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Are there gaps in our understanding of marine plastic pollution?

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The leakage of waste plastic into the environment, especially the marine environment, has become an issue of global concern. In response, governments have implemented various measures from plastic product bans[1], requirements for greater producer responsibility and product design, to ambitious new recycling targets[2-4]. Given the emotive nature of this topic, scientific evidence is crucial to assess the magnitude of the threat posed by marine plastic; to inform public and private sector responses; and to monitor the effectiveness of these responses.

A large body of research has been conducted on the state and ecological impacts of plastic in the South African marine environment over the past five decades. Hughes[5] was one of the first ecologists to report the impacts of plastic ingestion and entanglement in turtles. Shaughnessy's[6] research on entanglement of Cape fur seals off South Africa in the 1970s, and Ryan's[7] work on plastic ingestion by seabirds from southern Africa to Antarctica in the 1980s, provided early insights into the impact of macro- and microplastics. Ryan and Moloney's[8] research on trends in abundance and composition of beach plastic from 1984 to 1989, published 30 years ago in the *South African Journal of Science*, is now thought to be the first use of the term 'microplastics' in the context of marine plastic pollution.

However, little has been done to consolidate this extensive body of research in order to support decision-makers in assessing the threat of marine plastic to South African ecosystems, human health and the economy. The Department of Science and Innovation, through the Waste RDI Roadmap, initiated a process in May 2019 to produce a 'science review of marine plastic pollution in South Africa'. The aim of this review was to consolidate existing scientific evidence and to use this evidence to assess the current gaps in knowledge and the implications of these evidence gaps. This would inform whether a targeted research agenda on marine plastic pollution is needed for South Africa. Five science review papers were prepared and are presented in this issue of the *South African Journal of Science*. They provide valuable insights into the sources, pathways, fates and resultant impacts of marine plastic debris in South Africa, highlighting key evidence gaps. Some of these evidence gaps are summarised here.

Verster and Bouwman estimate that between 15 000 and 40 000 tonnes per year of waste plastic is carried into South Africa's oceans from land-based sources. This is six-fold less than the estimate by Jambeck et al.[9] who placed South Africa 11th in the world in terms of mass of mismanaged plastic waste. However, the authors acknowledge that while most marine plastic originates inland, scientific evidence on the land-based sources of marine plastic and the role of inland water systems (rivers, dams, estuaries) as temporary sinks and potential long-term secondary sources, is scarce. The potential impact of microplastics on drinking water sources, the efficacy of waste-water treatment works in removing plastics, and the resultant management of treatment sludge, need to be better understood.

This paucity of data on land-based sources of plastics entering the ocean is reconfirmed by Ryan, who notes that 'either we are greatly overestimating the amounts of plastic entering the sea, or we are failing to measure a major sink of marine plastics'. The amounts of litter stranding on our beaches and floating at sea are at least an order of magnitude less than those predicted by the model of global leakage.[9] The transport and fate of plastics in the South African marine environment, and changes over time, are relatively well understood given the amount of research already undertaken on these topics. The coastal surveys that have been conducted since the 1980s provide an important foundation from which to build future monitoring programmes.

Research on the ecological impacts of plastics in the marine environment has the longest track record in South Africa. However, Naidoo et al. note that our understanding of the ecological impacts on populations of marine species is limited, and the transfer of plastics along the food chain to humans, and associated impacts on human health, remain unknown. Given the economic importance of South Africa's fishing industry, further research on the effects of plastic on commercial species of fish and invertebrates, including species processed to fish meal, is recommended. As noted by the authors: 'This gap must be filled in order to make predictive decisions in regard to safety for consumption.' Given the limited R&D funding available in South Africa, we need to decide what research we should undertake ourselves, and what we can leave to the international research community.

Despite decades of research on plastics in South Africa's oceans, research on the impacts on ecosystem services and the economy is almost non-existent. Arabi and Nahman point out that while pockets of information are available on the impacts on recreation and tourism, there is an urgent need 'to quantify the environmental and social impacts of marine plastic debris in economic terms, in order to provide an understanding of the costs of inaction'. In particular, research is needed on the impacts on ecosystem services relating to fisheries and aquaculture, heritage, habitat provision, biodiversity and nutrient cycles, as well as the associated direct and indirect economic impacts and non-market costs.

