012. Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biol. Lett. 8, 817–820.
Gouin, T., Roche, N., Lohmann, R., Hodges, G., 2011. A thermodynamic approach for assessing the environmental exposure of chemicals absorbed to microplastic. Environ. Sci. Technol. 45, 1466–1472.
Graham, E., Thompson, J., 2009. Deposit- and suspension-feeding sea cucumbers (Echinodermata) ingest plastic fragments. J. Exp. Mar. Biol. Ecol. 368, 22–29.
Gray, H., Lattin, G., Moore, C.J., 2012. Incidence, mass and variety of plastics ingested by Laysan (*Phoebastria immutabilis*) and Black-footed Albatrosses (*P. nigripes*) recovered as by-catch in the North Pacific Ocean. Mar. Pollut. Bull. 64, 2190–2192.
Gregory, M.R., 1977. Plastic pellets on New Zealand beaches. Mar. Pollut. Bull. 8, 82–84.
Gregory, M.R., 1978. Accumulation and distribution of virgin plastic granules on New Zealand beaches. J. Mar. Freshw. Res. 12, 399–414.
Gregory, M.R., 1983. Virgin plastics on some beaches of eastern Canada and Bermuda. Mar. Environ. Res. 10, 73–92.
Gregory, M.R., 1996. Plastic 'scrubbers' in hand cleansers: a further (and minor) source for marine pollution identified. Mar. Pollut. Bull. 32, 867–871.

Harrison, J.P., Ojeda, J.J., Romero-Gonzales, M.E., 2012. The applicability of reflectance micro-Fourier-transform infrared spectroscopy for the detection of synthetic microplastics in marine sediments. Sci. Total Environ. 416, 455–463.
Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075.
Hidalgo-Ruz, V., Thiel, M., 2013. Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project. Mar. Environ. Res. 87–88, 12–18.
Hirai, H., Takada, H., Ogata, Y., Yamashita, R., Mizukawa, K., Saha, M., Kwan, C., Moore, C., Gray, H., Laursen, D., Zettler, E.R., Farrington, J.W., Reddy, C.M., Peacock, E.E., Ward, M.W., 2011. Organic micropollutants in marine plastics debris from the open ocean and remote and urban beaches. Mar. Pollut. Bull. 62, 1683–1692.
Hoss, D.E., Settle, L.R., 1990. Ingestion of plastic by teleost fishes. In: Shomura, R.S., Godrey, M.L. (Eds.), Proceedings of the Second International Conference on Marine Debris 2–7 April 1989, Honolulu, Hawaii. U.S. Department of Commerce, pp. 693–709. NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-154.
Imhof, H.K., Schmid, J., Niessner, R., Ivleva, N.P., Laforsch, C., 2012. A novel, highly efficient method for the separation and quantification of plastic particles in sediments of aquatic environments. Limnol. Oceanogr. Methods 10, 524–537.
Ivar do Sul, J.A., Costa, M.F., 2007. Marine debris review for Latin America and the Wider Caribbean Region: from the 1970 until now and where do we go from here? Mar. Pollut. Bull. 54, 1087–1104.
Ivar do Sul, J.A., Spengler, A., Costa, M., 2009. Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). Mar. Pollut. Bull. 58, 1229–1244.
Ivar do Sul, J.A., Costa, M.F., Barletta, M., Cysneiros, F.J.A., 2013. Presence of pelagic microplastics around an Archipelago of the Equatorial Atlantic. Mar. Pollut. Bull. 75, 305–309.
Karapanagioti, H.K., Klontza, I., 2008. Testing phenanthrene distribution properties of virgin plastic pellets and plastic eroded pellets found on Lesvos island beaches (Greece). Mar. Environ. Res. 65, 283–290.
Karapanagioti, H.K., Endo, S., Ogata, Y., Takada, H., 2011. Diffuse pollution by persistent organic pollutants as measured in plastic pellets sampled from various beaches in Greece. Mar. Pollut. Bull. 62, 312–317.
Khordagui, H.K., Abu-Hilal, A.H., 1994. Industrial plastic on the southern beaches of the Arabian Gulf and the western beaches of the Gulf of Oman. Environ. Pollut. 84, 325–327.
Kühn, S., van Franeker, J.A., 2012. Plastic ingestion by the northern fulmar (*Fulmarus glacialis*) in Iceland. Mar. Pollut. Bull. 64, 1252–1254.
Kukulka, T., Proskurowski, G., Morét-Ferguson, S., Meyer, D.W., Law, K.L., 2012. The effect of wind mixing on the vertical distribution of buoyant plastic debris. Geophys. Res. Lett. 39, L07601.
Kusui, T., Noda, M., 2003. International survey on the distribution of stranded and buried litter on beaches along the Sea of Japan. Mar. Pollut. Bull. 47, 175–179.
Lattin, G.L., Moore, C.J., Zellers, A.F., Moore, S.L., Weisberg, S.B., 2004. A comparison of neustonic plastic and zooplankton at different depths near the southern California shore. Mar. Pollut. Bull. 49, 291–294.
Law, K.L., Morét-Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic subtropical gyre. Science 329, 1185–1188.
Liebezeit, G., Dubaish, F., 2012. Microplastics in beaches of the East Frisian Islands Spiekeroog and Kachelotplate. Bull. Environ. Contam. Toxicol. 89, 213–217.
Lindborg, V.A., Ledbetter, J.F., Walat, J.M., Moffett, C., 2012. Plastic consumption and diet of Glaucous-winged Gulls (*Larus glaucescens*). Mar. Pollut. Bull. 64, 2351–2356.
Lithner, D., Damberg, J., Dave, G., Larsson, A., 2009. Leachates from plastic consumer products — screening for toxicity with *Daphnia magna*. Chemosphere 74, 1195–1200.
Lithner, D., Larsson, A., Dave, G., 2011. Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. Sci. Total Environ. 409, 3309–3324.
Lobelle, D., Cunliffe, M., 2011. Early microbial biofilm formation on marine plastic debris. Mar. Pollut. Bull. 62, 197–200.
Lusher, A.L., McHugh, M., Thompson, R.C., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar. Pollut. Bull. 67, 94–99.
Majer, A.P., Vedolin, M.C., Turra, A., 2012. Plastic pellets as oviposition site and means of dispersal for the ocean-skater insect *Halobates*. Mar. Pollut. Bull. 64, 1143–1147.
McDermid, K.J., McMullen, T.L., 2004. Quantitative analysis of small-plastic debris on beaches in the Hawaiian Archipelago. Mar. Pollut. Bull. 48, 790–794.
Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., Kaminuma, T., 2001. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environ. Sci. Technol. 35, 318–324.
Maximenko, N., Hafner, J., Niiler, P., 2012. Pathways of marine debris derived from trajectories of Lagrangian drifters. Mar. Pollut. Bull. 65, 51–62.
Mizukawa, K., Takada, H., Ito, M., Geok, Y.B., Hosoda, J., Yamashita, R., Saha, M., Suzuki, S., Miguez, C., Frias, J., Antunes, J.C., Sobral, P., Santos, I., Micaelo, C., Ferreira, A.M., 2013. Monitoring of a wide range of organic micropollutants on the Portuguese coast using plastic resin pellets. Mar. Pollut. Bull. 70, 296–302.
Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environ. Res. 108, 131–139.
Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A comparison of plastic and plankton in the North Pacific Central Gyre. Mar. Pollut. Bull. 42, 1297–1300.
Moore, C.J., Moore, S.L., Weisberg, S.B., Latin, G.L., Zellers, A.F., 2002. A comparison of neustonic plastic and zooplankton abundance in southern California's coastal waters. Mar. Pollut. Bull. 44, 1035–1038.
Morét-Ferguson, S., Law, K.L., Proskurowski, G., Murphy, E.K., Peacock, E.E., Reddy, C.M., 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Mar. Pollut. Bull. 60, 1873–1878.
Morris, A.W., Hamilton, E.I., 1974. Polystyrene spherules in the Bristol Channel. Mar. Pollut. Bull. 5, 26–27.
Murray, F., Cowie, P.R., 2011. Plastic contamination in the decapod crustacean Nephrops norvegicus (Linnaeus, 1758). Mar. Pollut. Bull. 62, 1207–1217.
Ng, K.L., Obbard, J.P., 2006. Prevalence of microplastics in Singapore's coastal marine environment. Mar. Pollut. Bull. 52, 761–767.
Ogata, Y., Takada, H., Mizukawa, K., Hiraia, H., Iwasaa, S., Endo, S., Mato, Y., Saha, M., Okuda, K., Nakashima, A., Murakami, M., Zurcher, N., Booyatumanondo, R., Zakaria, M.P., Dung, L.Q., Gordon, M., Miguez, C., Suzuki, S., Moore, C., Karapanagiotik, H.K., Weerts, S., McClurg, T., Burres, E., Smith, W., Van Velkenburg, M., Lang, J.S., Lang, R.C., Laursen, D., Danner, B., Stewardson, N., Thompson, R.C., 2009. International Pellet Watch: global monitoring of persistent organic pollutants (POPs) in coastal waters. 1. Initial phase data on PCBs, DDTs, and HCHs. Mar. Pollut. Bull. 58, 1437–1446.
Oliveira, M., Ribeiro, A., Guilhermino, L., 2012. Effects of exposure to microplastics and PAHs on microalgae *Rhodomonas baltica* and *Tetraselmis chuii*. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 163, S19–S20.
Possatto, F.E., Barletta, M., Costa, M.F., Ivar do Sul, J.A., Dantas, D.V., 2011. Plastic debris ingestion by marine catfish: an unexpected fisheries impact. Mar. Pollut. Bull. 62, 1098–1102.
Provencher, J.F., Gaston, A.J., Mallory, M.L., 2009. Evidence for increased ingestion of plastics by northern fulmars (*Fulmarus glacialis*) in the Canadian Arctic. Mar. Pollut. Bull. 58, 1092–1095.
Provencher, J.F., Gaston, A.J., Mallory, M., O'hara, P.D., Gilchrist, H.G., 2010. Ingested plastic in a diving seabird, the thick-billed murre (*Uria lomvia*), in the eastern Canadian Arctic. Mar. Pollut. Bull. 60, 1406–1411.
Ramos, J.A.A., Barletta, M., Costa, M.F., 2012. Ingestion of nylon threads by Gerreidae while using a tropical estuary as foraging grounds. Aquat. Biol. 17, 29–34.
Rebolledo, E.L.B., Van Franeker, J.A., Jansen, O.E., Brasseur, S.M.J.M., 2013. Plastic ingestion by harbour seals (*Phoca vitulina*) in The Netherlands. Mar. Pollut. Bull. 67, 200–202.
Reddy, M.S., Adimurthy, S.S., Ramachandraiah, G., 2006. Description of the small plastics fragments in marine sediments along the Alang-Sosiya ship-breaking yard, India. Est. Coast. Shelf Sci. 68, 656–660.
Rillig, M.C., 2012. Microplastic in terrestrial ecosystems and the soil? Environ. Sci. Technol. 46, 6453–6454.
Rios, L.M., Jones, P.R., Moore, C., Narayan, U.V., 2010. Quantitation of persistent organic pollutants adsorbed on plastic debris from the Northern Pacific Gyre's "eastern garbage patch". J. Environ. Monit. 12, 2226–2236.
Rios, L.M., Moore, C., Jones, P.R., 2007. Persistent organic pollutants carried by synthetic polymers in the ocean environment. Mar. Pollut. Bull. 54, 1230–1237.
Rodríguez, A., Rodríguez, B., Carrasco, M.N., 2012. High prevalence of parental delivery of plastic debris in Cory's shearwaters (*Calonectris diomedea*). Mar. Pollut. Bull. 64, 2219–2223.
Rochman, C.M., Hoh, E., Hentschel, B.T., Kaye, S., 2013. Long-term field measurement of sorption of organic contaminants to five types of plastic pellets: implications for plastic marine debris. Environ. Sci. Technol. 47, 1646–1654.
Roy, P.K., Hakkarainen, M., Varma, I.K., Albertsson, A.C., 2011. Degradable polyethylene: fantasy or reality. Environ. Sci. Technol. 45, 4217–4227.
Ryan, P.G., 1988. The characteristics and distribution of plastic particles at the sea-surface off the southwestern Cape Province, South Africa. Mar. Environ. Res. 25, 249–273.
Ryan, P.G., 2008. Seabirds indicate changes in the composition of plastic litter in the Atlantic and southwestern Indian Oceans. Mar. Pollut. Bull. 56, 1406–1409.
Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Phil. Trans. R. Soc. B 364, 1999–2012.
Ryan, P.G., Bouwman, H., Moloney, C.L., Yuyama, M., Takada, H., 2012. Long-term decreases in persistent organic pollutants in South African coastal waters detected from beached polyethylene pellets. Mar. Pollut. Bull. 64, 2756–2760.
Shah, A.A., Hasan, F., Hameed, A., Ahmed, S., 2008. Biological degradation of plastics: a comprehensive review. Biotechnol. Adv. 26, 246–265.
Shaw, D.G., Day, R.H., 1994. Colour- and form-dependent loss of plastic microdebris from the North Pacific Ocean. Mar. Pollut. Bull. 28, 39–43.
Shiber, J.G., 1979. Plastic pellets on the coast of Lebanon. Mar. Pollut. Bull. 10, 28–30.
Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M., Watanuki, Y., 2013. Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. Mar. Pollut. Bull. 69, 219–222.
Teuten, E.L., Rowland, S.J., Galloway, T.S., Thompson, R.C., 2007. Potential for plastics to transport hydrophobic contaminants. Environ. Sci. Technol. 41, 7759–7764.
Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Björn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P.H., Tana, T.S., Prudente, M., Boonyatumanond, R., Zakaria, M.P., Akkhavong, K., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagino, Y., Imamura, A., Saha, M., Takada, H., 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Phil. Trans. R. Soc. B 364, 2027–2045.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838.

Thompson, R.C., Swan, S.H., Moore, C.J., vom Saal, F.S., 2009. Our plastic age. Phil. Trans. R. Soc. B 364, 1973–1976.

Turner, A., Holmes, L., 2011. Occurrence, distribution and characteristics of beached plastic production pellets on the island of Malta (central Mediterranean). Mar. Pollut. Bull. 62, 377–381.

Ugolini, A., Ungherese, G., Ciofini, M., Lapucci, A., Camaiti, M., 2013. Microplastic debris in sandhoppers. Mar. Pollut. Bull. 129, 19–22.

Van, A., Rochman, C.M., Flores, E.M., Hill, K.L., Vargas, E., Vargas, S.A., Hoh, E., 2012. Persistent organic pollutants in plastic marine debris found on beaches in San Diego, California. Chemosphere 86, 258–263.

Van Franeker, J.A., Bell, P.J., 1988. Plastic ingestion by petrels breeding in Antarctica. Mar. Pollut. Bull. 19, 672–674.

Van Franeker, J.A., Blaize, C., Danielsen, J., Fairclough, K., Gollan, J., Guse, N., Hansen, P.L., Heubeck, M., Jensen, J.K., Le Guillou, G., Olsen, B., Olsen, K.O., Pedersen, J., Stienen, E.W.M., Turner, D.M., 2011. Monitoring plastic ingestion by the northern fulmar *Fulmarus glacialis* in the North Sea. Environ. Pollut. 159, 2609–2615.

Van Noord, J.E., 2013. Diet of five species of the family Myctophidae caught off the Mariana Islands. Ichthyol. Res. 60, 89–92.

Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., Da Ros, L., 2013. Microplastic particles in sediments of Lagoon of Venice, Italy: first observations on occurrence, spatial patterns and identification. Est. Coast. Shelf Sci. 130, 54–61.

von Moos, N., Burkhardt-Holm, P., Köhle, A., 2012. Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure. Environ. Sci. Technol. 46, 11327–11335.

Wegner, A., Besseling, E., Foekema, E.M., Kamermans, P., Koelmans, A.A., 2012. Effects of nanopolystyrene on the feeding behavior of the blue mussel (*Mytilus edulis* L.). Environ. Toxicol. Chem. 31, 2490–2497.

Wilber, R.J., 1987. Plastics in the North Atlantic. Oceanus 30, 61–68.

Wright, S.L., Thompson, R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492.

Yamashita, R., Tanimura, A., 2007. Floating plastic in the Kuroshio Current area, western North Pacific Ocean. Mar. Pollut. Bull. 54, 485–488.

Zarfl, C., Matthies, M., 2010. Are marine plastic particles transport vectors for organic pollutants to the Arctic? Mar. Pollut. Bull. 60, 1810–1814.

Zitko, V., Hanlon, M., 1991. Another source of pollution by plastics: skin cleans with plastic scrubbers. Mar. Pollut. Bull. 22, 41–42.

Supplementary content

Tables S1, S2, S3, S4 and S5.

Table S1: Peer-reviewed papers on the occurrence of microplastics on plankton samples ordered chronologically. Location, types of plastics, contaminations patterns, mesh size of the plankton nets and the main focus of the works were detailed.

Location	Types of items and contamination pattern	Mesh size	Main focus	Reference
UK	50-100 fibres L^{-1}	-	Fibres occurred from the surface to 100m deep.	Buchanan ,1971
North Atlantic	3,500 pellets km^{-2}	333µm	Plastics widespread in the *Sargassum* Sea surface.	Carpenter and Smith, 1972
North Atlantic	0.275 pellets m^{-3}	333µm	PE pellets also ingested by fish.	Carpenter et al., 1972
Bristol Channel	11.3 pellets m^{-3}	130 µm	PS pellets just negatively buoyant. Eastern coast more contaminated.	Morris and Hamilton, 1974
North Atlantic	100-1,000 pellets/km^2	333-500 µm	Plastics and pellets concentrated between 28-40°N. Relation with ocean currents.	Wilber, 1987
South Africa	3640 items km^{-2} 42.4 g km^{-2}	90µm	Fragments, fibres and polystyrene were the majority.	Ryan, 1988
Lab	-	-	Microplastic pellets in skin cleaners from Canadian markets.	Zitko and Hanlon, 1991
North Pacific	83,800 fragments km^{-2}	53µm	81.5% were fragments with 0.5mm; size distribution varied with colour.	Shaw and Day, 1994
Lab	-	-	Microplastics from clean products and airblasting.	Gregory, 1996
NPCG	334,271 fragments km^{-2}	333µm	Higher plastic to plankton ratio. Lines from fishery.	Moore et al., 2001
California coast	10 fragments m^{-3}* 60 fragmentsm^{-3}**	333µm	More floating plastics after a storm event.	Moore et al., 2002
California coast	~4 pieces m^{-3}	333µm	Plastics in the entire water column.	Lattin et al., 2004
North Sea	0.01-0.05 fibres m^{-3}	280µm	CPR survey. Significant increase in the amounts of plastics from 1960/70s to 1980/90s.	Thompson et al., 2004
Singapore	~4 fragments L^{-1}	-	Surface microlayer (50-60µm) and subsurface (1m) samples.	Ng and Obbard, 2006

Kuroshio Current	~1X10^{5} fragments km^{-2}	330µm	Amounts increased with the distance from the coast. Include PS fragments.	Yamashita and Tanimura, 2007
Lab		~200µm	Facial cleaners tested for characterization of PE microplastics.	Fendall and Sewell, 2009
North Atlantic	-	335µm	60% has 2-6mm. Densities significantly higher at 30°N. Most fragments.	Morét-Ferguson et al., 2010
North Atlantic	10,000 to 100,000 fragments km^{-2}	335µm	> 6100 tows, 60% with plastics.	Law et al., 2010
Northeast Pacific	0.004 to 0.19 fragments m^{-3}	500µm	Surface and subsurface sampling. Fibres, fragments and pellets reported (< 2.5mm).	Doyle et al., 2011
Pacific	-	-	PS fragments (464±29µm) generated by boring crustaceans incrusted on floating buoys and aquaculture.	Davidson, 2012
Mediterranean	0.116 fragments m^{-2}	333µm	90% of the tows contaminated by filaments, polystyrene and thin plastic films.	Collignon et al., 2012
North Atlantic	-	335µm	Plastic concentrations depend on wind speed.	Kukulka et al., 2012
SPSG	~26,898 fragments km^{-2}	333µm	Higher amounts associated with weaker winds.	Eriksen et al., 2013
North Sea	64 pellets L^{-1}; 88 fibres L^{-1}	40µm	Microplastics associated with industries (paper facility plants). Fragments were absent.	Dubaish and Liebezeit, 2013
Equatorial Atlantic	~1 fragment m^{-3}	300 µm	Microplastics, as well as larvae, were retained around an Archipelago. Autochthonous sources of fragments were suggested.	Ivar do Sul et al., 2013

Location: NPCG= North Pacific Central Gyre; SPSG = South Pacific Subtropical Gyre.
*Before a storm event **After a storm event.