The series of review papers is well summed up by Ryan et al. who note: 'In South Africa, we have a long history of studying marine plastics, and we already know enough about their impacts on marine systems to justify implementing policies to reduce the leakage of waste plastic into the environment.' Monitoring programmes will be critical to assessing the effectiveness of these policy interventions. Given that most of South Africa's marine plastic pollution originates on land, it is important to implement monitoring programmes close to the points of leakage.

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Land-based sources and pathways of marine plastics in a South African context

We review and evaluate the major land-based sources and pathways of plastic waste that lead to marine pollution in a South African context. Many of the formal solid waste and waste-water management facilities in South Africa are not fully functional, contributing towards plastic releases to the environment. Much plastic also enters the environment directly by informal and illegal dumping. Once in the environment, plastic is transported and distributed by air, inland waterways and human activity, with complex dynamics that are not fully understood. Depending on the size and type of plastic and environmental factors like wind action and run-off, plastic can be deposited into sinks such as soil, river sediments and vegetation, or carried to the ocean. Contrary to an initial assumption that South Africa is the 11th worst contributor to marine plastic pollution, we estimate from more accurate and recent data that between 15 000 and 40 000 tonnes per year is carried to the oceans. This amount is six-fold less than a previous estimate. Despite many data and information gaps that require urgent attention through research and monitoring, it is clear that the status quo will lead to a worsening of already severe plastic pollution of all environments. South Africa needs to reduce plastic entering the environment by reducing illegal and informal dumping, effectively implementing and improving waste management infrastructure, and intensifying long-term awareness campaigns. Most importantly, however, immediate and effective mitigation is required.

Significance:

- More accurate and recent data show that between 15 000 and 40 000 tonnes of plastic is carried to the oceans from South Africa per year – six-fold less than the widely used previous estimate.
- Riverine sediments are potentially major sinks for plastic en route to the ocean.
- Management of treated waste-water sludge, as well as the state of waste-water treatment plants (WWTPs) are key concerns. WWTPs are reported to remove most plastic from the water content. The state of South African WWTPs have deteriorated to such an extent that up to 40% of the country's waste water is untreated and data and management practices of sludge are unavailable.
- There are major data gaps in the South African waste sector, which lead to miscalculations and uncertainties about the country's contribution to marine plastic debris.

Introduction

Marine plastic debris is a global concern that needs urgent attention and mitigation.[1] Although numerical estimates differ[2], the majority of plastic reaching the marine environment comes from land-based sources. Li et al.[3] estimate that up to 80% of marine plastic debris is from land-based sources[3], but this estimate is largely based on data from the Caribbean islands and the proportions of land-based to sea-based sources show great regional variation[4]. Land-based plastic debris enters the marine environment mainly as formal, informal and illegal debris, carried by rivers, waste- and storm-water outlets, or is blown directly into the oceans by wind.[5] Recently, microplastic has also been found in air[6,7] – a finding that expands our knowledge of plastic mobility and long-range distribution. Although most literature on plastic pollution remains marine based, more attention is being given to riverine research as rivers act as a major transport pathway of plastics to the oceans.[8-13] Rivers play a role in the transformation of plastic into smaller pieces through abrasion, chemical, biological or UV degradation.[14] Freshwater sediments also act as sinks for plastic that may become secondary sources during floods or high-flow conditions.

Generally, one can distinguish three major categories of plastics found in the environment. Large plastic items, arbitrarily termed macroplastics (>5 mm in longest dimension) are items such as packaging, foams, plastic bags and ear bud stems. Large debris breaks down through a myriad of processes into smaller pieces called microplastics (<5 mm in longest dimension). Fibres released from fabrics (often from washing of clothes) are also considered microplastics due to their size. Not only do macroplastics cause direct harm to larger animals through ingestion, suffocation and entanglement[15], but microplastics cause similar problems to smaller animals.

Many plastics are manufactured as complex mixtures of chemicals. Plastics can also take up additional chemicals from the environment such as persistent organic pollutants and metals such as mercury. The incorporated and accumulated chemicals could be transferred to terrestrial, freshwater and marine organisms that have taken them up through ingestion or assimilation, posing a threat to human, biotic and ecosystem health.[16,17]

Here, in a South African context, we consider the land-based sources of macro- and microplastics. We discuss the sources of plastic that can become marine plastic, its distribution mechanisms, and how plastics eventually reach the oceans. An understanding of the underpinning factors and knowledge gaps is necessary to inform effective and integrated land-based remediation and intervention options and policies.

Plastics are complex

There are many types of polymers and many ways to characterise their properties, such as chemical and crystalline structures, production processes, design, density, hardness, capacity to absorb water, electrical conductivity, and

degradability.[18] Table 1 provides a summary of common polymers, some common uses, as well as their typical densities. The density of a polymer is important as it relates to buoyancy in fresh and marine water which is pertinent to the current series of articles. It should be noted that densities given here are approximate.

Table 1: Types and some uses of selected polymers arranged according to their typical densities, as well as the densities of different waters (adapted[19-21])

Type of polymer	Density (g/cm³)	Common uses
Natural rubber	0.016–0.36	Cool boxes, floats, cups
Polyethylene – low density	0.91–0.93	Plastic bags, outdoor furniture
Polyethylene – high density	0.94–0.97	Bottles, pipes
Polypropylene	0.85–0.94	Rope, bottle caps, gear, strapping
Polystyrene – expanded	0.016–0.36	Cool boxes, floats, cups
Polystyrene	0.96–1.05	Utensils, containers, microbeads
Polystyrene – high impact	1.04	Shelves, printed graphics
Polyamide ('– nylon')	1.12–1.14	Fishing nets, rope
Polycarbonate (bisphenol-A)	1.2	CDs, glass alternative, lenses
Polyurethane	1.2	Rubbers, sealants, paints
Methacrylate (acrylic)	1.19	Alternative for plate glass
Cellulose acetate	1.28	Cigarette filters, fabric fibre
Cellulose nitrate	1.35	Printing inks, nail polish, foil
Polyvinyl chloride	1.38	Film, pipe, containers
Polylactic acid (biodegradable)	1.21–1.43	Packaging, cups
Polyethylene terephthalate (PET)	1.34 - 1.39	Bottles, strapping bands
Melamine	1.57	Flooring, dinnerware, dry boards
Polytetrafluoroethylene	2.15–2.20	Bearings, lining of pipes, non-stick cookware
Distilled water	1.00	
Brackish water	1.005–1.012	
Sea water	1.025–1.027	

Although many plastic items consist of only one monomer such as ethylene or propylene, there are plastic products that consist of multiple monomers called co-polymers[15,22] to address existing or specific needs. Depending on polymerisation efficiency, monomers trapped in the polymer matrix may leach or desorb to the environment, or into organisms that have ingested them. Bisphenol-A is one such monomer that is known to leach and has endocrine disruptive properties.[15,22]

Many kinds of additives are incorporated into plastics to attain desired properties; some are listed in Table 2.[19] Some of these additives (up to 70% of the mass) may be released from the article to the environment and to organisms that have ingested them. There are many known toxicological implications associated with both the monomers and additives.[15]

In addition to the chemicals incorporated during manufacture, synthetic polymers that are mostly made up of non-water soluble organic materials, act as organisms do by absorbing or adsorbing pollutants such as metals and persistent organic pollutants from the environment, concentrating pollutants from land, refuse dumps, water, and perhaps even from air.[23-25] Mercury and DDT for instance, have been detected at higher concentrations in plastics than in water, supporting a concentration effect akin to bio-concentration. Plastics, suspended matter, and biota passively concentrate hydrophobic molecules from water through adsorption (therefore remaining in solution in the plastic matrix), absorption (such as ionic, steric or covalent binding), or a combination thereof depending on matrix volume, polymer characteristics and ambient concentrations.[26] Plastics that thus had their chemical compositions altered in fresh water and reach the marine environment via rivers and outflows (such as industrial and sewage outflows) should therefore be considered as transport facilitators of concentrated chemicals to the oceans. The incorporated and accumulated chemicals could be transferred to terrestrial, freshwater and marine organisms that take them up through ingestion or assimilation, posing a threat to human, biotic and ecosystem health.[16,17]