Table S2: Peer-reviewed papers on the occurrence of microplastics on muddy and sandy sediments ordered chronologically. Location, methodology, contaminations patterns, and the main focus of the works were detailed.

Location	Methodology	Contamination pattern	Main focus	Reference
New Zealand	-	<1 m^{-1} - >5000 m^{-1}	Description of sampled plastic pellets.	Gregory, 1977
New Zealand	-	-	Description of sampled plastic pellets.	Gregory, 1978
Lebanon	-	-	Description of sampled plastic pellets.	Shiber, 1979
Canada, Bermuda	-	-	Description of sampled plastic pellets.	Gregory, 1983
Gulf of Oman and Arabian Gulf	3X1m² on 1m wide transects	50-80,000 pellets m^{-2}	Stranded pellets related to spills during shipping.	Khordagui and Abu-Hilal, 1994
Sea of Japan	100m²	341 items 100m^{-2}	Japan had more fragments than Russia (where pellets were absent).	Kusio and Noda, 2003
UK	-	~0.5-6 fibres 50ml^{-1} sediment	Subtidal sediments more contaminated than sandy and estuaries.	Thompson et al., 2004
Hawaii	61X61cm, 5.5cm deep	~950 plastics L^{-1}	High tide line has more hard plastic fragments and pellets.	McDermid and McMullen, 2004
India	5-10kg, 5cm deep (scoop)	~81.43 mg plastic kg^{-1} sandy	Items fragmented on the beach.	Reddy et al., 2006
Singapore	surface (1cm) and subsurface (~10cm)	0-4 items $replicate^{-1}$	Urban beaches are more contaminated by polyethylene fragments.	Ng and Obbard, 2006
Fernando de Noronha	900cm² in the strandline	0.005 g plastic g^{-1} sandy	13 of 15 quadrats were contaminated; pellets identified only on windward beaches. Hard plastic fragments and pellets	Ivar do Sul et al., 2009
Northeast Brazil	988cm² in the strandline	0.29 fragments cm^{-2}	Hard plastic fragments (1-20 mm) and pellets.	Costa et al., 2010
Tamar estuary, UK	50ml (upper 3cm)	<2-8 fragments 50ml^{-1} sediment	Microplastics denser than macroplastics; downwind sites more contaminated by microplastic fragments.	Browne et al., 2010
Island of Malta	1m^2	0.7-167 pellets m^{-2}	Pellets prevalent on the backshore; pellets associated with tar.	Turner and Holmes, 2010
Hawaii	5-cm-diameter		PE change physical properties of beaches	Carson et al., 2011

	sediment cores		increasing permeability and lowering subsurface temperatures.	
Belgian coast	Van Veen grab	166 items kg^{-1} (harbours)	Plastic pellets in harbours; plastics on beach sediments have tripled since 1993.	Claessens et al., 2011
9 countries all over the world	1cm deep; sewage and washing machines effluents	2-31 fibres $250ml^{-1}$ of sediment	Fibres from sewage via washing clothes. High plastic amounts in high population areas.	Browne et al., 2011
East Frisian Islands	500g sediment, 1cm deep	210 granules kg^{-1}; 460 fibres kg^{-1}	Fragments and pellets absent.	Liebezeit and Dubaish, 2012
47 beaches all over the world	Scanning Electron Microscope		Virgin plastic pellets surface is smooth and uniform. Eroded pellets surface is rough and uneven.	Fotopoulou and Karapanagioti, 2012
Continents			Absence of works on microplastics in terrestrial soils.	Rillig, 2012
-	Munich Plastic Sediment Separator (MPSS)	-	Construction of a density separator of microplastics from sediment samples.	Imhof et al., 2012
-	µ-FT-IR	-	Applicability of reflectance µ-Fourier-transform infrared spectroscopy to the detection of microplastics in sediments.	Harrison et al., 2012
Lagoon of Venice	box-corer, 1-5cm deep	672 - 2175 fragments kg^{-1} sediment	Plastic fragments (PE and PP, 30-500µm) accumulated at low hydrodynamic sites.	Vianello et al., 2013
Chile	50X50 cm, 2cm deep	~27 fragments m^{-2}	Volunteer survey. 90% of samples (N=39) contaminated by plastic fragments (1-4.75mm).	Hidalgo-Ruz and Thiel, 2013

Table S3: Peer-reviewed papers on the ingestion of microplastics by vertebrates (fish, seabirds and marine mammals), each group ordered chronologically. Details about the biota and the main focus of the works were presented. All were field surveys of contaminated animals.

	Biota	Main focus	Reference
VERTEBRATES	***Fish***		
	Fish	8 of 14 species ingested plastic white pellets.	Carpenter et al., 1972
	Myctophidae	35% ingested plastic fragments (1-2.79mm); number of plastics was related to the fish size.	Boerger et al., 2010
	Ariidae	23% ingested nylon fibres and hard plastic fragments.	Possatto et al., 2011
	Fish	9% ingested plastics fragments (~2.2mm) and threads; net feeding was considered relevant during sampling.	Davison and Asch, 2011
	Gerreidae	~13% ingested blue nylon fragments (1-5mm) probably during feeding.	Ramos et al., 2012
	Stellifer brasiliensis, Stellifer stellifer	~8% ingested blue nylon fragments; highest number was in adults during the late rainy season in the middle estuary.	Dantas et al., 2012
	Myctophidae	~40% (mostly *M. lychnobium* and *C. andreae*) ingested plastics. No relation with the fish size.	van Noord, 2013
	Pelagic and demersal fish	~36% ingested fibres and fragments (~1-2mm); semi synthetic debris related with sewage effluents.	Lusher et al., 2013
	Seabirds		
	Shearwaters and Albatrosses	Albatross chicks were feed (pellets and fragments) at the breeding colony by parents; shearwaters ingested smaller items.	Fry et al., 1987*
	Petrels	Migratory seabirds probably ate fragments (~2.0-5mm) and pellets plastics outside Antarctica.	van Franeker and Bell, 1988
	Petrels, shearwaters and prions	Ingested pellets decrease for all species from 1980's to 2000's decades. Fragments increased.	Ryan, 2008
	Fulmarus glacialis	> 80% ingested fragments and pellets; ingestion rates are 3X greater than other studies.	Provencher et al., 2009
	Petrels, Albatrosses and shearwaters	~40% ingested fragments and pellets; most frequent among petrels (62%).	Colabuono et al., 2009*

Petrels, Albatrosses and shearwaters	28% ingested fragments and pellets; PCBs and other organic chemicals identified on fragments and pellets.	Colabuono et al., 2010*
Uria lomvia	11% ingested fragments; ingestion rates decreased when the latitude increased.	Provencher et al., 2010*
Fulmarus glacialis	Amounts of ingested pellets decreased and fragments (>1mm) increased (1980's to 2000's decades).	van Franeker et al., 2011
Fulmarus glacialis	> 90% ingested fragments; the incidence is higher when compared to other regions.	Avery-Gomm et al., 2012*
Fulmarus glacialis	78% ingested fragments and pellets; pollution levels in the North Atlantic decrease towards higher latitudes.	Kühn and van Franeker, 2012
Calonectris diomedea	83.5% ingested nylon threads; plastics were regurgitated by their parents during feeding.	Rodriguéz et al., 2012
Larus glaucescens	Fragments (<1cm) were found in 12% of boluses (N=589) collected by volunteers.	Lindborg et al., 2012
Phoebastria immutabilis, P. nigripes	>60% of albatrosses ingested fragments and nylon lines; lines related with fishing.	Gray et al., 2012
20 marine and aquatic bird species	2.7% of the Common Murre ingested fragments and pellets; small sample sizes limit conclusions about other groups.	Avery-Gomm et al., 2013*
Puffinus tenuirostris	Transference of PBDEs from ingested plastics to the tissues.	Tanaka et al., 2013
Marine Mammals		
Arctocephalus tropicalis, A. gazella	Microplastic fragments (~4.1mm) on scats associated with food (fish).	Eriksson and Burton, 2003
Balaenoptera physalus	Phthalates in blubber related to the ingestion of plastics.	Fossi et al., 2012
Phoca vitulina	12% ingested microplastics.	Rebolledo et al., 2013

* Not only microplastics were reported.

Table S4: Peer-reviewed papers on the ingestion of microplastics by invertebrates ordered chronologically. Details about the biota, type of ingested items and the main focus of the works were presented. All were controlled laboratory experiments testing the potential ingestion of microplastics.

	Biota	Type of items	Main focus	Reference
INVERTEBRATES	Amphipods, lugworms and barnacles	Microfibres	All ingested microplastics.	Thompson et al., 2004
	Mytilus edulis	Polystyrene microplastics	Mussels ingested and accumulated microplastics for at least 48 days.	Browne et al., 2008
	Holothurians	Fragments, PVC pellets and nylon	Holothurians ingested plastics in a variety of shapes and sizes.	Grahan and Thompson, 2009
	Nephrops norvegicus	Filaments and balls	83% ingested plastics related to the lobster fishery.	Murray and Cowie, 2011*
	M. edulis	Nanopolystyrene	Ingestion triggered the formation of pseudofeces and reduced filtration.	Wegner et al., 2012
	M. edulis	Polyetylene	Plastics ingested and causes effects to the animals.	von Moos et al., 2012
	Dosidicus gigas	Pellets, fishing line	8 out of 30 animals ingested plastics.	Braid et al., 2012*
	Arenicola marina	Polystyrene microplastic	Lugworms ingested but not accumulate plastics; contamination by PCB sorbed onto plastics.	Besseling et al., 2013
	M. edulis, Carcinus maenas	Polystyrene microplastic	Small amounts were transferred from mussels to crabs.	Farrel and Nelson, 2013
	Marine zooplankton	Polystyrene pellets	Copepoda, Tunicata, Euphausiacea, Cnidaria, Mollusca and Decapoda ingested microplastics in the laboratory. Potential impacts are highlighted.	Cole et al., 2013
	Talitrus saltator	Polyetylene pellets	Sandhoppers ingested and expelled microplastics in the laboratory. Effects not observed during the 7 days of experimentation.	Ugoloini et al., 2013*

* Include field survey.

Table S5: Peer-reviewed papers on the absorption of pollutants onto microplastic particles ordered chronologically. Type of plastics, measured pollutants, their concentrations and location of the works were detailed.

Type of plastic	Pollutants		Location	Reference
Pellets (PP)	PCBs	4-117 ng g-[1]	Japan	Mato et al., 2001
	DDE	0.16-3.1 ng g^{-1}		
	Nonylphenols	0.13-16 µg g^{-1}		
Pellets	PCBs	<28-2300 ng g^{-1}	Japan	Endo et al., 2005
Pellets and fragments (PP)*	PCBs	27-980 ng g^{-1}	NPCG and the California coastline	Rios et al., 2007
	PAHs	39-1200 ng g^{-1}		
	Aliphatic PAHs	1.1-8600 µg g^{-1}		
	DDTs	22-7100 ng g^{-1}		
Fragments (PVC, PP and PE)	PAH (Phenanthrene)	-	Laboratory experiment	Teuten et al., 2007
Pellets	PCBs	~300-600ng g^{-1}	US	Ogata et al., 2009
		~50-400ng g^{-1}	Japan, W Europe	
		<50ng g^{-1}	S Asia, Australia, S Africa	
	DDTs	~100-300ng g^{-1}	US, Vietnan	
		<20ng g^{-1}	Japan, W Europe, Australia, S Africa	
Pellets	PAH (Phenanthrene)	-	Laboratory experiment	Karapanagioti and Klontza, 2008
Pellets (PE)**	Al	7.05-49.79 µg g^{-1}	UK	Ashton et al., 2010
	Fe	25.85-64.97 µg g^{-1}		
	Mn	1.28-8.31 µg g^{-1}		
Pellets	PCBs	0.02-15.56 ng g^{-1}	Portugal	Frias et al., 2010
	PAHs	0.2-319.2 ng g^{-1}		
	DDTs	0.16-4.05 ng g^{-1}		
Fragments*	PCBs	1-2566 ng g^{-1}	NPCG	Rios et al., 2010
	PAHs	1-4395 ng g^{-1}		
	Aliphatic PAHs	1-6227 µg g^{-1}		

	Organochlorines	1-176 ng g^{-1}		
Pellets	PCBs PAHs DDTs HCHs	6000-290,000pg g^{-1} 100-500 ng g^{-1} 0.56-25 ng g^{-1} 0.09-1.41 ng g^{-1}	Greece	Karapanagioti et al., 2011
Microplastics	Organic pollutants	-	Laboratory experiment	Gouin et al., 2011
Fragments (PVC and PE)	Phenanthrene + DDT	-	Laboratory experiment	Bakir et al., 2012
Pellets (PE)	PCBs HCHs DDTs	41-113 (1980's)-25-61 (2000's) ng g^{-1} 5-112 (1980's)- 2-5 (2000's) ng g^{-1} 18-1281 (1980's)- 8-30 (2000's) ng g^{-1}	South Africa	Ryan et al., 2012
Pellets and fragments	PAHs PCBs Chlordanes DDTs	30 ng g^{-1}-1900 ng g^{-1} non-detect-47 ng g^{-1} 1.8 ng g^{-1}-60 ng g^{-1} non-detect-76 ng g^{-1}	San Diego, USA	Van et al., 2012
Pellets	PCBs PAHs	-	San Diego, USA	Rochman et al., 2013
Pellets	PAHs	386-1996 ng g^{-1}	Santos, Brazil	Fisner et al., 2013
Pellets	PCBs PAHs HCHs DDTs Hopanes	10.5-307 ng g^{-1} 50-24,000 ng g^{-1} 0-0.86 ng g^{-1} 0-49 ng g^{-1} 8.3-71 µg/g	Portugal	Mizukawa et al., 2013

* Not only microplastics.
** Other metals were also quantified.

CAPÍTULO II

Pelagic microplastics around an archipelago of the Equatorial Atlantic

The Saint Peter and Saint Paul Archipelago, in the Equatorial Atlantic Ocean. Source: Comissão Interministerial para os Recursos do Mar (CIRM).

Research highlights

- Microplastics occur in an isolated archipelago in the Equatorial Atlantic Ocean;
- The observed items had secondary sources and were fragments, threads and rubber crumbs;
- Plastics accumulate near (<100 m) the seamount;
- Fishing is probably a source of these synthetic polymer items.

Marine Pollution Bulletin 75 (2013) 305–309

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Baseline

Pelagic microplastics around an archipelago of the Equatorial Atlantic

Juliana A. Ivar do Sul[a,*], Monica F. Costa[a], Mário Barletta[a], Francisco José A. Cysneiros[b]

[a] Laboratório de Ecologia e Gerenciamento de Ecossistemas Costeiros e Estuarinos, Departamento de Oceanografia, Universidade Federal de Pernambuco, Av. Arquitetura s/n, CEP 50740-550 Recife, PE, Brazil

[b] Departamento de Estatística, Universidade Federal de Pernambuco, Recife, PE, Brazil

ARTICLE INFO

Keywords:
Plankton samples
Small-scale survey
Hard plastic fragments
Synthetic threads
Rubber crumbs
Saint Peter and Saint Paul Archipelago

ABSTRACT

Plastic marine debris is presently widely recognised as an important environmental pollutant. Such debris is reported in every habitat of the oceans, from urban tourist beaches to remote islands and from the ocean surface to submarine canyons, and is found buried and deposited on sandy and cobble beaches. Plastic marine debris varies from micrometres to several metres in length and is potentially ingested by animals of every level of the marine food web. Here, we show that synthetic polymers are present in subsurface plankton samples around Saint Peter and Saint Paul Archipelago in the Equatorial Atlantic Ocean. To explain the distribution of microplastics around the Archipelago, we proposed a generalised linear model (GLM) that suggests the existence of an outward gradient of mean plastic-particle densities. Plastic items can be autochthonous or transported over large oceanic distances. One probable source is the small but persistent fishing fleet using the area.

© 2013 Elsevier Ltd. All rights reserved.

Plastics are a complex problem in the marine environment. The quantities and consequences of macroplastics in the oceans and coastal habitats have been well documented in the literature for at least four decades (e.g., Ivar do Sul and Costa, 2007; Moore, 2008; Barnes et al., 2009). Presently, the scientific community is focused on microplastics (defined as plastics with less than 5 mm), a size fraction much more abundant (Law et al., 2010; Browne et al., 2011; Andrady, 2011) and probably most hazardous to marine organisms (Eriksson and Burton, 2003; Thompson et al., 2004). The ingestion of microplastics has been documented for vertebrates (Moore, 2008; Boerger et al., 2010) and invertebrates (Wright et al., 2013) from every level of the marine food web and is very likely to be related to the plastics' size, shape and colour, although additional studies are needed to clarify these questions. Expected consequences of an ingestion event are physical injuries and blockage, but microplastics are alsoefficient in the transport of sorbed organic and inorganic pollutants, which can contaminate animal tissues (Teuten et al., 2009; Tanaka et al., 2013).

The first attempt to quantify floating plastic debris was made in the Western North Atlantic Ocean (Carpenter and Smith, 1972; Law et al., 2010) nearly 40 years ago, but studies have also been reported for the North Pacific Ocean (e.g., Moore et al., 2001) since the turn of the XXI[st] century. Recently, other oceans were reported to also be contaminated by microplastics (e.g., Collignon et al., 2012). Therefore, the problem seems to be widespread throughout the ocean basins. However, the appropriate sampling procedures are difficult, especially in remote areas, and many years of studies will be needed to characterise the magnitude of microplastic pollution. Experts have suggested that floating plastics from archived plankton samples should be used to further improve our present knowledge (Arthur et al., 2009), revealing information on microplastic amounts and spatial distributions. This sample re-purposing has been already done successfully in large-scale studies (i.e., Thompson et al., 2004; Law et al., 2010; Morét-Ferguson et al., 2010). Following this international trend but focused on a small-scale perspective, we examined existing plankton samples from the Saint Peter and Saint Paul Archipelago (0°55′N, 29°20′W), a remote oceanic seamount that rises only a few metres above sea level on the Mid-Atlantic Ridge (Fig. 1A).