Table 2: Examples of additive type, function and chemical name that can be found in manufactured plastics[19]

Additive	Function	Chemical name
Accelerants	Speeds up curing	Ethylene thiourea
Antidegradants	Reduces degradation	N,N'-bis(1,4-Dimethylpentyl)-p-phenylenediamine
Antioxidants	Slows down oxidation	2-2-Hydroxy-5-tert-octyphenyl-benzotriazole
Antizonants	Slows degradation by ozone	Nickel dibutyldithiocarbamate
Cross-linking additives	Links polymer chains	2-Mercaptobenzothiazole
Flame retardants	Reduces flammability	Tetradecachloro-p-terphenyl
Photosensitisers	Absorbs radiation	Benzophenones
Plasticisers	Makes the material more pliable	Bis(2-Ethylhexyl)terephthalate
Surfactants	Modifies surface properties	Polysiloxanes
UV stabilisers	Protects against UV damage	2-(2-Hydroxy-5-methylphenyl)benzotriazole

Sources of plastic in the environment

Waste in South Africa

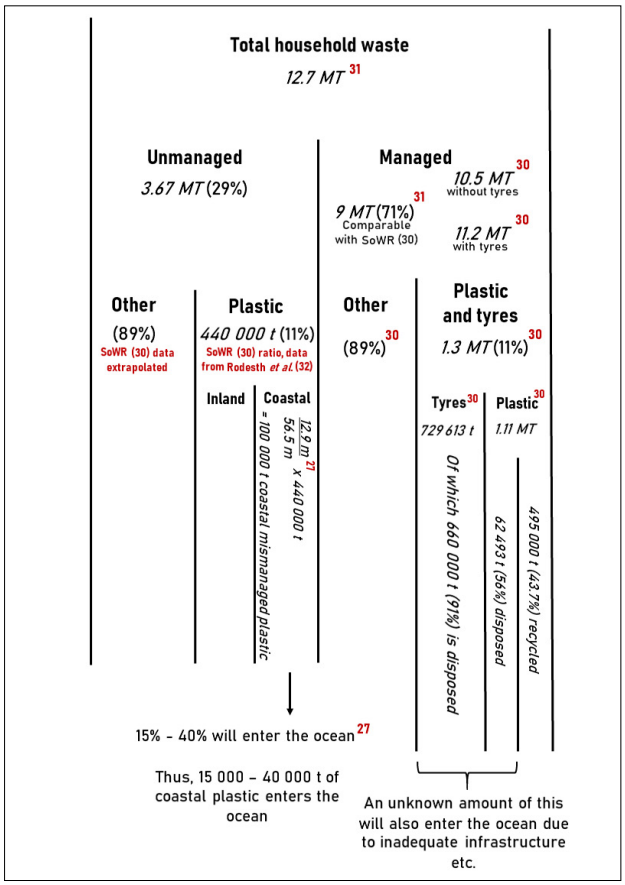
Jambeck et al.[27] ranked South Africa 11th in a list of countries contributing an estimated 90 000 to 250 000 tonnes to marine plastic in 2010, based on an estimate of 56% mismanaged waste with little actual supporting data. Key reasons considered for the loss of plastics to the environment were lack of waste removal infrastructure, logistical challenges in informal settlements and out-lying communities, poorly managed waste, and littering.[28] There are, however, concerns that some of the quantitative assumptions used in various assessments may not be accurate and therefore result in an over-estimation of the actual amounts that enter the South African marine environment.[2]

Solid waste removal is primarily a function of local government.[29] According to the 2018 *South African State of Waste* report (SoWR)[30], total non-mining waste generated in South Africa for 2017 was 54.2 million tonnes, which is 1.0 tonne per capita of 56.5 million people. South Africa generated 1.1 million tonnes of plastic waste in 2017[30] equating to 19 kg plastic per capita per year, or 53 g per person per day. Jambeck et al.[27] used a figure of 2 kg per day of all waste (not only plastic waste) and an estimate of 12.9 million people living within 50 km of the coast of South Africa, to obtain an amount of 505 000 tonnes of plastic waste per year in the coastal areas (assuming equal distribution between inland and coastal plastic waste generation figures).

SoWR[30] reported that 43.7% of plastic waste is recovered and/or recycled, with the remainder disposed of (618 880 tonnes). Assuming that 29% of the 12.7 million tonnes of household waste does not enter the formal waste management stream, 3.67 million tonnes of waste is mismanaged plastic in South Africa[31] (Figure 1). Of the domestic waste handled (GW01, GW50, GW51, GW52, GW54), 11% per mass is plastic

and tyre waste.[30] Assuming a similar proportion of unmanaged waste is plastic and tyre waste, South Africa releases 440 000 tonnes of unmanaged plastic waste into the environment. The 12.9 million coastal inhabitants living within 50 km from the coast release 100 000 tonnes of plastic waste into the coastal environment. Jambeck et al.[27] assumed that 15–40% of the mismanaged plastic waste would enter the oceans. For South Africa's coastal population, we calculate that 15 000–40 000 tonnes of plastic could reach the oceans (Figure 1) – more than six-fold less than Jambeck et al.'s[27] estimate of 90 000 to 250 000 tonnes coastal plastic waste. Although this figure does not include formally managed waste that also enters the environment via secondary pathways and other factors, such as burning of portions of formally unmanaged waste, we highlight that the estimated contribution of South Africa's plastic input to the ocean is significantly less than previously claimed.

However, an important data uncertainty remains: illegal and informal waste dumping. Illegal waste was recognised in the SoWR[30], but no estimates were provided. However, we do not believe that the difference between estimates can be made up by illegal waste dumping. For higher-resolution and more accurate numbers, more data should be collected locally and used to improve estimates.



Data sources in red

Figure 1: Breakdown of available data on household and plastic waste in South Africa.

Socio-economics and mismanagement of waste

Major drivers associated with plastic debris in the environment of an area are economic challenges and disadvantaged communities.[30] Most South African households (91%) are low-income households.[29] In urban municipalities, 82.7% of households have weekly solid waste removal services, while only 4.9% make use of their own dumpsites.[29] In rural municipalities, only 1% of households have formal waste collection at least once a week, while 75.1% make use of own refuse dumps.[29] Poverty combined with rapid urbanisation and insufficient waste management results in logistical challenges in waste collection.[30] Roads in informal settlements are often too narrow to be accessed by garbage trucks. Weak waste management by municipalities leaves many individuals, households and communities with the responsibility of disposing of their own domestic waste. Waste that is not formally collected is disposed of on communal dumps.[30] Without proper infrastructure, plastic and other waste is lost to the environment through wind and water run-off.[30] Vandalism of fencing at waste management sites also allows the leakage of plastic through wind (personal observations of C.V. and H.B.).

Waste removal includes removal by local authorities, private companies or community members (Table 3). It ranges from 92% in the Western Cape to 20% in the Limpopo Province. Of the South African provinces, the Western Cape and Gauteng have the most efficient formal waste collection systems, while Limpopo and the Eastern Cape have the lowest formal waste collection availability and inevitably the highest portions of informal or communal refuse dumps.[30]

Table 3: Breakdown of waste collection services in each province for 2016[30]

Province	Formal waste removal	Communal/own refuse dump	Communal container/central collection point	Other
Western Cape*	92%	4%	4%	1%
Eastern Cape*	39%	53%	1%	8%
Northern Cape*	68%	25%	1%	6%
Free State	74%	21%	1%	5%
KwaZulu-Natal*	43%	49%	2%	6%
North West	58%	37%	1%	4%
Gauteng	88%	7%	2%	3%
Mpumalanga	40%	52%	1%	8%
Limpopo	20%	72%	0%	7%