Our initial hypothesis is that, despite its geographic isolation, this archipelago is not free from pelagic microplastic pollution. Searching for microplastics in this remote environment is very different from conducting plankton tows in the centres of subtropical gyres, where large, positively buoyant plastics are known to accumulate, mainly due to surface currents and winds (Moore et al., 2001; Moore, 2008; Morét-Ferguson et al., 2010; Maximenko et al., 2012). In this equatorial region, the mechanisms that drive the local distribution of microplastics around the Saint Peter and Saint Paul Archipelago are not known but are probably more influenced by smaller-scale phenomena (particle aggregation or animal activities) (Hidalgo-Ruz et al., 2012) than by variables acting over whole oceanic basins. In the Archipelago, the prevailing wind-driven current is the northern branch of the oligotrophic South Equatorial Current (SEC), which flows westward (Lumpkin and

* Corresponding author. Tel.: +55 81 21267223; fax: +55 81 21268225.
E-mail address: julianasul@gmail.com (J.A. Ivar do Sul).

0025-326X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpolbul.2013.07.040

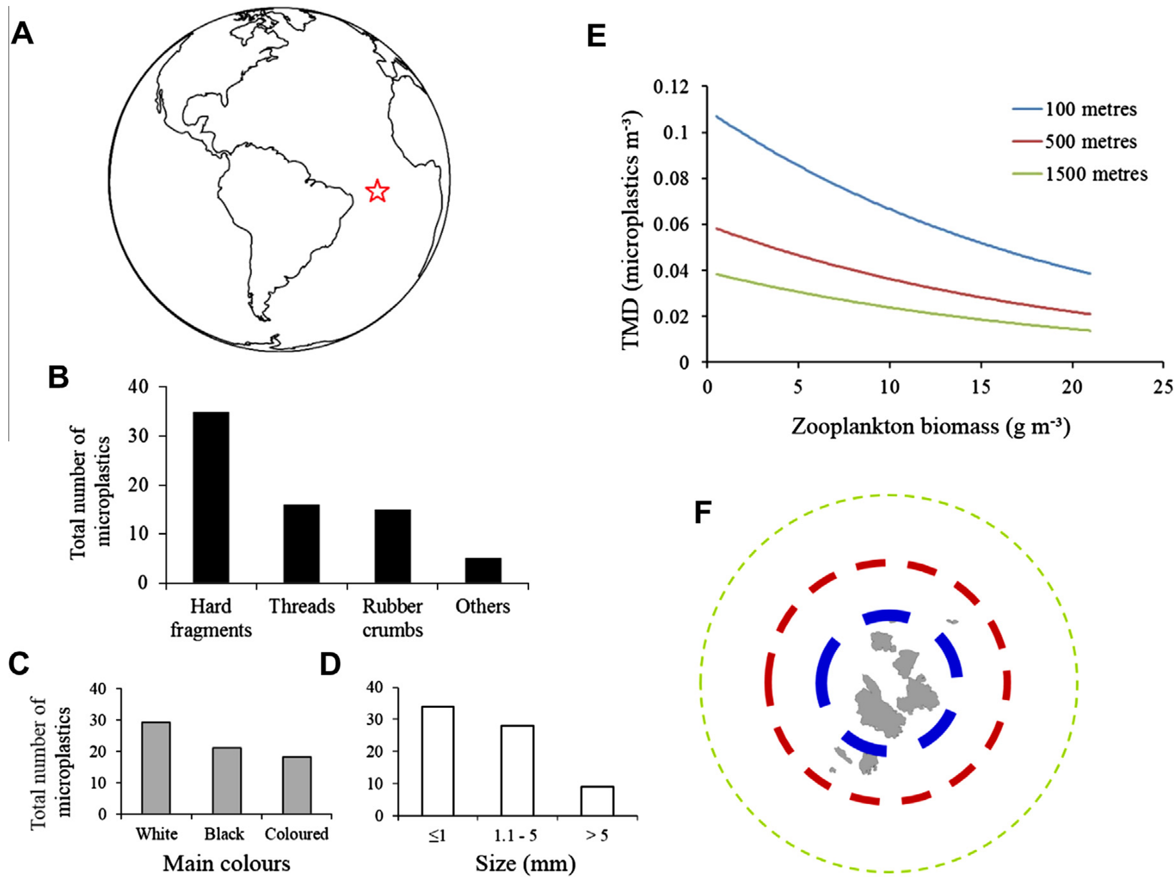


Fig. 1. (A) Saint Peter and Saint Paul Archipelago (☆). Shapes (B), sizes (C) and colours (D) of the observed microplastics ($N = 71$). (E) Total mean density of microplastics (TMD microplastics m^{-3}) versus zooplankton biomass ($g\ m^{-3}$). The curves are the fitted values calculated according to our model. (F) The Saint Peter and Saint Paul Archipelago in the centre of the circles, which represent the sampling distances: blue, <100 m; red, 100 < distance < 500 m; and green, 500 < distance < 1500 m. The colours are the same as those plotted in Fig.1E. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Garzoli, 2005). In addition, the Equatorial Undercurrent (EU) is a shallow current (40–150 m depth) derived from the North Brazil Current, which flows eastward, eventually reaching the sea surface (Stramma and Schott, 1999). Both of these currents are parallel to the Equator (Stramma and Schott, 1999; Lumpkin and Garzoli, 2005).

Around oceanic islands and seamounts, horizontal interactions between biological and physical mechanisms aggregate and concentrate plankton (at small scales), frequently enhancing biological production (Genin, 2004). In this context, initial research aroundthe Saint Peter and Saint Paul Archipelago intended to test variations of zooplankton biomass, abundance and diversity. Subsurface (0–0.6 m from the surface) plankton tows (5–10 min at 2 knots) were conducted at three distances from the Archipelago (<100 m, 100–500 m and 500–1500 m) in April, August and November 2003 and in March 2004. Samples were collected with a conical–cylindrical plankton net (0.6 m mouth diameter), with 300 μm mesh size and 2 m length, equipped with a flowmeter. The samples were fixed (4% formalin) before storage.

For plastic surveys, these archived plankton samples were filtered through a 0.45 μm filter and freeze-dried. The dried material was weighed and observed under a stereomicroscope (5×). Plastic items were separated and classified regarding their appearance, shape, size and colour.

The dry material present in the samples was composed almost exclusively of zooplankton. From the 88 horizontal subsurface tows, 41% contained at least one, and a maximum of eight, microplastics. A total of 71 individual items were recognised and were classified according to their shape as hard fragments, threads and rubber crumbs (Figs. 1B and 2). The total mean density was approximately 1 item per 100 m^3 of seawater. All the microplastics derived from the breakdown of larger objects (Barnes et al., 2009; Ivar do Sul et al., 2009), i.e., were secondary-sourced plastics (Arthur et al., 2009; Hidalgo-Ruz et al., 2012). The particle sizes varied from ~1 mm to >5 mm (Fig. 1C), and the predominant colours were white/transparent, black and a third group of coloured items (Fig. 1D). The 300 μm mesh size is the most commonly used mesh for microplastics sampling (Hidalgo-Ruz et al., 2012) and was successfully applied to sample microplastics.

Surprisingly, we did not find any plastic resin pellets, commonly present in oceanic plankton samples (Moore et al., 2001; Law et al., 2010) and on beaches of oceanic islands, such as the Fernando de Noronha Archipelago (3°S, 32°W) (Ivar do Sul et al., 2009). There, the occurrence of plastic pellets was restricted to windward beaches, constantly exposed to the northern branch of the SEC, which is also the prevalent large-scale wind-driven current observed in the Saint Peter and Saint Paul Archipelago. Therefore, local sources of items might be prevalent over long-range oceanic transport of plastics near round the Saint Peter and Saint Paul Archipelago.

At the Archipelago, all the identified microplastics have secondary sources. The pieces were weathered fragments of larger plastic items, most likely polypropylene and polyethylene, which represent the majority of the plastic polymers produced (and consequently discarded) worldwide (Andrady, 2011). In equatorial oceans, where the sunlight radiation is intense, constant throughout the year and shines 12 h day^{-1}, plastics are exposed to extreme

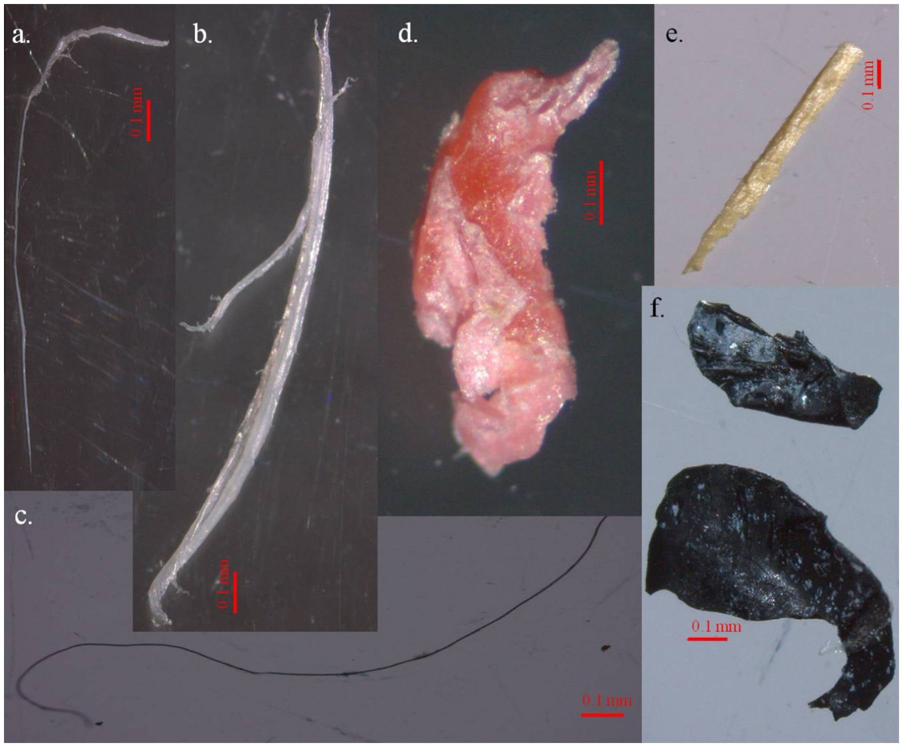


Fig. 2. Threads (a, b and c) and fragmented polymers (d, e and f) collected in subsurface waters around the Saint Peter and Saint Paul Archipelago, Equatorial Atlantic Ocean. All the collected plastics were less than 2.5 cm in length.

degradation conditions because light-induced oxidation is undoubtedly the main factor responsible for the fragmentation of plastics in the marine environment (Andrady, 2011).

The observed threads (Fig. 2a–c) are possibly related to fishery activities near the Archipelago (Vaske et al., 2005; Luiz and Edwards, 2011). Fisheries are a recognised source of microplastics to the marine environment (Moore, 2008; Andrady, 2011), and their secondary-sourced fragments were previously identified in plankton tows elsewhere (i.e., Moore et al., 2001; Collignon et al., 2012; Hidalgo-Ruz et al., 2012). To illustrate the magnitude of this activity in the Archipelago, commercial fishing has been named responsible for the extinction of shark populations (Luiz and Edwards, 2011). Therefore, we considered that at least part of these fragments had autochthonous sources. However, as previously noted by other researchers, it is much more difficult to determine even the most probable source of hard plastic fragments (e.g., Barnes et al., 2009; Ivar do Sul et al., 2009).

Once the presence of microplastic fragments in the Archipelago was confirmed, we asked if there was any particular behaviour (in this case, the occurrence of microplastics) related to the distance (<1500 km) from this seamount, as observed for other living and non-living particles around the Archipelago (Macedo-Soares et al., 2012; Brandão et al., 2013). To explain the distribution of microplastics around the Archipelago, a generalised linear model (GLM) was developed.

Environmental variables that were considered relevant (and that were available for the area) for explaining the distribution of pelagic plastics around the Archipelago were assessed. These variables were the monthly total precipitation, water temperature and salinity, wind velocity and direction and chlorophyll *a* level. Water temperature and salinity were measured *in situ* concomitantly with plankton tows. Chlorophyll *a* values were obtained from the literature (Macedo-Soares et al., 2012), and wind velocity, wind direction and precipitation were obtained from the nearest oceanic mooring (0°, 35°W) (http://www.pmel.noaa.gov/pirata/). We identified two main seasons at the Archipelago (Table 1), characterised by high (300 mm) and low (25 mm) total monthly precipitation (Macedo-Soares et al., 2012). Other environmental variables also varied seasonally (Table 1).

Table 1
Environmental conditions observed in the study area during the sampling. August and November are rainy months, and March and April are dry months.

Season/ environmental condition	Water temperature (°C)	Salinity	Chlorophyll *a* (mg m^{-3})	Wind velocity (m s^{-1})	Wind direction
Rainy	26	36	0.1	4.9	NE
Dry	28	38	1	6.5	SE

Selected environmental variables were used as covariates in the GLM together with the zooplankton biomass and the sampling distances from the Archipelago. Zooplankton biomass (dry weight) ranged from 0.34 to 20.81 g m^{-3} during both the rainy and dry seasons.

The initial dataset with 630 lines, corresponding to the detailed microplastic characteristics of the 88plankton tows, was altered by adding values in different lines to form a new dataset with fewer zeros, which allowed the use of more consistent statistical methods. First, lines were merged for the rainy and dry seasons separately. Because the number of zeros was still excessive, we merged the lines in the matrix considering the main colour of microplastics (white, black and coloured) (Fig. 1D). The procedure was then repeated, considering microplastic size classes (<1 mm, 1.1–5 mm, >5 mm) and shapes (Fig. 1C and B, respectively). The final dataset had 18 lines representing the two sampling seasons (rainy and dry) and three distances (<100 m, 100–500 m and 500–1500 m) from the Archipelago. This sum resulted in a new variable, the Total Mean Density of microplastics(TMD microplastics m^{-3}).

Then, we started developing the GLM with eight environmental covariates (i.e., monthly total precipitation, water temperature and salinity, zooplankton biomass, sampling distances from the Archi-

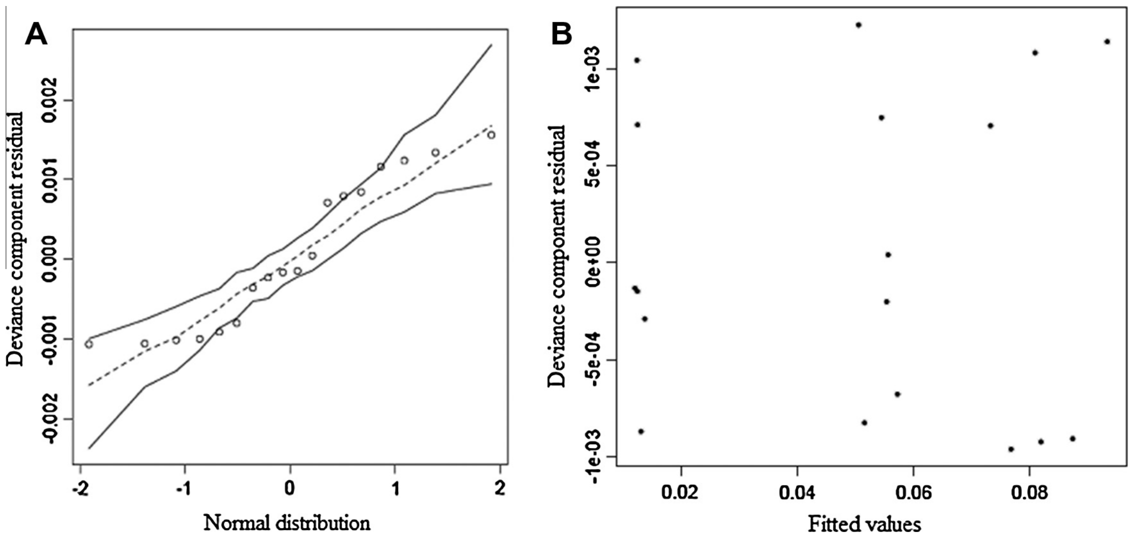


Fig. 3. (A) Normal probability plot with envelopes of the fitted model. (B) Plot of deviance component residual versus fitted values.

pelago, wind velocity and direction, and chlorophyll *a*) (forming the saturated model). We used an Exploratory Data Analysis (EDA), a stepwise process and the AIC criteria to select the most adequate GLM until no further improvement was possible. Non-significant variables were progressively eliminated until the final model was obtained (Eq. (1)). Those variables with numerical values that remained fairly constant throughout the year (mainly because the Archipelago is in an equatorial oceanic region) or that apparently did not influence the densities of plastic fragments were left out of the model. Finally, the selected covariates included in the GLM were those two that could significantly ($p < 0.1$) explain the TMD of microplastics around the Saint Peter and Saint Paul Archipelago (Eq. (1)).

To validate the selected model, a residual analysis was also conducted. The normal probability plot with envelopes (Fig. 3A) did not show any unusual behaviour. Thus, the hypothesis of normal distribution for the errors of the model can be used. The plot of deviance-component residuals versus fitted values (Fig. 3B) also presented a randomised behaviour. The GLM was built using R software (R Development Core Team 2009).

Our final GLM has two (from initial 8) covariates, zooplankton-biomass (Zoo_{biom}) and sampling distances from the Archipelago ($Dist_{100}$, $Dist_{500}$ and $Dist_{1500}$), which were significant to explain the behaviour of the TMD of microplastics (Y_i) sampled around the Archipelago:

$$Y_i = \exp\{\beta_0 + \beta_1 \mathrm{Dist}_{500i} + \beta_2 \mathrm{Dist}_{1500i} + \beta_3 \mathrm{Zoo}_{\mathrm{biom}i}\} + \varepsilon_i \quad i = 1, \ldots, 18 \tag{1}$$

where i is the number of observations, $\varepsilon_i \sim \mathrm{N}(0, \sigma^2)$, Dist_{500i} = (1 if i^{th} 100 < distance $\leqslant$ 500 m; 0 in other cases), and Dist_{1500i} = (1 if i^{th} 500 < distance $\leqslant$ 1500 m; 0 in other cases).

The fitted curves are defined as follows:

$$\widehat{\mathrm{TMD}} = \exp\{-2.2097 - 0.0499\mathrm{Zoo}_{\mathrm{biom}}\} \text{ if distance} \leqslant 100\text{ m} \tag{2}$$

$$\widehat{\mathrm{TMD}} = \exp\{-2.8185 - 0.0499\mathrm{Zoo}_{\mathrm{biom}}\} \text{ if } 100 < \text{distance} \leqslant 500\text{ m} \tag{3}$$

$$\widehat{\mathrm{TMD}} = exp\{-3.2393 - 0.0499\mathrm{Zoo}_{\mathrm{biom}}\} \text{ if } 500 < \text{distance} \leqslant 1500\text{ m} \tag{4}$$

The residual deviance is 0.012 (14 df) with a p-value = 0.449 for the goodness-of-fit test. The Akaike Information Criterion (AIC) = -70.057 ($\widehat{\sigma}^2$ = 0.0008). The GLM indicates that the Total Mean Density ($\widehat{\mathrm{TMD}}$) of microplastics decreases outward, while the zooplankton biomass is constant (Fig. 1E and Eqs. (2)–(4)).

Oceanographic mechanisms around the Saint Peter and Saint Paul Archipelago promote the topographic trapping of zooplankton (Genin, 2004; Macedo-Soares et al., 2012; Brandão et al., 2013). Therefore, microplastics may likewise aggregate and be retained bysmall-scale circulation patterns. Reef fish (Macedo-Soares et al., 2012) and semi-terrestrial decapod larvae (Brandão et al., 2013) are more abundant at distances < 100 m from the Archipelago than further away. However, holopelagic decapods (Brandão et al., 2013), which reproduce in pelagic environments, follow the opposite trend. This pattern reinforces the results shown by our model and our suggestion of the occurrence of autochthonous sources. Microplastics might be retained close to the Archipelago, as are reef fish larvae.