**Coastal provinces*

Excluded from the SoWR and data used for national waste estimates is the portion of mismanaged waste.[31] Of total domestic waste generated in South Africa, 29% (3.67 million tonnes per annum) is not collected or treated via formal waste management processes.[31] Because of inadequate waste management and a lack of consumer awareness and education, waste that is not collected is littered or illegally dumped[30,31] (Figure 2). Rural communities may be largely ignorant of the adverse effects of plastics in the environment, resulting in a lack of motivation to keep the area clean.[32] We highlight the need for education about proper waste disposal practices and the provision of formal waste management services, especially in rural communities, as both income and settlement type largely determine the efficiency of waste management.[31]

Coastal cities report large debris loads deposited into the ocean directly via storm-water drainage systems.[33-36] Between 2000 and 2002, some 3000 to 4000 tonnes of debris were estimated to be deposited into the ocean by the City of Cape Town each year, most of which originated from informal settlements on the banks of canals.[33] Data from beach clean-ups and debris booms in Cape Town suggest an increase in the plastic load during rainy seasons.[35] Recent beach clean-up data from Cape Town shows 9 of the 10 most frequently found items are associated with fast food containers, with the 10th being earbud sticks.[37]

Access to running water for households is related to microplastic concentrations in rivers – particularly to the concentration of fibres.[38] If access to running water and proper waste-water treatment is limited, as is the case for many rural communities in South Africa, waste water is discharged directly from households into river systems and clothes are often washed directly in rivers. As mechanical[19] and handwashing of fabrics in water releases fibres, washing may contribute significant amounts of fibres to rivers. An average mechanical wash load of 6 kg of clothes can release more than 700 000 fibres per wash.[39] However, we could find no useful data on laundry activities in South Africa.

Waste management in South Africa is mainly not compliant with applicable regulations.[30] Some issues that were identified at disposal sites were lack of access control, daily covering, auditing, and monitoring. To tackle this problem, infrastructure is needed, and waste removal and treatment services should be delivered to all communities. Education and awareness will lay the groundwork to reduce littering and burning. Education campaigns in schools and local authorities have been implemented in Gauteng, North West, Western Cape and the Free State.

The informal waste sector is an integral part of the South African waste removal and recycling system, with more than 25 000 trolley pickers at kerbside and 36 000 landfill waste pickers in 2014.[30] Waste pickers tend to select high-value products and often leave the rest, which can then enter the environment.

Photo: C. Verster

Figure 2: Illegal dumpsite next to a river in the Free State Province.

Transport sector

Global estimates conclude that automotive tyre wear or 'rubber dust' contributes up to 0.81 kg/year/person to the environmental microplastic load.[40] Road transport is the dominant mode of transport in South Africa. It will continue to be so in the foreseeable future as 71% of the national transport infrastructure budget in 2018 went to road infrastructure improvement.[41] Although no data are available on tyre wear in South Africa, it is likely to be a source contributing to the environmental microplastic load that will also reach the oceans.

Industry

The plastic manufacturing and packaging industries contribute to the load of environmental plastic debris, but the amount of leakage is poorly understood. Much of the leakage is in the form of primary pellets, recyclate flakes, and powders released to the environment during manufacturing or transport. During the 2015 coastal clean-up campaign, 53.9% of the number of microplastics found on beaches were industrial pellets.[42] Microscopic plastic particles are mixed with silica and other materials as abrasives and in sandblasting, and are likely to leak to the environment if not properly contained.[19]

Operation Clean Sweep was initiated in the USA and globally launched in 2011 to contain primary plastic and recyclates within the manufacturing process; which is a goal endorsed by Plastics SA to combat the release of plastics into the environment during production and recycling.[28]

Microplastics

Microplastics in aquatic ecosystems come from sources such as waste-water treatment plant (WWTP) effluent, sewer overflows, discharge, and run-off from sludge used in agricultural applications and industries.[43] In South Africa, urban run-off and informal settlements are other possible sources due to littering and inadequate waste management.

Microplastics may enter an aquatic system in two different forms. They can enter the system as primary microplastics[44] or as secondary microplastics that form as breakdown products of larger items. When using cosmetic products like facial scrubs, between 4600 and 94 500 microbeads, which are primary microplastics, can be released[45] but little data are available on their retention by WWTPs[44]. Microbeads are also used in other applications such as sandblasting, soaps and washing powder. Although microbeads have not been banned in South Africa unlike in Canada, the USA, United Kingdom, France, Sweden, Taiwan, South Korea and New Zealand, the South African cosmetics industry has implemented some initiatives to replace microbeads with other materials. Where WWTP outflows are directly to the sea, any microplastics that remain in the effluent will also be directly released to the sea.

When released into the environment untreated, waste water can add large amounts of microplastics, especially microbeads, to riverine loads. Even though international results show that WWTPs can remove 97–99% of microplastics, treated waste water still releases large numbers of microplastics due to the high initial volume.[43,44] Many of the WWTPs in South Africa are no longer fully functional. Of 68 audited WWTPs, only 8.2% were compliant with effluent quality.[30] In 2014, about 30% of the country's sewage treatment plants were considered to be in a 'critical state' (needing urgent intervention), and another 25% in a 'high risk' state.[46] This leaves up to 40% of the country's waste water untreated[47], increasing the likelihood of increased microplastic release to receiving marine and fresh waters. This plastic then becomes trapped in sludge, which is then often deposited on agricultural land.[48] Run-off by water and pickup of microplastics by wind from agricultural land should therefore be considered a possible source of microplastic to rivers and oceans.

Only a handful of studies have looked at microplastics in South African freshwater systems.[19,49] High concentrations of microplastic fragments were found in sections of the Vaal River associated with more turbulent flow[19] (Figure 3). Urban rivers like the Crocodile and Klip Rivers had microplastic levels up to 4.5 particles per litre (Figure 3). Levels of microplastic in sediments of the Bloukrans River ranged between 6 and 160 particles per kg dry sediment in summer (high flow) and winter (low flow), respectively.[49]

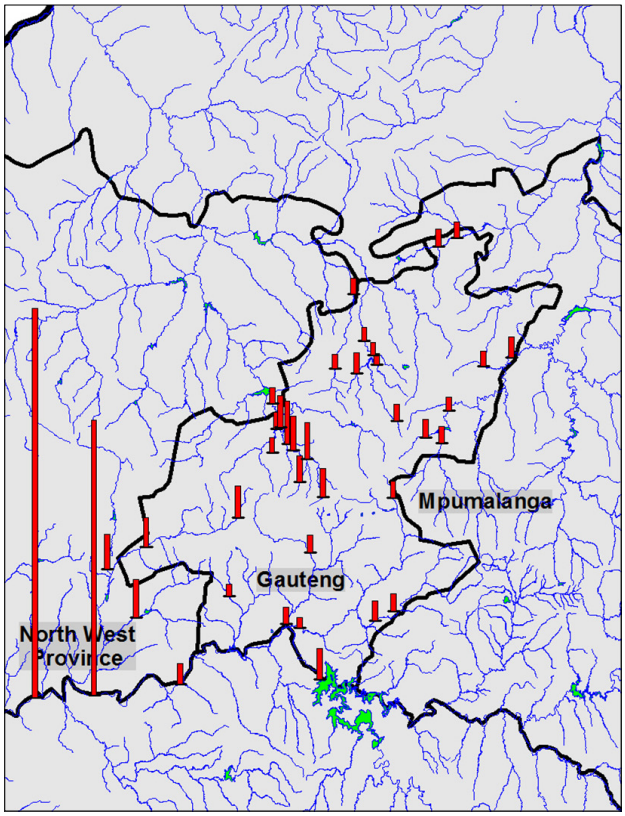


Figure 3: Distributions of total particles (fragments and fibres) per litre. The tallest bar represents 56 particles per litre.[19]