Moreover, microplastics are known to be ingested by planktivorous fishes (Boerger et al., 2010), which are then preyed on by top predators. A possible pathway along the trophic web in the Saint Peter and Saint Paul Archipelago is suggested because the transfer of microplastics along marine food webs is a demonstrated issue (Eriksson and Burton, 2003; Farrell and Nelson, 2013). *Cypselurus cyanopterus* is an example of a planktivorous fish preyed on by seabirds, such as *Sula leucogaster*, and large pelagic fishes, such as *Thunnus albacares* (Vaske et al., 2005), which are important ecologic and economic taxa that might be exposed to microplastic pollution. This exposure is a concern in the context of the environment's isolation and the risk of microplastics pollution at the individual to community levels.

References

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605.

Arthur, C., Baker, J., Bamford, H., (Eds.), 2009. Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Micro-plastic Marine Debris, September 9–11, 2008. NOAA Technical, Memorandum NOS-OR&R-30.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. Roy. Soc. B 364, 1985–1998.

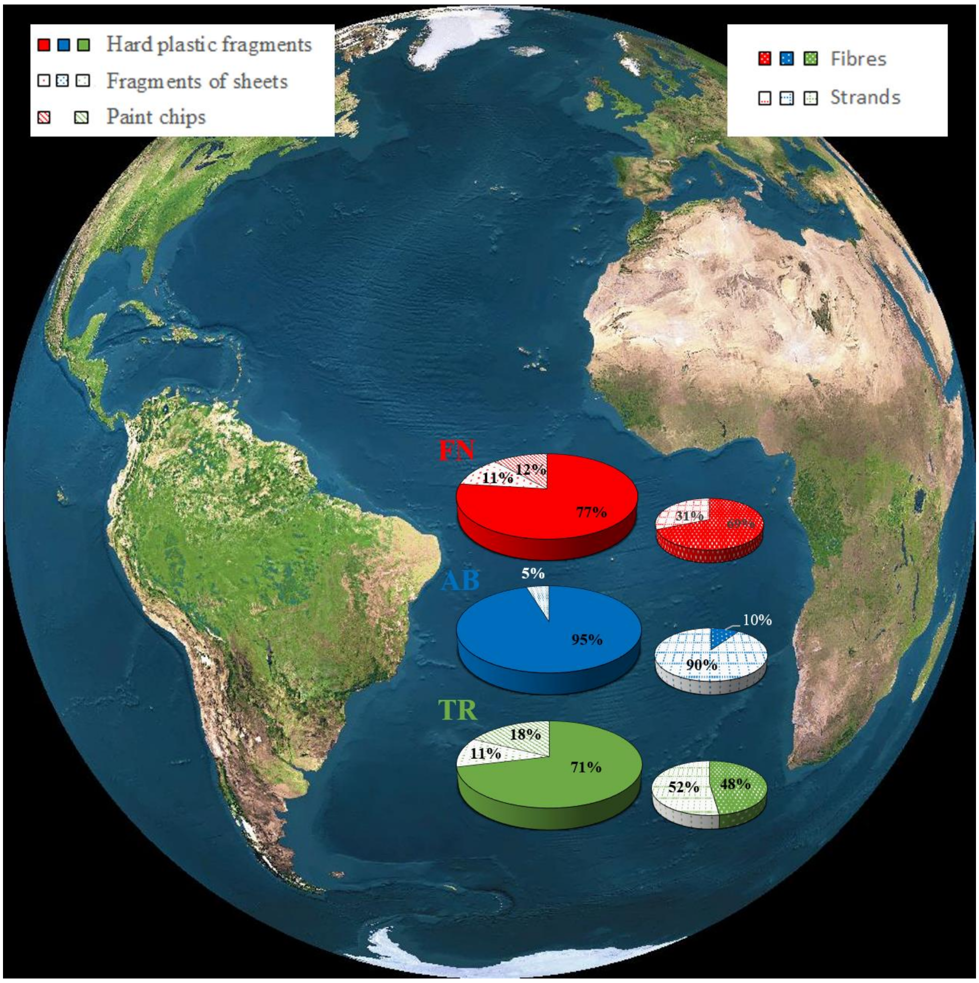
Boerger, C.M., Lattin, G.L., Moore, S.L., Moore, C.J., 2010. Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Mar. Pollut. Bull. 60, 2275–2278.

Brandão, M.C., Koettker, A.G., Freire, A.S., 2013. Distribution of decapod larvae in the surface layer of an isolated equatorial oceanic archipelago: the cases of benthic *Grapsus grapsus* (Brachyura: Grapsidae) and pelagic *Sergestes edwardsi* (Dendrobranchiata: Sergestidae). Helgol. Mar. Res. 67, 155–165.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179.
Carpenter, E.J., Smith, K.L., 1972. Plastics on the Sargasso Sea surface. Science 175, 1240–1241.
Collignon, A., Hecq, J.H., Glagani, F., Voisin, P., Collard, F., Goffart, A., 2012. Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Mar. Pollut. Bull. 64, 861–864.
Eriksson, C., Burton, H., 2003. Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. Ambio 32, 380–384.
Farrell, P., Nelson, K., 2013. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). Environ. Pollut. 177, 1–3.
Genin, A., 2004. Bio-physical coupling in the formation of zooplankton and fish aggregations over abrupt topographies. J. Mar. Syst. 50, 3–20.
Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the Marine environment: a review of methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075.
Ivar do Sul, J.A., Costa, M.F., 2007. Marine debris review for Latin America and the Wider Caribbean region: from the 1970s until now, and where do we go from here? Mar. Pollut. Bull. 54, 1087–1104.
Ivar do Sul, J.A., Spengler, A., Costa, M.F., 2009. Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). Mar. Pollut. Bull. 58, 1236–1238.
Law, K.L., Morét-Ferguson, S., Maximenko, N., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic subtropical gyre. Science 329, 1185–1188.
Luiz, O.J., Edwards, A.J., 2011. Extinction of a shark population in the Archipelago of Saint Paul's Rocks (Equatorial Atlantic) inferred from the historical record. Biol. Conserv. 144, 2873–2881.
Lumpkin, R., Garzoli, S.L., 2005. Near-surface circulation in the Tropical Atlantic Ocean. Deep-Sea Res. I 52, 495–518.
Macedo-Soares, L.C.P., Freire, A.S., Muelbert, J.H., 2012. Small-scale spatial and temporal variability of larval fish assemblages at an isolated oceanic island. Mar. Ecol. Prog. Ser. 444, 207–222.
Maximenko, N., Hafner, J., Niiler, P., 2012. Pathways of marine debris from trajectories of Lagrangian drifters. Mar. Pollut. Bull. 65, 51–62.
Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environ. Res. 108, 131–139.
Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A comparison of plastic and plankton in the North Pacific Central Gyre. Mar. Pollut. Bull. 42, 1297–1300.
Morét-Ferguson, S., Law, K.L., Proskurowski, G., Murphy, E.K., Peacock, E.E., Reddy, C.M., 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Mar. Pollut. Bull. 60, 1873–1878.
R Development Core Team, 2009. R: A Language and Environment for Statistical Computing. In: R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0 <http://www.R-project.org>.
Stramma, L., Schott, F., 1999. The mean flow field of the tropical Atlantic Ocean. Deep-Sea Res. II 46, 279–303.
Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M., Watanuk, Y., 2013. Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. Mar. Pollut. Bull. 69, 219–222.
Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Björn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P.H., Tana, T.S., Prudente, M., Boonyatumanond, R., Zakaria, M.P., Akkhavong, K., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagino, Y., Imamura, A., Saha, M., Takada, H., 2009. Transportand release of chemicals from plastics to the environment and to wildlife. Philos. Trans. Roy. Soc. B 364, 2027–2045.
Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838.
Vaske, T. Jr., Lessa, R.P., Nóbrega, M., Montealegre-Quijano, S., Marcante Santana, F., Bezersra, J.I. Jr., 2005. A checklist of fishes from Saint Peter and Saint Paul Archipelago, Brazil. J. Appl. Ichthyol. 21, 75–79.
Wright, S.L., Thompson, R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492.

<u>CAPÍTULO III</u>

Microplastics in the pelagic environment around oceanic islands of the Western Tropical Atlantic Ocean



Relative contribution of hard plastic fragments, fragments of sheets, and paint chips (left) and fibres and strands (right) on the sea surface around Fernando de Noronha (red pizza), Abrolhos (blue pizza) and Trindade (green pizza).

Highlights

- Pelagic microplastics are widespread on the Pacific and North Atlantic Ocean's surface;
- For the first time, the presence fragments and fibres is reported in the western tropical Atlantic;
- Fragments and fibres were mostly related to marine-based sources;
- Plastic pellets were almost absent;
- Microplastic pollution threatens marine biota, including endemic species.

Water Air Soil Pollut (2014) 225:2004
DOI 10.1007/s11270-014-2004-z

Microplastics in the pelagic environment around oceanic islands of the Western Tropical Atlantic Ocean

Juliana A. Ivar do Sul · Monica F. Costa · Gilberto Fillmann

Received: 13 December 2013 / Accepted: 14 May 2014
© Springer International Publishing Switzerland 2014

Abstract Recent evidence suggests that microplastic pollution is widespread in every oceanic basin; however, there is limited data available for the tropical South Atlantic Ocean. The purpose of this study was to examine the distribution, density and characteristics of plastic particles in plankton samples collected in the western tropical Atlantic Ocean. Neustonic tows ($N=160$) were conducted near three important insular environments (Fernando de Noronha, Abrolhos and Trindade), and the presence of microplastics in the ocean surface of these areas was confirmed for the first time. The collected microplastic particles included hard plastic fragments, plastic films, paint chips and fibres and strands, which were classified as a secondary source of microplastics. The stock of plastic originates from both land-based and marine-based sources. This type of marine pollution in the tropical Atlantic Ocean is a potential threat to important ecological species.

Keywords Pelagic ecosystems · Oceanic islands · Blue Amazon · Southern Hemisphere · Neustonic samples · Small-scale survey

J. A. Ivar do Sul · M. F. Costa (✉)
Laboratório de Gerenciamento de Ecossistemas Costeiros e Estuarinos, Departamento de Oceanografia, Universidade Federal de Pernambuco, Recife, PE, Brazil
e-mail: mfc@ufpe.br

G. Fillmann
Laboratório de Microcontaminates Orgânicos e Ecotoxicologia Aquática, Universidade Federal do Rio Grande, Rio Grande, RS, Brazil

1 Introduction

The prediction that plastic marine debris would be one of the most important pollutants in the twenty-first century is now widely recognised. The fates and consequences of macroplastics (>5 mm) in oceanic and coastal environments and to the marine biota have been documented over the last 40 years (Moore 2008; Barnes et al. 2009; Thompson et al. 2009). However, the fragmentation of macroplastics to mesoplastics and microplastics remains poorly understood (Andrady 2011). Therefore, the current focus of the scientific community is on one of the smallest fractions of plastic pollution (i.e. microplastics <5 mm) (Barnes et al. 2009; Ivar do Sul and Costa 2014).

Recently, research on microscopic plastic particles has significantly increased worldwide (Cole et al. 2011; Hidalgo-Ruz et al. 2012; Ivar do Sul and Costa 2014). Microplastics pose a substantial threat to marine biota via ingestion because they are similar in size to many organisms in the benthos and plankton communities. Therefore, microplastics are widely available to the entire marine food web (Wright et al. 2013). Uptake depends on the size, shape and density of the particles (Browne et al. 2011). For vertebrates, the ingestion of plastics was suggested to be related to the type and colour of plastics prevalent in the marine environment (Ryan 2008). Studies on invertebrates are predominantly restricted to laboratory experiments (Wright et al. 2013), and the extent of the problem remains largely speculative (Ivar do Sul and Costa 2014). Moreover, the organic and inorganic chemical compounds in seawater may adsorb onto microplastic particles (Teuten et al. 2007) and potentially transport the pollutants over large oceanic areas (Zarfl and Matthies 2010). If ingested, contaminants may be released into gastrointestinal tracts and eventually contaminate tissues and organs (Tanaka et al. 2013).

Microplastics are directly released into the environment (i.e. primary source microplastics) (Thompson et al. 2009; Fendall and Sewell 2009) and continually formed at sea through degradation and subsequent fragmentation from larger plastic items (i.e. secondary source fragments) (Andrady 2011). The relative importance of secondary and primary source microplastics in the open ocean has yet to be established; however, recent evidence indicates that fragments are mostly sampled (e.g. Ryan 2008; Law et al. 2010). Polyethylene (PE) and polypropylene (PP) have a high probability of ending up in marine environments (Andrady 2011) because they are more widely produced (Table 1) and discarded. These polymers are denser than seawater, which makes them positively buoyant. Polyethylene terephthalate (PET) and rigid polystyrene (PS) are also polymers that are widely used in the production of throw-away plastics; however, they are not observed on the sea surface because they sink.

The sea surface and beach sediments are environmental matrices that are more widely studied in terms of microplastic pollution (Hidalgo-Ruz et al. 2012). The literature, which covers many regions over varying time periods, confirms that microplastic pollution is ubiquitous and frequently contaminates the sea surface, especially in the Northern Hemisphere (Ivar do Sul and Costa 2014). Pelagic plastics have been reported in the North Pacific and Atlantic Oceans, at the centre of subtropical gyres (Moore et al. 2001; Law et al. 2010) and along urbanised coastal areas (Lattin et al. 2004; Doyle et al. 2011). Microplastics have been sampled in the western Mediterranean Sea (Collignon et al. 2012), the North Sea (Dubaish and Liebezeit 2013) and the Laurentian Great Lakes (Eriksen et al. 2013a).

In the equatorial region, microplastics have been sampled around a remote archipelago in the Atlantic Ocean (Ivar do Sul et al. 2013). However, data on the presence and characteristics of microplastic pollution in the Southern Hemisphere is significantly more limited. Surface tows have confirmed the presence of microplastics in the South Pacific subtropical gyre. They occurred in smaller densities but within the same range of magnitude as the density of microplastics in the North Pacific (Eriksen et al. 2013b). In the Atlantic Ocean, Ryan (1988) reported the presence of pelagic plastics around the African continent, whereas Barnes et al. (2009) confirmed their occurrence in the Southern Ocean.

Because no systematic study has been developed for the western tropical Atlantic, this study aimed to confirm the presence of floating microplastic particles in that region for the first time. Sampling was conducted around three insular environments (i.e. Fernando de Noronha Archipelago, Abrolhos Archipelago and Trindade Island) located within the 'Blue Amazon', a domain of approximately 4.5 million km^2 that includes the continental shelf and the Brazilian Exclusive Economic Zone (EEZ). The oligotrophic South Equatorial Current (SEC) is the major southern pathway by which water is transported into the tropical Atlantic (Stramma and Schott 1999). The central and southern branches of the SEC and the Brazilian Current are the main superficial currents that reach the studied islands (Lumpkin and Garzoli 2005) (Fig. 1a). The local circulation patterns remain unknown.

The mountain peaks of a volcanic cordillera along the Mid-Atlantic Ridge form the Fernando de Noronha Archipelago (Fig. 1a). The main island has an area of 17 km^2 and is the only inhabited island with a population of 3,000 residents. An additional 80,000 tourists visit the archipelago annually. The average air temperature is approximately 25 °C, and constant winds have a predominant SE direction (Fig. 1b). The Abrolhos Archipelago is on an enlargement of the Brazilian continental shelf (Fig. 1a). This archipelago is formed by five small (100–1,000 m in length) islands (i.e. Santa Bárbara, Redonda, Siriba, Sueste and Guarita) arranged in a semicircle (Fig. 1c). Only one island is inhabited (<10 people); however, 4,000 tourists visit the archipelago annually. The average air temperature is approximately 27 °C, and constant winds have predominantly SE/E direction (Fig. 1c). The volcanic islands of Trindade (8 km^2) and Martin Vaz in the Trindade-Vitória seamount chain are 5,600 m above the ocean floor and 600 m above sea level (Fig. 1a). The average air temperature is approximately 24 °C, and constant winds have a predominant NE/E direction (Fig. 1d). Unlike the other studied islands, Trindade is a military base where activities are restricted and tourism is prohibited.

Table 1 Polymers compositions identified by analytical procedures (appearance/shape) in surface seawater samples. The material density (relative to seawater) and percentage production were obtained from Andrady (2011)

Polymer type		Relative density	Percentage production	Appearance/shape	Reference
Low-density polyethylene	HDPE	0.91–0.93[a]	21	Fibres, fragments, pellets	Law et al. 2010; Morét-Ferguson et al. 2010; Ng and Obbard 2006; Thompson et al. 2004; Ryan 1988
High-density polyethylene	HDPE	0.94[a]	17	Fibres, fragments, pellets	Law et al. 2010; Morét-Ferguson et al. 2010; Ng and Obbard 2006; Thompson et al. 2004; Ryan 1988
Polypropylene	PP	0.85–0.83[a]	24	Fibres, strands, fragments	Doyle et al. 2011; Law et al. 2010; Morét-Ferguson et al. 2010; Thompson et al. 2004; Ryan 1988
Polystyrene	PS	1.05[a]	6	Resin pellets	Carpenter et al. 1972
Polyvinyl chloride	PVC	1.38[b]	19	–	–
Polyethylene terephthalate	PET	1.37[b]	7	–	–
Acrylic, polyamide, polyester	–	[b]	–	Fibres	Thompson et al. 2004

[a] Positively buoyant in seawater

[b] Negatively buoyant in seawater

After microplastics in the western tropical Atlantic were detected, we determined the density, type, size and colour of the microplastics, which objectively reflects the contamination patterns of the entire western Atlantic. Finally, the contamination patterns of Fernando de Noronha, Abrolhos and Trindade were compared.

2 Materials and Methods

2.1 Survey Methods

One hundred and sixty neustonic plankton tows were conducted around the islands of Fernando de Noronha, Abrolhos and Trindade using an inflatable boat. Samples were collected in the austral summers of 2011/2012 and 2012/2013 using a manta trawl net (3.5 m in length with a 300-μm mesh size) that was equipped with a flowmeter (Moore et al. 2001). The size of the rectangular net opening was 0.9×0.15 m^2. Each sample was obtained at an average speed of 1.5 knots for 15 min. The tows were conducted at the windward and leeward side of each island according to the prevailing winds (Fig. 1b, c, d). Samples (500 ml) were fixed in 4 % formalin before storage. In the laboratory, samples were filtered and freeze-dried. The dried material was weighed (0.01 g) and observed under a stereomicroscope (5X) (Ivar do Sul et al. 2013).

The microplastics were separated and classified according to their appearance/shape, size and colour. The following five categories were defined: hard plastic fragments, plastic films, paint chips, fibres and strands (Fig. 2 a-e). Plastic resin pellets were only detected in small amounts (n=4, 1.6 % of the total) and not treated as a separate category in this study. When detected, they were classified as hard plastic fragments because of their visual appearance and hardness. Polystyrene foam was not observed in these samples. For fragments, films and paint chips, each item was individually sorted, counted and measured (longest axis—mm). The volume (m^3) of each individual tow was obtained with a flowmeter and used to calculate the density of microplastic particles, which was expressed as particles per cubic metre of seawater.

In this study, fibres and strands were treated separately. By visual identification, the strands were observed to be significantly thinner than the fibres (Fig. 2d, e). Although the fibres and strands have been sorted, they have not been separated and individually measured because high amounts were detected in the contaminated samples. However, we combined all of the fibres and strands from each sample in a Petri dish that used millimetre paper with 3×3 mm^2 squares as a reference. Then, we measured the area (mm^2) of the

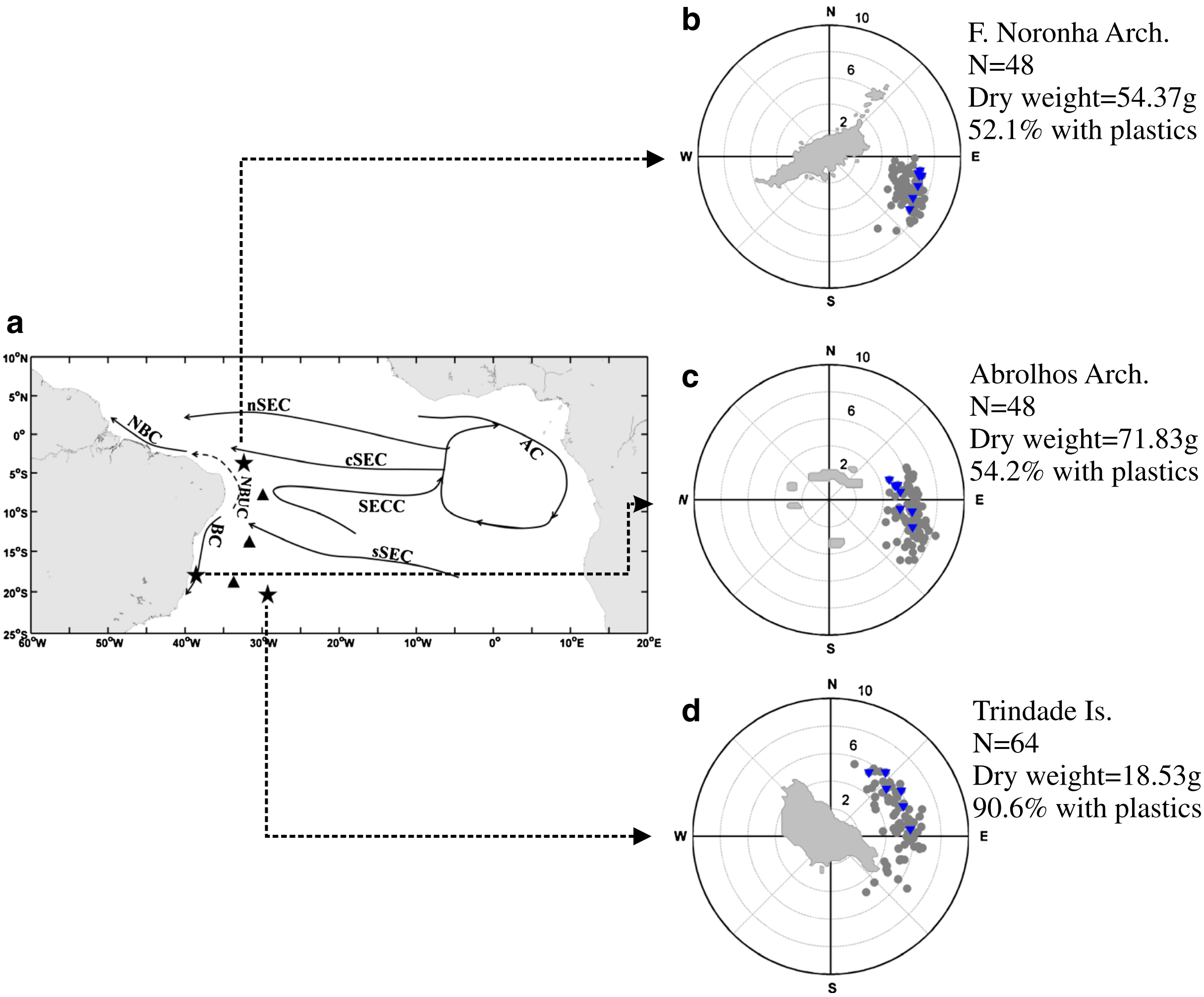


Fig. 1 **a** Position of the Fernando de Noronha Archipelago, Abrolhos Archipelago and Trindade Island in the western tropical Atlantic in relation to main surface currents (*nSEC*, *cSEC* and *sSEC* South Equatorial Current; north, central and southern branches, respectively; *SECC* South Equatorial Counter-Current; *BC* Brazil Current; *NBC* North Brazilian Current; *NBUC* North Brazilian Under-Current; and *AC* Agulhas Current); *filled stars* indicate the studied islands and *filled triangles* indicate the position of the oceanic moorings (8° S-30°W, 14° S-32°W, 19°S-34°W). Predominant wind direction and speed (ms^{-1}) in **b** Fernando de Noronha (November, 2012), **c** Abrolhos (March, 2013) and **d** Trindade (January, 2012). Wind direction and speed are monthly averages (http://www.pmel.noaa.gov/pirata/) from 5 years (2005-2013) (filled grey circles) and from the specific sampling months (filled blue inverted triangles)

square (or squares) covered by the fibres and strands, which resulted in a unit (density) expressed in square millimetres per cubic metre of seawater. All images were obtained with AxioVs40 V 4.8.2.0 software from Carl Zeiss Vision.

2.2 Statistical Analysis

Factorial analysis of variance (ANOVA) was used to determine the differences between several microplastic variables (total number of particles, total area (mm^2) of fibres/strands, particles m^{-3}, area m^{-3}) amongst the studied islands, leeward and windward sides of each island, categories of sampled items and colours (i.e. white/transparent versus coloured microplastic). The data were transformed (Box and Cox 1964) to increase the normality of the distribution. An a posteriori Fisher's LSD test was used to determine significantly different means at a probability level of 0.05 when the results from the ANOVA showed a significant difference.

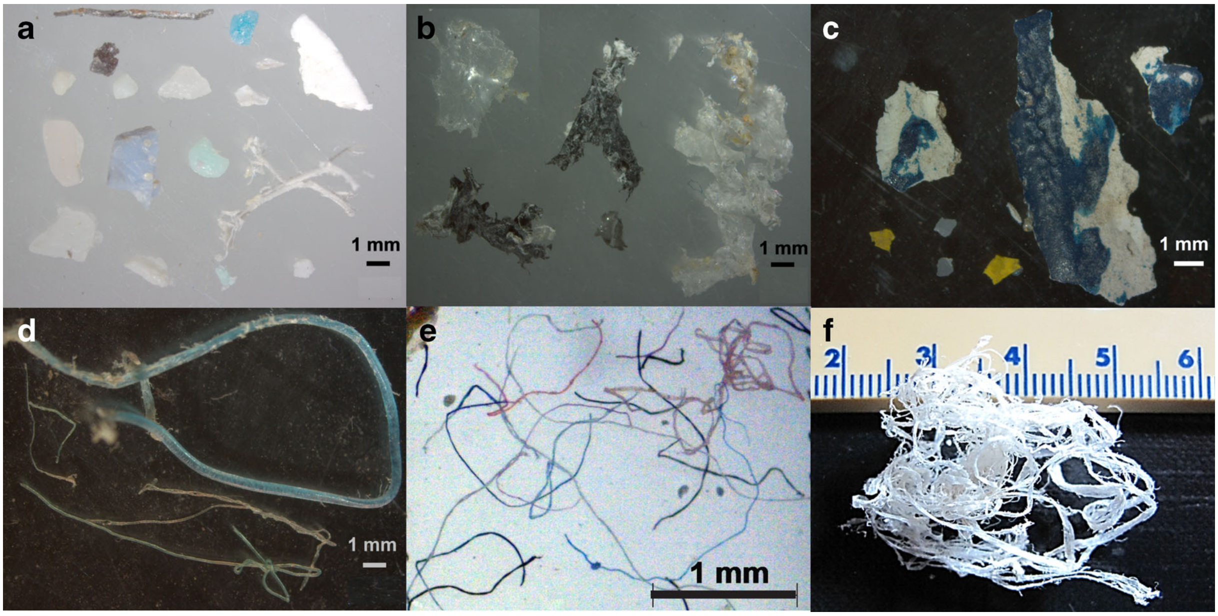


Fig. 2 Hard plastic fragments (**a**), plastic films (**b**), paint chips (**c**), fibres (**d**, **f**) and strands (**e**) collected from surface waters in the western tropical Atlantic Ocean

3 Results and Discussion

3.1 General Contamination Patterns

More than 16,000 m^3 of seawater was filtered during the samplings. Plankton samples weighed 144.7 g (total dry weight) and included marine algae, zooplankton, ichthyoplankton and other materials (e.g. terrestrial leaves and feathers). Two outliers were identified for Fernando de Noronha and Abrolhos, which represented 56 and 40 % of the dry weight, respectively. From the 160 net tows, 68 % contained microplastics from the five predefined categories (Fig. 2). Proportionally, Trindade was the most contaminated with ~90 % (n=64) of all samples containing microplastic debris. Approximately half of the samples collected from Abrolhos (n=48) and Fernando de Noronha (n=48) contained microplastic debris.

Therefore, the presence of pelagic microplastics in the western tropical Atlantic Ocean was confirmed. Surface tows have been successfully applied to sample microplastics in the open ocean (Hidalgo-Ruz et al. 2012) using small-scale ~1.5 km (Ivar do Sul et al. 2013) and large-scale ~4 × 10^3 km (Law et al. 2010) surveys. Several microplastic categories sampled in this study (i.e. hard plastic fragments, plastic films and paint chips) (Fig. 2) are comparable to others that have been collected elsewhere (Morét-Ferguson et al. 2010; Doyle et al. 2011; Eriksen et al. 2013a), including in the equatorial Atlantic Ocean (Ivar do Sul et al. 2013). Amongst them, hard plastic fragments commonly represent the majority of plastic items detected in plankton samples (Moore et al. 2001). Indeed, few primary source plastics (i.e. resin plastic pellets) were sampled in this study. However, they were commonly collected with other floating microplastic particles (e.g. Morét-Ferguson et al. 2010; Eriksen et al. 2013b), such as in the net tows conducted in the South Atlantic Ocean in the early 1980s (Morris 1980). Moreover, in the western Atlantic, the occurrence of plastic pellets on windward beaches in the Fernando de Noronha Archipelago has been previously reported (Ivar do Sul et al. 2009). After studying the gastrointestinal tracts of seabirds that ingested plastics in a marine environment, Ryan (2008) also reported the dominance of plastic fragments. The proportion of plastic pellets significantly decreased from 1980 to the 2000s, but because the total load of ingested plastics did not significantly vary between decades, the author attributed this change to the increase in secondary source plastics in the environment (Ryan 2008).

These evidences suggest that the highest proportion of total floating particles is plastic fragments, whereas the smallest proportion is pellets (Morét-Ferguson et al. 2010; Doyle et al. 2011; Eriksen et al. 2013b). During the last 30–40 years, an increase in the use of single-use, throw-away products, which are eventually lost to the ocean, has been observed. Additionally, there has been an increase in the number of routes and fleets in the sea and the use of synthetic nets in the fishing industry. Plastic debris degrades slowly in marine environments. The fragmentation processes of various polymers remain speculative and restricted to controlled laboratory experiments. Therefore, over the last few decades, fragments have been continually formed at sea and transported from coastal areas to the open ocean, where they accumulate. If this is confirmed, the number of secondary source plastics in open oceans will continually increase until the fragmentation process stabilises.

Fibres and strands have not been frequently reported in plankton tows and remain associated with sedimentary environments (Ivar do Sul and Costa 2014). Numerous previous works have used archived samples to study microplastic debris on the sea surface (e.g. Law et al. 2010; Morét-Ferguson et al. 2010). Fibres may be lost when chemical substances (e.g. formaldehyde) are used to preserve the plankton samples. Indeed, because plastic fragments are prevalent and relatively easy to distinguish, fibres can be misidentified during laboratory work unless they occur in significant amounts, which is when the fibres can be differentiated as synthetic materials. Analytical techniques are still required to conclusively identify the type of polymer (Browne et al. 2011). Finally, the presence of fibres and strands in this study was detected in higher amounts compared with previous studies in the literature.

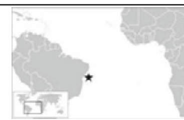
3.2 Fragments and Paint Chips

A total of 243 plastic particles were sampled (Table 2, Fig. 2a, b, c), and the mean contamination was determined to be 1.52 particles per tow. Hard plastic fragments (78 %) (Fig. 2a) were significantly more sampled (ANOVA, $p = 0.000$) than plastic films and paint chips. The majority (75 %) were 5 mm or smaller. Plastic films (9 % of the total) were also <5 mm in size (70 %) (Table 2). In the Atlantic Ocean, most (70–90 %) of the sampled particles were smaller than 10 mm and usually <5 mm (Law et al. 2010; Morét-Ferguson et al. 2010; Ivar do Sul et al. 2013). Because of their size, they are available to any level of the marine food web (Wright et al. 2013), from primary producers to large top predators (Ivar do Sul and Costa 2014). Few studies have reported on the prevalence of specific colours (e.g. Shaw and Day 1994); therefore, ingestion is more likely related to the availability of particles in the marine environment than to any colour-based selectivity amongst vertebrates (Boerger et al. 2010). However, additional studies are required. In this study, white and transparent plastic particles were more prevalent, but not significantly, than coloured particles (Table 3) (ANOVA, $p > 0.05$). This pattern was previously observed in the North Pacific Ocean (Shaw and Day 1994). The colour distribution of the floating plastics may be an indicator of the residence time of the plastic on the sea surface and may reveal any ingestion preferences by the marine biota. Therefore, the effect of microplastic colour has to be addressed in future studies.

Paint chips represented 12 % of the sampled plastic particles for the islands studied (Table 2, Fig. 2c). They are usually generated in boatyards, shipyards and at sea during the repair, maintenance and cleaning of vessel hulls. In the marine environment, they measure several centimetres to a few micrometres in length (Turner 2010). Moreover, evidence suggests that they can also fragment in the marine environment through erosion, a largely unstudied process. However, it is expected that antifouling substances used in paint formulations are released during this process (Singh and Turner 2009; Turner 2010), which is potentially threatening to the environment and its biota. Their distribution in the sea surface has not yet been systematically addressed (Turner 2010); however, a few studies have conclusively identified these particles in neuston samples (Morét-Ferguson et al. 2010; Eriksen et al. 2013a). There is a small port in Fernando de Noronha that maintains and services traditional boats; therefore, the presence of paint chips is expected. There is no port on Trindade; however, it is along the route of many boats and ships, which may remain in the area for extended periods (i.e. longline fishing vessels) (Pinheiro et al. 2010).

In the western tropical Atlantic, the mean concentration of plastic particles in the neuston was 0.03 particles per cubic metre of seawater (Table 4). Around the São Pedro e São Paulo Archipelago (Ivar do Sul et al. 2013), in the Southeast Bering Sea and along the southern California coast (Doyle et al. 2011), the densities of microplastics were on the same order of magnitude as those sampled in this study. The highest density of a single tow (0.13 particles m^{-3}) around the island of Trindade was comparable to coastal regions near highly urbanised areas (i.e. Los Angeles, CA) (Doyle et al. 2011) and values reported for other oceanic basins (Ivar do Sul and Costa 2014; Table 4).

Table 2 Compilation of results related to particle size (mm)

				
		Noronha Arch.	Abrolhos Arch.	Trindade Is.
		N=48	N=48	N=64
Hard fragments	N	20	61	109
	Mean value (mm)	3.6	2.8	1.9
	Standard deviation (mm)	3.4	2.6	1.9
	Minimum value (mm)	0.22	0.17	0.11
	Maximum value (mm)	12.56	14.59	11.22
	< 5 mm (%)	80	86	92
Plastic films	N	3	3	17
	Mean value (mm)	4.4	10.1	3.5
	Standard deviation (mm)	2.5	6.4	4.7
	Minimum value (mm)	2.26	2.76	0.09
	Maximum value (mm)	7.1	13.82	16.94
	< 5 mm (%)	66	33	76
Paint chips	N	3	0	27
	Mean value (mm)	0.4	–	1.5
	Standard deviation (mm)	0.1	–	1.9
	Minimum value (mm)	0.28	–	0.053
	Maximum value (mm)	0.56	–	10.37
	< 5 mm (%)	100	–	97
	Total	26	64	153
	Particles tow $^{-1}$	0.54	1.3	2.4

Paint chips were not observed around the Abrolhos Archipelago

3.2.1 Comparisons of the Studied Areas

Considering the total number of sampled particles (Table 2), Trindade was significantly more contaminated than Abrolhos and Fernando de Noronha (ANOVA, p=0.000). If only hard plastic fragments and plastic films were considered, both Trindade and Abrolhos were significantly more contaminated (ANOVA, p=0.000) by microplastic particles than Fernando de Noronha. Similarly, considering the density of microplastic debris (particles m^{-3}), Trindade and Abrolhos were significantly more contaminated than Fernando de Noronha (ANOVA, p=0.005). The majority of items were hard plastic

Table 3 Colours of particles sampled from the three studied islands. The percentage in parenthesis is related to the total number of sampled items (n=243)

	Category			
Colour	Hard plastic fragments	Plastic films	Paint chips	Total
Transparent/white	106	9	0	115 (47 %)
Blue/green	52	7	13	72 (30 %)
Black/grey	18	5	17	40 (16 %)
Yellow	11	0	1	12 (5 %)
Red	4	0	0	4 (2 %)

Table 4 Comparison of the present study with other sampled areas in relation to the distance from the coast (km)

Distance from the coast (km)	Location	Contamination patterns (particles m^{-3})	Source
0–5	California coast, USA	10[a]	Moore et al. 2002
0–100	Mediterranean Sea	1.21	Collignon et al. 2012
0–500	NE Pacific Ocean	0.004–0.19	Doyle et al. 2011
~1,000	Equatorial Atlantic Ocean	0.01	Ivar do Sul et al. 2013
~2,000	NPCG	2.23	Moore et al. 2001
70	Abrolhos Archipelago	0.04	This study
350	Fernando de Noronha Archipelago	0.015	
1,200	Trindade Island	0.025	
70–1,200	Tropical Atlantic Ocean	0.03	

NPCG North Pacific central gyre

[a] Before the storm

fragments and films (ANOVA, p=0.010). However, there were no significant differences between the leeward and windward sides of each island in terms of microplastic pollution.

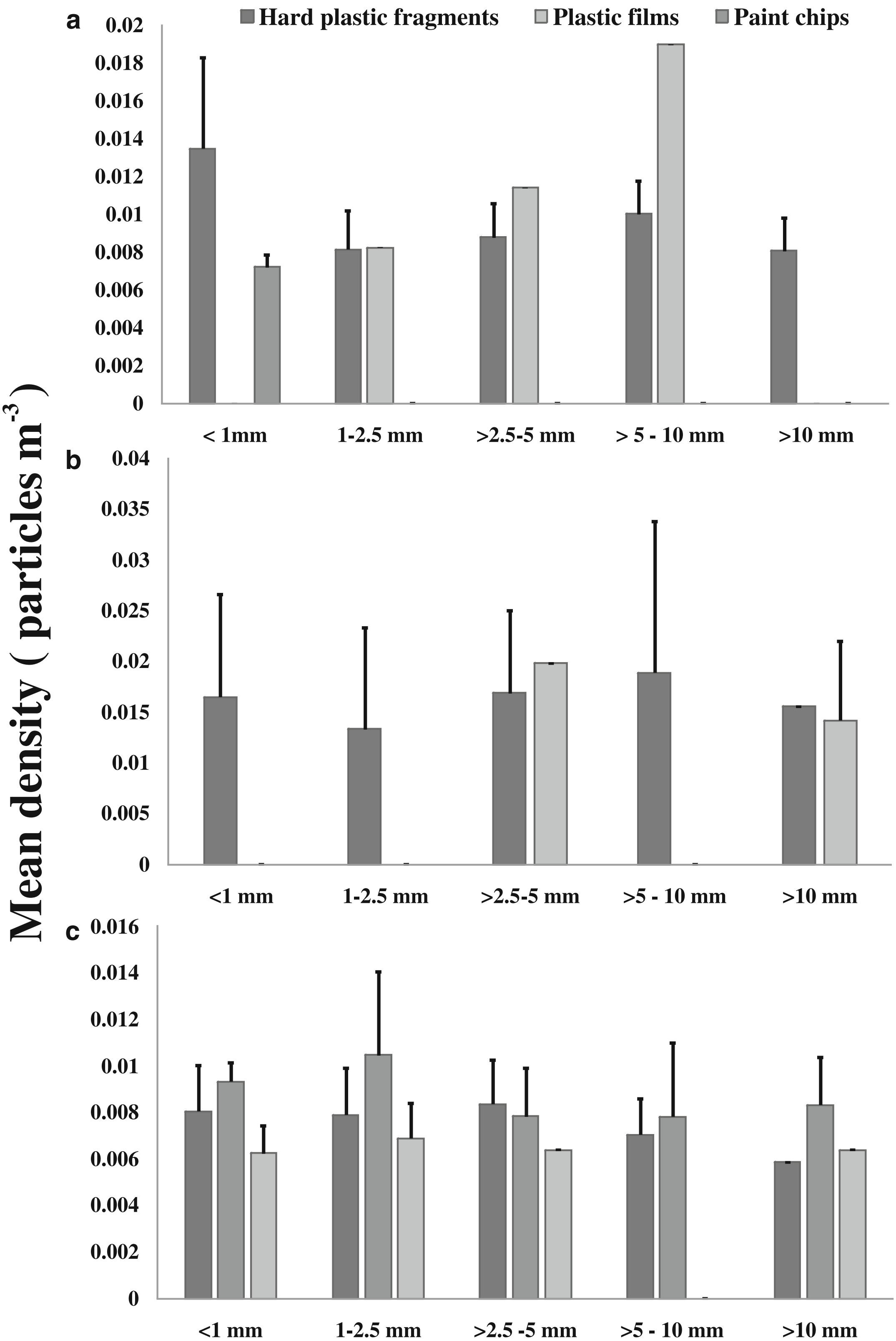
The Fernando de Noronha Archipelago is currently less contaminated by microplastic particles than other insular environments located in the western tropical Atlantic. The source of the floating particles that were sampled was probably not directly correlated to the garbage generated on the studied islands (i.e. autochthonous sources). An extremely different scenario was observed for Fernando de Noronha because it has a higher population density and receives thousands of tourists each year compared to the other islands. Therefore, the microplastics floating around Fernando de Noronha, Abrolhos and Trindade are being transported by prevailing currents and winds on the sea surface until they accumulate in the open ocean. It is difficult to discern whether these degraded fragments are being transported over long distances from land-based sources or if they are plastic items that were illegally dumped at sea (i.e. marine-based sources). Plastic fragments do not retain information regarding their origin or most probable source (Barnes et al. 2009; Doyle et al. 2011; Ivar do Sul et al. 2009). In Abrolhos, for instance, significant sedimentation rates (0.1–0.8 cm $year^{-1}$) from large hydrographical basins (i.e. Doce and Jequitinhonha) are able to reach the inner shelf around the archipelago (Knoppers et al. 1999), which is only 70 km from the shore. Therefore, continental discharges may contribute to the amount of plastic sampled, as was observed along highly populated coasts in the Northern Hemisphere (Ivar do Sul and Costa 2014).

A general trend of increasing density (particles m^{-3}) with decreasing particles size was not observed in this study (Fig. 3). This pattern was previously reported in the North Pacific gyre (Moore et al. 2001) and along the California coast (Doyle et al. 2011), where it was suggested to be related to the long-time permanence of secondary source plastic particles in the marine environment (Andrady 2011). In the western tropical Atlantic, the absence of such a pattern may indicate that plastics are continuously being released into the gyre faster than plastics are being fragmented in the ocean.

3.3 Fibres and Strands

A total area of 1,177 mm^2 of microplastics in the form of fibres and strands were sampled. One item represented 75 % of this area (Fig. 2f). This item may indicate that larger nets and ropes are fragmenting into smaller fibres and strands in marine environments. The fragmentation process may be more significant in tropical areas because the plastics are exposed to extreme degradation conditions (Andrady 2011; Ivar do Sul et al. 2013). The horizontal interactions between biological and physical mechanisms aggregate and concentrate plankton (Genin 2004), and most likely plastics (Ivar do Sul et al. 2013), near oceanic islands. Thus, fibres and strands were retained and sampled

Fig. 3 Size versus density (particles m^{-3}) of hard plastic fragments, plastic films and paint chips in **a** Fernando de Noronha, **b** Abrolhos and **c** Trindade. Note that the scale of the y-axis is different for (**a**), (**b**) and (**c**) ▶


a
Hard plastic fragments
Plastic films
Paint chips
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
< 1mm
1-2.5 mm
>2.5-5 mm
> 5 - 10 mm
>10 mm
b
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
<1 mm
1-2.5 mm
>2.5-5 mm
>5 - 10 mm
>10 mm
c
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
<1 mm
1-2.5 mm
>2.5 -5 mm
>5 - 10 mm
>10 mm
Mean density (particles m-3)

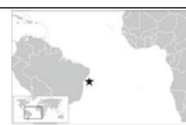
around the islands of Trindade, Fernando de Noronha and Abrolhos. For comparison, when the outlier is excluded (Table 5), this area (fibres plus strands) represents one third of the total area occupied by hard plastic fragments, plastic films and paint ships (>900 mm^2) in the same sample. If the hard plastic fragments were sorted on a Petri dish as fibres, they would occupy a larger surface area than the fibres and would be considered to be comparatively prevalent. In this way, the plankton tows sampled in this study were also more contaminated with plastic fragments as well as others that have been reported elsewhere (Barnes et al. 2009; Hidalgo-Ruz et al. 2012; Ivar do Sul and Costa 2014). The mean contamination was 1.88 mm^2 of fibres and strands per tow for all of the islands.

By visual identification, fibres (Fig. 2d) resemble fragments of fishing lines and have commonly been sampled in other surface plankton tows (e.g. Moore et al. 2001; Morét-Ferguson et al. 2010), including in the equatorial Atlantic Ocean (Ivar do Sul et al. 2013). Larger fishing lines are already widely recognised as a threat to marine biota, including large vertebrates and invertebrates (i.e. coral reefs, lobsters) because of the risk of entanglement (Moore 2008). It is possible that small fragments form fibres in the marine environment could potentially be ingested.

Strands are easily identified as synthetic polymers. Using a stereomicroscope, they are distinguished from natural particulates because of their bright and diverse colours (i.e. blue, red, green), which do not resemble marine animal and plant tissue (Browne et al. 2011). Strands have previously been reported in neuston samples that used meshes with smaller apertures in the sampling procedure (Thompson et al. 2004; Dubaish and Liebezeit 2013). In the North Sea, strands were correlated with the discharge of a local sewage treatment plant and most likely originated from the abrasion of synthetic textiles (i.e. polyester and polyacrylate) in washing machines (Dubaish and Liebezeit 2013). Browne et al. (2011) first observed the contamination of wastewaters by microplastic strands when studying the deposition of plastic on sediments around urbanised areas.

However, the presence of strands in the open ocean can also be related to fishing. It is possible that ropes and

Table 5 Compilation of results related to the area (mm^2) of fibres and strands

				
		Noronha Arch.	Abrolhos Arch.	Trindade Is.
		N=48	*N*=48	*N*=64
Fibres	Number of contaminated tows	16	1	14
	Area (mm²)	40.13	0.47	114.02
	Mean (mm²)	2.5	–	8.8
	Standard deviation (mm²)	1.3	–	6.8
	Minimum (mm²)	0.75	–	0.13
	Maximum (mm²)	5.02	–	20.86
Strands	Number of contaminated tows	13	1	33
	Area (mm²)	18.16	4.42	124.93
	Mean (mm²)	1.4	–	3.6
	Standard deviation (mm²)	1.2	–	5.3
	Minimum contamination (mm²)	0.16	–	0.39
	Maximum contamination (mm²)	4.37	–	29.39
	Total (mm²)	58.29	4.89	238.95
	mm² tow $^{-1}$	1.21	0.1	3.73

An outlier of 875 mm^2 (fibre) was removed from the Trindade island results nets (mainly PP) fragment in the marine environment and form strands (Thompson et al. 2004; Murray and Cowie 2011). This is a relevant source of plastics for islands located far from continental shores; however, no conclusive origins have been determined. In the Clyde Sea, lobsters (*Nephrops*) ingested microplastic strands that had fragmented from fishing ropes (Murray and Cowie 2011). Such plastics are particularly hazardous because they may clump and knot, which may prevent egestion (Murray and Cowie 2011; Cole et al. 2011). This type of microplastic debris was also reported in the gastrointestinal tracts of mesopelagic and benthophagous fish in oceanic (Davison and Asch 2011) and estuarine (Possatto et al. 2011) areas. It appears that they are distributed worldwide within the marine environment and its biota. Depending on the type and shape of the polymer, an increased bioavailability of adsorbed organic chemical compounds to marine environments could be observed (Browne et al. 2011), which further emphasises the environmental risks of microplastics to marine biota.

3.3.1 Comparisons Amongst the Studied Areas

The island of Trindade was predominately contaminated with microplastics in the form of fibres and strands when the area of the Petri dish and the total number of tows were considered (Table 5). However, no significant differences to the other islands were reported when both the total sample area (ANOVA, p=0.345) and density (mm^2/m^3) (p=0.331) of fibres were considered. Similarly, no significant patterns were reported for the leeward and windward sides of the islands.

Around the island of Trindade, fishing is a regular activity, even in swallow waters <2 km from the island (Pinheiro et al. 2010). Four different fisheries were identified (i.e. pelagic longline, bottom line, trolling and handline), which included the Brazilian fleet and clandestine vessels (Pinheiro et al. 2010). Indeed, signs of overfishing are evident (Pinheiro et al. 2010, 2011). In the São Pedro e São Paulo Archipelago, fishing was mainly associated with the occurrence of plastic threads (Ivar do Sul et al. 2013). This association was also reported in other studies on worldwide microplastic pollution (e.g. Moore et al. 2001; Morét-Ferguson et al. 2010). If fishing or maritime activities as a whole are confirmed as potential sources of microplastic fibres and strands to the marine environment, this type of pollution threatens all the insular habitats in this study, the Brazilian EEZ and the entire western tropical Atlantic.

4 Final Remarks

Floating microplastic particles are polluting the western tropical Atlantic, as confirmed by neustonic tows that were conducted around important insular environments. Microplastic pollution is most likely to be widespread over the entire surface of the tropical Atlantic Ocean, especially regarding the types of items. In this study, the contamination patterns were less than 1,000 particles km^{-2}. The counterpart gyre in the North Atlantic is significantly more contaminated with microplastics (>20,000 particles km^{-2} at 30° N) (Law et al. 2010); however, densities similar to those measured in our study have been reported in the Caribbean Sea.

Secondary source microplastics were largely dominant, which is a pattern that has also been reported for other oceanic basis, including subtropical gyres. The prevalence of fragments makes inferences about sources limited. Their origin is likely from either land-based or marine-based sources, such as from damaged fishing gear or other maritime activities that are performed at sea. However, only a few categories of items were sampled in this survey (Fig. 2), which was a recurring finding for all of the islands studied. Therefore, it is reasonable to assume that at least part of these fragments originated from the same source, which is occurring in the entire western Atlantic Ocean. FTIR analysis is the standard method that is used to conclusively determine the type of polymer, which reveals information regarding the possible source and origin of the microplastic fragment in the marine environment.

The presence of marine-based sources, if confirmed, emphasises the increased vulnerability of these islands and its organisms to marine pollution. Floating plastics emanate from everywhere, and there is currently no mechanism to abate this type of pollution (see recent discussion in Ivar do Sul and Costa 2014). Scientific predictions suggest that climate changes may affect circulation patterns and, consequently, the movement, accumulation and retention of plastic debris in space and time (Howell et al. 2012). The presented results could then also be used as a threshold measurement for contamination patterns in the western tropical Atlantic region.

Because the presence of microplastic debris was confirmed, it is important to predict the probable threat it poses to the marine biota in the western tropical Atlantic. Microplastics are known to be ingested by vertebrates and invertebrates in the plankton, nekton and benthos communities, which introduces them into the marine food web (Ivar do Sul and Costa 2014). The islands of Fernando de Noronha, Abrolhos and Trindade are, naturally, regions of high endemism and are most at risk for microplastic debris pollution.

For example, the Abrolhos Archipelago shelters the richest marine biodiversity in the South Atlantic Ocean (Werner et al. 2000). The archipelago is also an important region for the calving and feeding of newborn humpback whales (*Megaptera novaeangliae*) along the Brazilian coast. The ingestion of microplastics by cetaceans was reported in the Mediterranean Sea (Fossi et al. 2012); therefore, whales, including pups and juveniles, are at the eminent risk of ingesting microplastic pollution in the archipelago.

In conclusion, the evidence of microplastic pollution in this study and in the São Pedro e São Paulo Archipelago (Ivar do Sul et al. 2013) confirm that microplastic pollution is widespread throughout the western tropical Atlantic Ocean. In the near future, it is also important to investigate the marine region adjacent to the Rocas Atoll, where microplastics are also likely to be found. The focus of the scientific community must be on the continuous process of identifying sources of microplastic debris in the global oceans.

Acknowledgments We are grateful to the National Council for Scientific and Technological Research (CNPq) for the Ph.D. scholarship provided to Juliana A. Ivar do Sul (Process 551944/2010-2). We also thank the CNPq (Project 557184/2009-6) and the Brazilian Navy for the financial and logistic support provided to the project "Environmental contamination by persistent organic compounds, plastic fragments and pellets around the Trindade Island". We would also like to acknowledge Fundação Pró-Tamar and the Instituto Chico Mendes de Proteção à Biodiversidade (ICMBio) for assistance during field surveys in Fernando de Noronha and Abrolhos. Dr. Keyla Travassos, Oc. Luís Henrique B. Alves and Biol. Fernando C. de Sales Junior are acknowledged for their help during fieldwork in Abrolhos, Fernando de Noronha and Trindade, respectively. We thank the anonymous referee for the invaluable criticisms and contributions. M.F.C. and G.F. are CNPq Fellows.

References

Andrady, A. L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin, 62*, 1596–1605.

Barnes, D. K. A., Galgani, F., Thompson, R. C., & Barlaz, M. (2009). Environmental accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B, 364*, 1985–1998.

Boerger, C. M., Lattin, G. L., Moore, S. L., & Moore, C. J. (2010). Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. *Marine Pollution Bulletin, 60*, 2275–2278.

Box, G. E. P., & Cox, D. R. (1964). An analysis of transformations. *Journal of the Royal Statistical Society-Series B, 26*, 211–252.

Browne, M. A., Crump, P., Niven, S. J., Teuten, E. L., Tonkin, A., Galloway, T., et al. (2011). Accumulations of microplastic on shorelines worldwide: sources and sinks. *Environmental Science Technology, 45*, 9175–9179.

Carpenter, E. J., Anderson, S. J., Harvey, G. R., Miklas, H. P., & Peck, B. B. (1972). Polystyrene spherules in coastal waters. *Science, 175*, 749–750.

Cole, M., Lindeque, P., Halsband, C., & Galloway, S. C. (2011). Microplastics as contaminants in the marine environment: a review. *Marine Pollution Bulletin, 62*, 2588–2597.

Collignon, A., Hecq, J. H., Galgani, F., Voisin, P., & Collard, F. (2012). Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. *Marine Pollution Bulletin, 64*, 861–864.

Davison, P., & Asch, R. G. (2011). Plastic ingestion by mesopelagic fishes in the North Pacific subtropical gyre. *Marine Ecology Progress Series, 432*, 173–180.

Doyle, M. J., Watson, W., Bowlin, N. M., & Sheavly, S. B. (2011). Plastic particles in coastal pelagic ecosystems of the Northeast Pacific Ocean. *Marine Environmental Research, 71*, 41–52.

Dubaish, F., & Liebezeit, G. (2013). Suspended microplastics and black carbon particles in the Jade system, southern North Sea. *Water, Air, and Soil Pollution, 224*, 1–8.

Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Farley, W. E. H., et al. (2013a). Microplastic pollution in the surface waters of the Laurentian Great Lakes. *Marine Pollution Bulletin, 77*, 177–182.

Eriksen, M., Maximenko, N., Thiel, M., Cumminsa, A., Lattin, G., Wilson, S., et al. (2013b). Plastic pollution in the South Pacific subtropical gyre. *Marine Pollution Bulletin, 68*, 71–76.

Fendall, L. S., & Sewell, M. A. (2009). Contributing to marine pollution by washing your face: microplastics in facial cleansers. *Marine Pollution Bulletin, 58*, 1225–1228.

Fossi, M. C., Panti, C., Guerranti, C., Coppola, D., Giannetti, M., Marsili, L., et al. (2012). Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (Balaenoptera physalus). *Marine Pollution Bulletin, 64*, 2374–2379.

Genin, A. (2004). Bio-physical coupling in the formation of zooplankton and fish aggregations over abrupt topographies. *Journal of Marine System, 50*, 3–20.

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the marine environment: a review of methods used for identification and quantification. *Environmental Science Technology, 46*, 3060–3075.

Howell, E. A., Bograd, S. J., Morishige, C., Seki, M. P., & Polovina, J. J. (2012). On North Pacific circulation and associated marine debris concentration. *Marine Pollution Bulletin, 65*, 16–22.

Ivar do Sul, J. A., & Costa, M. F. (2014). The present and future of microplastic pollution in the marine environment. *Environmental Pollution, 185*, 352–364.

Ivar do Sul, J. A., Spengler, A., & Costa, M. (2009). Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). *Marine Pollution Bulletin, 58*, 1229–1244.

Ivar do Sul, J. A., Costa, M. F., Barletta, M., & Cysneiros, F. J. A. (2013). Presence of pelagic microplastics around an archipelago of the Equatorial Atlantic. *Marine Pollution Bulletin, 75*, 305–309.

Knoppers, B., Ekau, W., & Figueiredo, A. G. (1999). The coast and shelf of East and Northeast Brazil and material transport. *Geo-Marine Letters, 19*, 171–178.

Lattin, G. L., Moore, C. J., Zellers, A. F., Moore, S. L., & Weisberg, S. B. (2004). A comparison of neustonic plastic and zooplankton at different depths near the southern California shore. *Marine Pollution Bulletin, 49*, 291–294.

Law, K. L., Morét-Ferguson, S., Maximenko, N. A., Proskurowski, G., Peacock, E. E., Hafner, J., et al. (2010). Plastic accumulation in the North Atlantic subtropical gyre. *Science, 329*, 1185–1188.

Lumpkin, R., & Garzoli, S. L. (2005). Near-surface circulation in the Tropical Atlantic Ocean. *Deep-Sea Research. I, 52*, 495–518.

Moore, C. J. (2008). Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. *Environmental Research, 108*, 131–139.

Moore, C. J., Moore, S. L., Leecaster, M. K., & Weisberg, S. B. (2001). A comparison of plastic and plankton in the North Pacific central gyre. *Marine Pollution Bulletin, 42*, 1297–1300.

Moore, C.J., Moore, S.L., Weisberg, S.B., Lattin, G., Zellers, A. (2002). A comparison of neustonic plastic and zooplankton abundance in southern California's coastal waters. *Marine Pollution Bulletin, 44*, 1035–1038.

Morét-Ferguson, S., Law, K. L., Proskurowski, G., Murphy, E. K., Peacock, E. E., & Reddy, C. M. (2010). The size, mass, and composition of plastic debris in the western North Atlantic Ocean. *Marine Pollution Bulletin, 60*, 1873–1878.

Morris, R. J. (1980). Plastic debris in the surface waters of the South Atlantic. *Marine Pollution Bulletin, 11*, 164–166.

Murray, F., & Cowie, P. R. (2011). Plastic contamination in the decapod crustacean *Nephrops norvegicus* (Linnaeus, 1758). *Marine Pollution Bulletin, 62*, 1207–1217.

Ng, K. L., & Obbard, J. P. (2006). Prevalence of microplastics in Singapore's coastal marine environment. *Marine Pollution Bulletin, 52*, 761–767.

Pinheiro, H. T., Martins, A. S., & Gasparini, J. L. (2010). Impact of commercial fishing on Trindade Island and Martin Vaz Archipelago, Brazil: characteristics, conservation status of the species involved and prospects for preservation. *Brazilian Archives of Biology and Technology, 53*, 1417–1423.

Pinheiro, H. T., Ferreira, C. E. L., Joyeux, J.-C., Santos, R. G., & Horta, P. A. (2011). Reef fish structure and distribution in a south-western Atlantic Ocean tropical island. *Journal of Fish Biology, 79*, 1984–2006.

Possatto, F. E., Barletta, M., Costa, M. F., Ivar do Sul, J. A., & Dantas, D. V. (2011). Plastic debris ingestion by marine catfish: an unexpected fisheries impact. *Marine Pollution Bulletin, 62*, 1098–1102.

Ryan, P. G. (1988). The characteristics and distribution of plastic particles at the sea-surface off the southwestern Cape Province, South Africa. *Marine Environmental Research, 25*, 249–273.

Ryan, P. G. (2008). Seabirds indicate changes in the composition of plastic litter in the Atlantic and southwestern Indian Oceans. *Marine Pollution Bulletin, 56*, 1406–1409.

Shaw, D. G., & Day, R. H. (1994). Colour- and form-dependent loss of plastic microdebris from the North Pacific Ocean. *Marine Pollution Bulletin, 28*, 39–43.

Singh, N., & Turner, A. (2009). Trace metals in antifouling paint particles and their heterogeneous contamination of coastal sediments. *Marine Pollution Bulletin, 58*, 559–64.

Stramma, L., & Schott, F. (1999). The mean flow field of the tropical Atlantic Ocean. *Deep-Sea Research II, 46*, 279–303.

Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M., & Watanuki, Y. (2013). Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. *Marine Pollution Bulletin, 69*, 219–222.

Teuten, E. L., Rowland, S. J., Galloway, T. S., & Thompson, R. C. (2007). Potential for plastics to transport hydrophobic contaminants. *Environmental Science Technology, 41*, 7759–7764.

Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W. G., et al. (2004). Lost at sea: where is all the plastic? *Science, 304*, 838.

Thompson, R. C., Swan, S. H., Moore, C. J., & Vom Saal, F. S. (2009). Our plastic age. *Philosophical Transactions of the Royal Society B, 364*, 1973–1976.

Turner, A. (2010). Marine pollution from antifouling paint particles. *Marine Pollution Bulletin, 60*, 159–71.

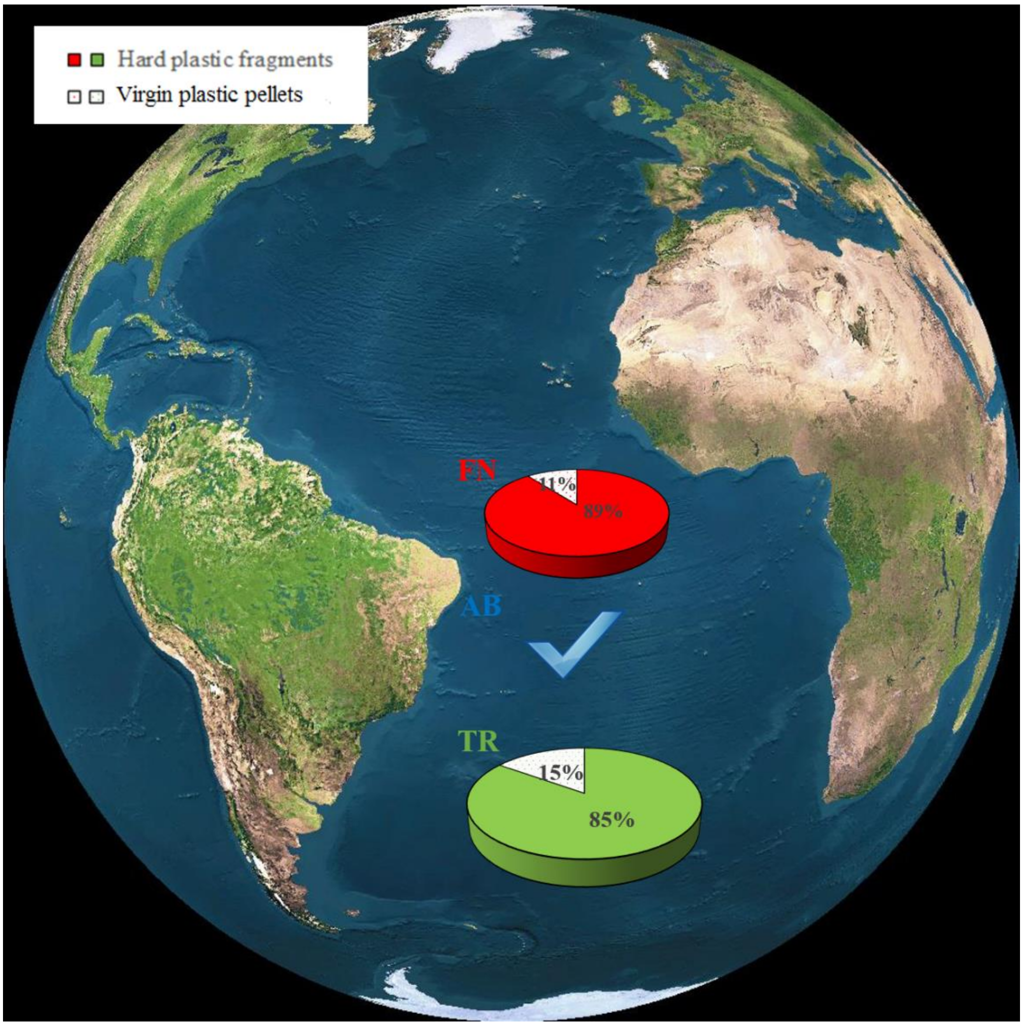
Werner, T., Pinto, L. P., Dutra, G. F., & Pereira, P. G. P. (2000). Abrolhos 2000: Conserving the southern Atlantic's richest coastal biodiversity into the next century. *Coastal Management, 28*, 99–108.

Wright, S. L., Thompson, R. C., & Galloway, T. S. (2013). The physical impacts of microplastics on marine organisms: a review. *Environmental Pollution, 178*, 483–492.

Zarfl, C., & Matthies, M. (2010). Are marine plastic particles transport vectors for organic pollutants to the Arctic? *Marine Pollution Bulletin, 60*, 1810–1814.

CAPÍTULO IV

Occurrence and characteristics of microplastics on insular beaches in the Western Tropical Atlantic Ocean



Relative contribution of hard plastic fragments and pellets on sandy beaches in Fernando de Noronha (red pizza) and Trindade (green pizza). Abrolhos was free from microplastic pollution on its beaches.

Highlights

- Microplastics pollute beach sediments worldwide, including oceanic islands;
- Microplastic fragments and pellets are the most sampled on beaches;
- In the western tropical Atlantic, Abrolhos Archipelago is, at present, free from this type of pollution;
- In Fernando de Noronha and Trindade, marine-based sources are probably prevalent over local sources;
- Microplastic pollution threatens marine fauna and their habitats use.

Occurrence and characteristics of microplastics on insular beaches in the Western Tropical Atlantic Ocean

Juliana A. Ivar do Sul[1*], Monica F. Costa[1] and Gilberto Fillmann[2]

[1] Laboratório de Gerenciamento de Ecossistemas Costeiros e Estuarinos, Departamento de Oceanografia, Universidade Federal de Pernambuco, Recife, PE, Brazil.

[2] Laboratório de Microcontaminates Orgânicos e Ecotoxicologia Aquática, Universidade Federal do Rio Grande, Rio Grande, RS, Brazil.

* Corresponding author. Tel.: +55(02181)2126 7223. E-mail: julianasul@gmail.com.

Abstract

Microplastics are widespread throughout oceans and seas and beaches are no exceptions. On beach sediments microplastics (<5mm) are commonly prevalent over macroplastics (>5mm), where fragments of larger items are sampled in greater amounts. The occurrence and characteristics of microplastics were investigated in beaches of Fernando de Noronha, Abrolhos and Trindade islands in the western tropical Atlantic Ocean. Despite no microplastic pollution was; identified in Abrolhos, small spatial variations were detected in Fernando de Noronha and Trinidade islands.

Keywords: Blue Amazon, oceanic islands, marine conservation, plastic fragments, virgin plastic pellets, size class.

Introduction

Macroplastics fragment on beach environments (i.e., secondary source fragments) (Andrady, 2011) and these fragments have been incorporated in coastal sediments around the world (Barnes et al., 2009). Field data confirm that microplastics (< 5mm) are an abundant size fraction of plastic debris pollution (e.g., Browne et al., 2011) being widespread throughout the oceans and seas (e.g., Depledge et al., 2013, Ivar do Sul and Costa, 2014), including deep-sea sediments (Cauwenberghe et al., 2013). Virgin plastic pellets and other particles manufactured to be of a microscopic size (i.e., primary source microplastics) are also incorporated to beach sediments after storm-water discharges and direct spills into the sea (e.g., McDermid and McMullen, 2004, Fendall and Sewell, 2009, Ivar do Sul et al., 2009).

Microplastics are probably much more hazardous than macroplastics to marine organisms from every level of the marine food web though ingestion (Wright et al., 2013). Evidences suggest that microplastic fragments, including fibres, can mimic natural food inciting ingestion events (Moore, 2008). Microplastic particles are also more efficient in the transport of sorbed organic and inorganic contaminants to remote areas, and can contaminate organisms once ingested (Tanaka et al., 2013).

Microplastics have been sampled on beach sediments through different methods, most focused on the recent particles deposited on the surface (e.g., Barnes et al., 2009, Hidalgo-Ruz et al., 2012). On mud sediments around industrialised areas, microplastics in the form of fibres are been commonly related to sewage and wastewater discharges (Browne et al., 2011). In oceanic islands, where small-sized sediments (i.e., sand) accumulate, beaches are frequently reported to be heavily impacted by ocean-borne plastics in the same size range of sediments, mainly in the Pacific Ocean (McDermid and McMullen, 2004, Moore, 2008, Hidalgo-Ruz et al., 2012, Ivar do Sul and Costa, 2014). In addition, in the Atlantic Ocean, primary source microplastic particles originating far from their shores and fragments were sampled on sandy beaches in the Fernando de Noronha archipelago (Ivar do Sul et al., 2009). Moreover, it is expected (Barnes et al., 2009, Ivar do Sul and Costa, 2014) that this type of marine debris pollution currently contaminates other insular beaches in the western tropical Atlantic Ocean, but the extent of the problem is still unknown.

Hence, the present study investigated, for the first time, the assessment of microplastic contamination (occurrence and physic characteristics) deposited on beaches in the Abrolhos archipelago and Trindade island, in the tropical western Atlantic Ocean

(Figure 1A), including a sample re-purposing in the Fernando de Noronha archipelago. Different aspects related to microplastic debris contamination were assessed and discussed.

Material and Methods

A total of 20 beaches were surveyed once in Fernando de Noronha (3°S, 32°W) (13 beaches), Abrolhos (17°S, 38°W) (3 beaches) and Trindade (20°S, 29°W) (4 beaches) islands during the austral summer season (2011/2012, 2012/2013). One sediment sample (80 g) was collected in the centre of the beach arc to grain size characterization. The dry sieving method and the Folk and Ward (1957) classification were applied in this study (Table 1).

In the tropical western Atlantic Ocean, the circulation of the atmosphere (i.e., southeast trade winds and the westerlies) primarily drives the upper ocean large-scale circulation in the southern hemisphere. The nearest oceanic moorings (http://www.pmel.noaa.gov/pirata/) were consulted to classify the sampled beaches into two groups: windward (9) and leeward (11) beaches, according to the prevailing winds in the area of the islands (Ivar do Sul et al., 2014) (Table 1).

For microplastic survey, the strandline (1m wide) was sampled by scraping the two first centimetres of sand from 900cm^2 quadrats (Ivar do Sul et al., 2009). Three quadrats were thrown along the strandline on each surveyed beach. Then, a total of 60 samples was collected. Sediment samples were taken to the laboratory where they were oven-dried at 100°C overnight. The dry samples were weighted and sieved through a 0Φ (1mm) sieve. Two types of plastics were identified and classified as hard plastic fragments and virgin plastic pellets (Figure 1D, E). Individual items were then sorted by size class and colour, measured and photographed. All images were obtained with the AxioVs40 V 4.8.2.0 software from Carl Zeiss Vision.

Density of plastics particles was expressed as particles per square meter (particles/m^2). Two hypotheses were tested with the Factorial Analysis of Variance (ANOVA): (1) there are differences in the total amounts of microplastics on windward and leeward beaches and; (2) types of microplastic particles are recurrent among the studied islands, but hard plastic fragments are prevalent. Data was transformed (Box-Cox transformation) to achieve normality, whilst homoscedasticity was tested with Levene's test. Where ANOVA showed a significant difference, an *a posteriori* Fisher LSD test was used to determine which mean was significantly different (α=0.05).

Table 1: Sampled beaches in Fernando de Noronha (350 km from the continent), Abrolhos (70 km from the continent) and Trindade (1,100km from the continent). Beaches are classified according to the prevailing winds in the area (LW=leeward; WW=windward). The approximate length of each beach and sediments characteristics are also presented.

		Beach	Length (m)	Sediments characteristics: Main grain size	Sediments characteristics: Classification of sorting	Sediments characteristics: Skewness
FERNANDO DE NORONHA	LW	Sancho	500	Fine sand	Good	Near symmetrical
		C. do Padre	500	Fine sand	Good	Near symmetrical
		Bode	350	Fine sand	Good	Near symmetrical
		Americano	200	-	-	-
		Boldró	700	Fine sand	Good	Near symmetrical
		Conceição	220	-	-	-
		Meio	100	Fine sand	Good	Near symmetrical
		Porto	200	Fine sand	Good	Coarse
		Air France	250	Medium sand	Good	Near symmetrical
	WW	E. dos Tubarões	85	Fine sand	Good	Coarse
		Atalaia	100	Medium sand	Moderate	Near symmetrical
		Sueste	510	Medium sand	Poor	Coarse
		Leão	540	Medium sand	Moderate	Coarse
ABROLHOS	LW	Caldeiras	100	Fine sand	Moderate	Coarse
	WW	Santa Bárbara	100	Coarse sand	Good	Near symmetrical
		Redonda	150	Coarse sand	Good	Near symmetrical
TRINDADE	WW	Cabritas	350	Medium sand	Moderate	Near symmetrical
		Tartaruga	200	Medium sand	Moderate	Near symmetrical
		Parcel	200	Coarse sand	Moderate	Near symmetrical
	LW	Príncipe	200	Coarse sand	Good	Near symmetrical

Results and Discussion

In this study, the presence of microplastics on insular beaches in the western tropical Atlantic Ocean was confirmed for the first time in the Trindade island (Figure 1); however, no plastic particle was found in sand samples from beaches of the Abrolhos archipelago. Microplastics were once again sampled on sandy beaches in the Fernando de Noronha archipelago as previously reported (Ivar do Sul et al., 2009).

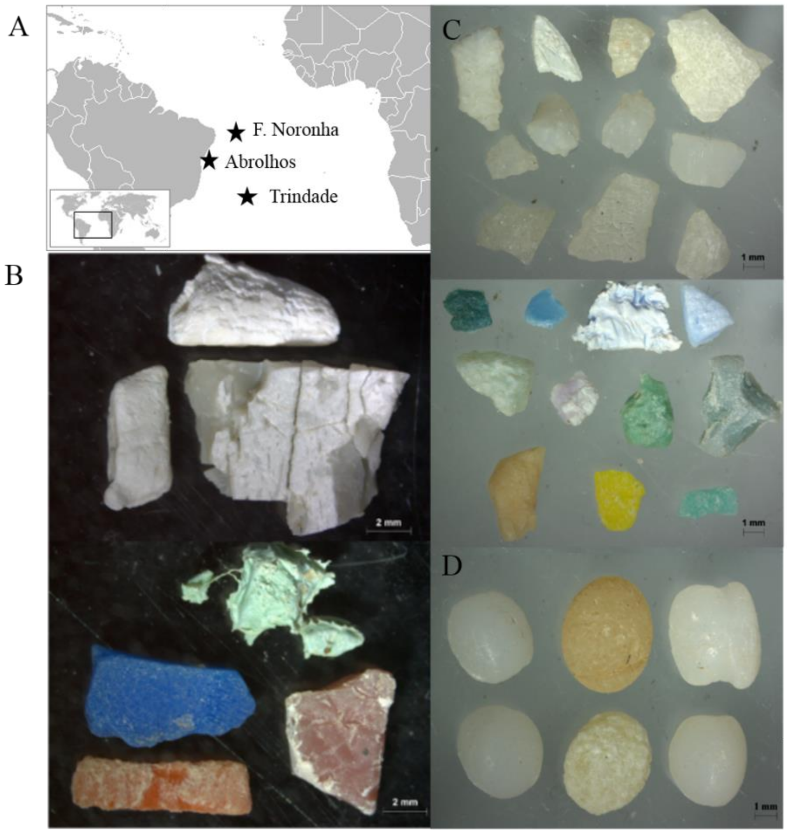


Figure 1: (A) Studied islands in the western tropical Atlantic Ocean: Fernando de Noronha, Abrolhos and Trindade. (B) Examples of white and coloured macroplastic (>5mm) fragments. (C) Examples of white and coloured microplastic fragments and (D) virgin plastic pellets. All images were obtained with the AxioVs40 V 4.8.2.0 software from Carl Zeiss Vision.

A total of 1,151 plastic particles were detected in sand samples in this survey. Twenty-three quadrats (40%) in 12 beaches (60%) were contaminated (Table 2). In the Trindade island, three beaches were contaminated, but no plastic particle was sampled on Príncipe beach (leeward side). In Fernando de Noronha, five beaches are at this time free from this type of marine pollution; a single fragment was sampled on three beaches; and five other beaches presented higher contamination hates (Table 2).

Quantitatively, windward beaches were more contaminated by plastic particles than the leeward beaches when all sampled beaches were considered (Hypothesis 1). This result confirmed the influence of surface currents transporting floating marine debris in the open ocean (i.e., Ivar do Sul et al., 2009). On the other hand, the absence of microplastic particles in Abrolhos Island during this survey is probably due to the beach sediment dynamics, which may remove all the sand, and consequently plastics, from beaches. This process is cyclical, and may underestimate microplastic particles sampling in a specific time.

Table 2: Microplastic particles sampled in Fernando de Noronha and Trindade islands. LW=leeward beaches and WW=windward beaches. In Abrolhos, no microplastic particle was sampled. Beaches are listed according to island, relative position and main grain size.

				Hard fragments		Pellets					
				White	Colour	White	Colour	Total	Mean (±Stdev)		Particles / m²
Fernando de Noronha	LW	Fine sand	Sancho	0	0	0	0	0	-	-	0
			C. do Padre	0	0	0	0	0	-	-	0
			Bode	1	0	0	0	1	0.33	(±0.5)	1.23
			Americano	0	0	0	0	0	-	-	0
			Boldró	0	0	0	0	0	-	-	0
			Conceição	1	0	0	0	1	0.33	(±0.5)	1.23
			Meio	0	0	0	0	0	-	-	0
			Porto	4	0	0	0	4	1.33	(±2)	4.94
	WW	Medium sand	Air France	3	0	0	0	3	1	(±1.5)	3.70
			Tubarões	45	0	32	0	77	25.67	(±22.8)	95.06
			Atalaia	20	7	21	7	55	18.33	(±7.8)	67.90
			Sueste	1	0	0	0	1	0.33	(±0.5)	1.23
			Leão	3	0	2	2	7	2.33	(±1.3)	8.64
Trindade	WW	Medium sand	Cabritas	194	14	121	43	372	124	(±81.1)	153.09
			Tartaruga	212	5	133	39	389	129.67	(±93.7)	160.08
			Parcel	147	40	41	9	237	79	(±60.4)	97.53
	LW	Coarse sand	Príncipe	0	0	0	0	0	-	-	0

In the islands of Fernando de Noronha and Trindade, mean densities of microplastics were lower than in the Eastern Island (805 ± 320.1 items/m²), which was significantly more contaminated than other beaches along the Chilean coast (Hidalgo-Ruz and Thiel, 2013). The Eastern Island is close to the eastern-centre region of the South Pacific subtropical gyre, where pelagic plastics accumulate (Lebreton et al., 2012), showing that ocenic islands actually act as deposit sites for pelagic microplastic debris at sea (Moore, 2008, Hidalgo-Ruz and Thiel, 2013). On Trindade windward beaches, however, densities reached the same order of magnitude than in the South Pacific Ocean (Hidalgo-Ruz and Thiel, 2013). Since this island is far from (1,100km) the continental shores, ocean-borne plastics may be prevalent over land-based sources of plastic debris.

Characteristics of microplastic particles

Microplastics have an average size of 3.72±2.21 mm in this study. Only two types of plastics were identified (hard plastic fragments and pellets) showing that types of items are recurrent in the tropical Atlantic (Ivar do Sul et al., 2013, Ivar do Sul et al., 2014). In terms of number of items, hard plastic fragments (Figure 1C) accounted for 60% of microplastic parricles (*n*=697). The numerical dominance of hard plastic fragments over virgin plastic pellets (Figure 1D) is a predicted trend, according to the literature, in the Pacific (Kushio and Noda, 2003, McDermid and McMullen, 2004, Hidalgo-Ruz and Thiel, 2013, Moore 2008) and Atlantic oceans (Browne et al., 2010). However, densities (particles/m^2) of hard plastic fragments were not significantly different than pellets ($p=0.416$) in the studied islands (Hypothesis 2).

Fibres and strands (Ivar do Sul et al., 2014) were not detected during this survey. In the North Sea, fragments were completely absent whereas fibres and pellets were systematically sampled on the sediment surface of coastal islands (Liebezeit and Dubaish, 2013). Moreover, synthetic fibres are being related to sewage discharges, including washing machine effluents, mainly around high-populated areas (Browne et al., 2011). The absence of fibres and the occurrence of plastic pellets may also indicate that microplastics were mostly from marine-based sources, and consequently transported by ocean currents, when compared with sewage discharges (e.g., Claessens et al., 2011, Hidalgo-Ruz and Thiel, 2013).

In this study, white and transparent plastic particles were more prevalent (75%) as previously observed elsewhere (e.g., Ivar do Sul and Costa, 2014). The colour distribution of the plastics on beaches, as well as on the sea surface (Ivar do Sul et al., 2014), may be an indicator of the residence time of the plastic on beach environments, the most likely site for generation of microplastics in the marine environment (Andrady, 2011).

Final remarks

This study confirms the widespread occurrence of microplastics in the marine ecosystem, especially considering that those islands as far away from direct sources of land-based contamination (e.g., rivers, drainage systems), which are major sources of plastics to the environment (Browne et al., 2011).

Spatial variation in microplastic concentrations was observed on a relatively small scale (distance of few km) in Fernando de Noronha and Trindade. This may be due to different current patterns, grain sizes, wave action and wind exposure of each beach. All beaches are isolated from obvious plastic debris sources (i.e., dense human population centres, plastic facilities). Then, it is most likely that plastics came from the adjacent marine area, where ships and fishing boats generate pelagic plastics, which are recognized sources of plastic debris to the marine environment (e.g., Andrady, 2011, Ivar do Sul and Costa, 2014) or from long-range transport of items (Barnes et al., 2009).

Beyond the already established effects of ingestion, chemical leaching, and contaminant adsorption (e.g., Moore, 2008), plastic pellets and microplastic fragments may change the physical properties of beaches by increasing permeability and lowering subsurface temperatures (~1°C) (Carson et al., 2011). This can affect the sex of temperature-determinant organisms, such as sea turtles (e.g., a reduction in the number of females). Bioturbation of sediments on sea turtles nesting areas may also redistribute microplastics along the surface layer (1m), underestimating the amounts of sampled plastics. These might affect the quantification of beach plastics in Trindade and Fernando de Noronha since these islands are important nesting areas for *Chelonia mydas*.

Currently, the most widely used (~90%) synthetic plastics are low- and high-density polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET) (Andrady, 2011). These polymers have been successfully identified in sediment samples by FTIR and other techniques (e.g., Browne et al., 2010, 2011), including pellets (e.g., Fotopoulou and Karapanagioti, 2012). Eroded PE pellets had their surface areas enlarged, indicating that they will interact more efficiently with chemical compounds in the marine environment (Fotopoulou and Karapanagioti, 2012). Microplastics fragments will probably follow the same pattern, representing greater risks to organisms through ingestion.

Recently, new methods to sample, quantify and/or identify microplastics on sediments have been developed by several research groups. Since a range of different methods have been applied, a direct comparison of data from different studies is not advisable (Ivar do Sul and Costa, 2014). Thus, a precise and comprehensive diagnosis of this kind of marine contamination on sedimentary habitats remains to be done.

Acknowledgments

We are grateful to the National Research Council (CNPq) for the PhD scholarship provided to Juliana A. Ivar do Sul (Process 551944/2010-2) and reseacrh grants to M.F. Costa and G. Fillmann (PQ No 314335/2009-9). We also thank CNPq (Project

557184/2009-6) and the Brazilian Navy for financial and logistic support to the Project "Environmental contamination by persistent organic compounds, plastic fragments and pellets around the Trindade Island". We would also like to acknowledge Instituto Chico Mendes de Proteção à Biodiversidade (ICMBio) for assistance during field surveys in Fernando de Noronha and Abrolhos. Dr. Keyla Travassos, Oc. Luís Henrique B. Alves and Sg. Alberto are acknowledged for help during fieldwork in Abrolhos, Fernando de Noronha and Trindade, respectively.

References

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596-1605.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Environmental accumulation and fragmentation of plastic debris in global. Phil. Trans. R. Soc. B 364, 1985-1998.

Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns of plastic debris along estuarine shorelines. Environ. Sci. Technol. 44, 3404-3409.

Browne, M. A., Crump, P., Niven, S. J., Teuten, E. L., Tonkin, A., Galloway, T., & Thompson, R. C. (2011). Accumulations of microplastic on shorelines worldwide: sources and sinks. *Environmental Science Technology, 45*, 9175−9179.

Carson, H.S., Colbert, S.L., Kaylor, M.J., McDermid, K.J., 2011. Small plastic debris changes water movement and heat transfer through beach sediments. Mar. Pollut. Bull. 62, 1708-1713.

Cauwenberghe, L.V., Vanreusel, A., Mees, J., Janssen, C.R., 2013. Microplastic pollution in deep-sea sediments. Environ. Pollut. 182, 495-499.

Claessens, M., Meester, S.D., Landuyt, L.V., Clerck, K.D., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199-2204.

Depledge, M.H., Galgani, F., Panti, C., Caliani, I., Casini, S., Fossi, M.C., 2013. Plastic litter in the sea. Mar. Environ. Res. 92, 279–281.

Fendall, L. S., Sewell, M. A. 2009. Contributing to marine pollution by washing your face: Microplastics in facial cleansers. Mar. Pollut. Bull. 58, 1225-1228.

Folk, R.L., Ward, W.C. 1957. Brazos River Bar: A Study in The significance of grain Size Parameters. J. Sediment. Petrol. 27, 3-27.

Fotopoulou, K.N., Karapanagioti, H.K., 2012. Surface properties of beached plastic pellets. Mar. Environ. Res. 81, 70-77.

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., Thiel, M. 2012. Microplastics in the Marine environment: a review of methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075.

Hidalgo-Ruz, V., Thiel, M., 2013. Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project. Mar. Environ. Res. 87-88, 12-18.

Ivar do Sul, J. A., Spengler, A., Costa, M., 2009. Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). Mar. Pollut. Bull. 58, 1229-1244.

Ivar do Sul, J. A., Costa, M. F., 2014. The present and future of microplastic pollution in the marine environment. Environ. Pollut.185, 352-364.

Ivar do Sul, J. A., Costa, M. F., Fillmann, G., 2014. Microplastics in the pelagic environment around oceanic islands of the Western Tropical Atlantic Ocean. Water Air Soil Poll. 225.

Kusui, T., Noda, M., 2003. International survey on the distribution of stranded and buried litter on beaches along the Sea of Japan. Mar. Pollut. Bull. 47, 175-179.

Liebezeit, G., Dubaish, F., 2013. Microplastics in beaches of the East Frisian Islands Spiekeroog and Kachelotplate. Bull. Environ. Contam. Toxicol. 89, 213-217.

McDermid, K.J., McMullen, T.L., 2004. Quantitative analysis of small-plastic debris on beaches in the Hawaiian Archipelago. Mar. Pollut. Bull. 48, 790-794.

Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environ. Res. 108, 131-139.

Wright, S. L., Thompson R. C., & Galloway, T. S. 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Poll. 178, 483–492

CONSIDERAÇÕES FINAIS

Os principais objetivos propostos para esta tese de Doutorado foram alcançados. Em consonância com a comunidade científica internacional, que vem reportando de maneira acelerada a contaminação por microplásticos em diversas bacias oceânicas, os diferentes enfoques abordados (amostras de água e de sedimento) representam importantes indícios de contaminação por microplásticos no oeste do Oceano Atlântico tropical. Os métodos amostrais empregados neste trabalho são amplamente utilizados por pesquisadores em várias partes do mundo, e são considerados capazes de diagnosticar o problema da poluição por microplásticos com eficiência.

Os tipos de partículas plásticas amostrados neste estudo possivelmente ocorrem na superfície do mar em todo setor oeste do oceano Atlântico tropical. Suas quantidades, entretanto, podem variar com a proximidade de ilhas, de fontes em terra e rotas de navegação em oceano aberto. Fragmentos plásticos duros foram amostrados na superfície do mar e também nas praias arenosas, mostrando que as águas oceânicas podem ser a fonte destes tipos de plásticos para as praias arenosas de ilha oceânicas.

Durante o curso deste doutorado (2010-2014), estudos específicos sobre microplásticos ganharam espaço não só em revistas científicas, muitas de alto fator de impacto, mas também em outros veículos de informação voltados ao público em geral. A Revista *Marine Pollution Bulletin*, pioneira na divulgação de estudos sobre lixo marinho, ainda continua sendo a principal escolha dos pesquisadores da área. Entretanto, outras revistas já dão importante destaque ao tema (por exemplo, *Environmental Pollution, Environmental Science and Technology,* entre outras).

Em agosto de 2103 quando foi concluída a revisão da literatura sobre o tema (Capítulo I), cerca de 130 artigos sobre microplásticos tinham sido publicados. Três meses depois, em novembro de 2013, quando o artigo foi disponibilizado no site da revista, este número já atingia facilmente a marca de 150 artigos, todos publicados em revistas disponíveis no Portal de Periódicos da CAPES. Atualmente (maio de 2014), mais de 200 artigos sobre a presença e os efeitos da poluição por microplásticos já estão disponíveis! Seus desdobramentos possivelmente são assunto para uma nova Tese de Doutorado. O reconhecimento dos esforços da comunidade brasileira que estuda resíduos plásticos poderia ser feito através de oportunidades de financiamento diretamente voltadas ao tema, com editais específicos para a amostragem e identificação de microplásticos, e modernização dos laboratórios a exemplo da União Europeia.

Primeiramente, a confirmação da presença de microplásticos em importantes ambientes insulares brasileiros expõe a vulnerabilidade destes ambientes a este tipo de poluição já que parte das fontes de plásticos estão baseadas no mar e são de difícil controle, fiscalização e até mesmo de sua identificação precisa. Cada embarcação realizando as mais diversas atividades marítimas pode ser uma fonte potencial de plásticos para o ambiente. Neste sentido faz-se imprescindível o completo estabelecimento do Anexo V da Convenção Internacional para Prevenção da Poluição por Navios (MARPOL 1973/75), endossado pelo Brasil há mais de 30 anos. O cenário atual indica, entretanto, que a MARPOL não vem sendo cumprida em sua totalidade. O problema é muito amplo, englobando, por exemplo, a melhora na infraestrutura dos portos brasileiros para o recebimento adequado do lixo gerado a bordo.

Em 2014, 40 anos após o estabelecimento da MARPOL, começa a ser implementada no Brasil a Política Nacional dos Resíduos Sólidos (PNRS), sancionada em 2010. A lei nº 12.305, de 2 de agosto de 2010, dispõe sobre a "gestão integrada e o gerenciamento de resíduos sólidos, incluídos os perigosos, às responsabilidades dos geradores e do poder público e aos instrumentos econômicos aplicáveis". Décadas após o estabelecimento de legislações internacionais sobre a poluição marinha, que apontas as fontes baseadas em terra como responsáveis por ~80% dos plásticos encontrados no ambiente marinho, espera-se que ações previstas na PNRS, ao menos, minimizem a entrada de itens plásticos grandes nos ambientes costeiros. Isso em vista desta nova legislação não abordar o tema microplásticos em seu texto e não prever ações específicas neste contexto.

Dois dos ambientes insulares estudados são Parques Nacionais Marinhos, ou seja, Unidades de Conservação de proteção integral de categoria II definidas pelo Sistema Nacional de Unidades de Conservação da Natureza (SNUC) (Lei nº 9.985, de 18 de julho de 2000). Neste caso, a predominância de fontes marinhas de plásticos enfatiza a vulnerabilidade destes ambientes e também a falta a de eficiência das medidas de proteção exigidas, já que todos os grupos animais marinhos que compõem a teia trófica estão expostos ao risco de ingestão de microplásticos e suas consequências nos ambientes estudados.

REFERÊNCIAS BIBLIOGRÁFICAS

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596−1605.

Arthur, C., Baker, J., Bamford, H., (Eds.), 2009. Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Micro-plastic Marine Debris, September 9–11, 2008. NOAA Technical, Memorandum NOS-OR&R-30.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Environmental accumulation and fragmentation of plastic debris in global. Phil. Trans. R. Soc. B 364, 1985-1998.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E.L., Tonkin, A., Galloway, T., Thompson, R.C., 2011. Accumulations of microplastic on shorelines worldwide: sources and sinks. Environ. Sci. Technol. 45, 9175−9179.

Buchanan, J.B., 1971. Pollution by synthetic fibres. Mar. Pollut. Bull. 2, 23.

Cole, M. Lindeque, P. Halsband, C. Galloway, S.C., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588−2597.

Costa, M.F., Ivar do Sul, J.A., Santos-Cavalcanti, J.S, Araújo, M.C.B., Spengler, A. Tourinho, T.S. 2010. Small and microplastics on the strandline: snapshot of a Brazilian beach. Environ. Monit. Assess. 168, 299-304.

Carpenter, E.J., Smith, K.L., 1972. Plastics on the Sargasso Sea surface. Science 175, 1240-1241.

Fendall, L.S., Sewell, M.A., 2009. Contributing to marine pollution by washing your face: Microplastics in facial cleansers. Mar. Pollut. Bull. 58, 1225-1228.

Gregory, M.R., 1977. Plastic pellets on NewZealand beaches. Mar. Pollut. Bull. 8, 82-84.

Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the Marine environment: a review of methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075.

Ivar do Sul, J.A., Costa, M.F., 2007. Marine debris review for Latin America and the Wider Caribbean Region: from the 1970s until now, and where do we go from here? Mar. Pollut. Bull. 54, 1087–1104.

Ivar do Sul, J.A., Spengler, A., Costa, M., 2009. Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). Mar. Pollut. Bull. 58, 1229-1244.

Ivar do Sul, J.A., Santos, I.R., Friedrich, A.C., Matthiensen, A. & Fillmann, G., 2011. Plastic pollution at a sea turtle conservation area in NE Brazil: contrasting developed and undeveloped beaches. Estuar. Coasts 34, 814-823.

Ivar do Sul, J.A., Costa, M.F., Barletta, M., Cysneiros, F.J.A., 2013. Presence of pelagic microplastics around an Archipelago of the Equatorial Atlantic. Mar. Pollut. Bull. 75, 305-309.

Ivar do Sul, J.A., Costa, M.F., 2014. The present and future of microplastic pollution in the marine environment. Environ. Pollut. 185, 352-364.

Mato, Y., Isobe, T., Takada, H., Kanehiro, H. Ohtake, C., Kaminuma, T., 2001. Plastic Resin Pellets as a Transport Medium for Toxic Chemicals in the Marine Environment. Environ. Sci. Technol. 35, 318-324.

Maximenko, N., Hafner, J., Niiler, P., 2012. Pathways of marine debris derived from trajectories of Lagrangian drifters. Mar. Pollut. Bull. 65, 51−62.

Moore, C.J., 2008. Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. Environ. Res. 108, 131-139.

Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A comparison of plastic and plankton in the North Pacific Central Gyre. Mar. Pollut. Bull. 42, 1297-1300.

Moore C.J., Phillips, C., 2010. Plastic ocean: how a sea captain's chance discovery launched a quest to save the oceans. New York, Avery.

Morét-Ferguson, S., Law, K.L., Proskurowski, G., Murphy, E.K., Peacock, E.E., Reddy, C.M., 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Mar. Pollut. Bull. 60, 1873-1878.

Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Phil. Trans. R. Soc. B 364, 1999-2012.

Santos, I.R., Friedrich, A.C., Ivar do Sul, J.A. 2009. Marine debris contamination along undeveloped beaches from northeast Brazil. Environ. Monit. Assess. 148, 455–462.

Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M., Watanuki, Y., 2013. Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. Mar. Pollut. Bull. 69, 219–222.

Thompson, R.C., Swan, S.H., Moore, C.J., vom Saal, F.S., 2009. Our plastic age. Phil. Trans. R. Soc. B 364, 1973-1976.

Wright, S.L., Thompson R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492.

Zarfl, C., Matthies, M., 2010 Are marine plastic particles transport vectors for organic pollutants to the Arctic? Mar. Pollut. Bull. 60, 1810 – 1814.