Pathways

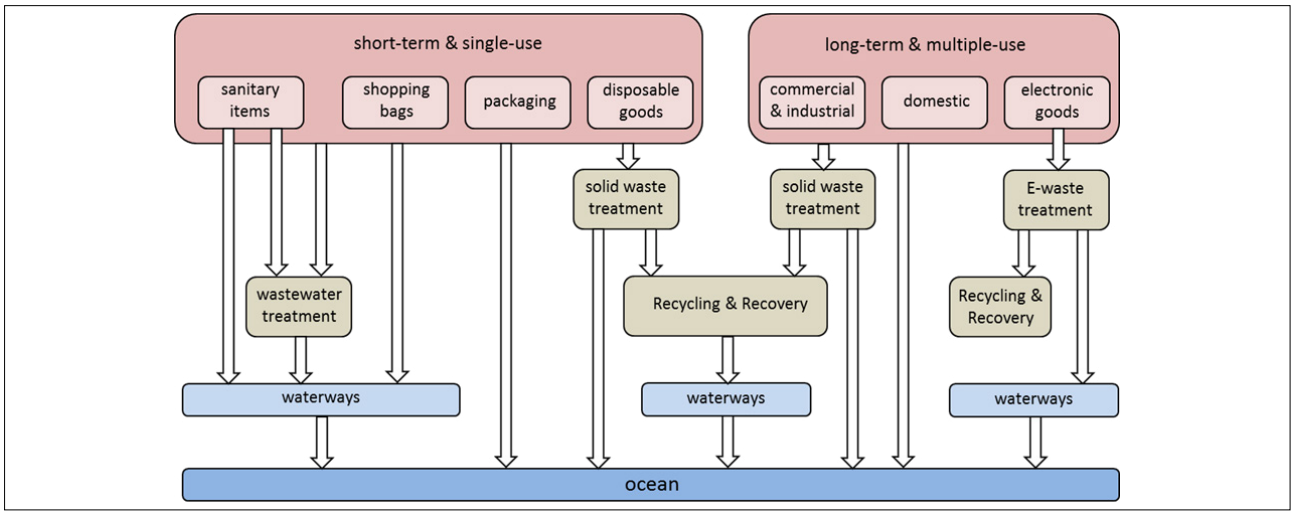
The size of a plastic item influences its environmental transport after release. Small microplastics (<200 μm), even heavier-than-water polymers like PET (Table 1), tend to be retained in the water column, while larger particles precipitate faster.[48] Larger, less buoyant items like bottles with air trapped inside, foams, and low-density polymer items, are found in surface water and riparian zones.

Plastic in the water column becomes covered by layers of biofilm through biofouling.[50] The more biotic material attaches to the plastic particle, the heavier it becomes, and sinks. This happens quicker for smaller particles. This process affects the movement and distribution of plastic particles and debris in fresh water[50], and probably its transportation potential to the marine environment.

Figures 4 and 5 illustrate the major sources and pathways of examples of macro- and microplastics reaching the marine environment. The reality is, however, far more complex and nuanced. Plastic in the environment is subjected to many factors that influence its movement, distribution, shape and toxicity. Rivers act as the main conduits for marine plastic (Figure 4). Rivers also play a role in the transformation of plastic. As plastic can sink, especially in less dense fresh water (Table 1), riverbeds can act as temporary sinks for plastic that can get resuspended and carried further downstream during high flow events. Hydrodynamics and the effect of impoundments play a critical role in the movement and distribution of plastics in any freshwater system.[49] These movements and interactions are quite well documented for marine systems[51,52], but such understanding for riverine systems is lacking for South Africa. A scoping study on microplastic for riverine surface water found microplastic concentrations (both fibres and fragments at near equal proportions) ranging between 0.32 particles per litre in the Suikerbosrand River to 56 particles per litre in the Vaal River after heavy rains.[19] Preliminary results for South African groundwater indicate the presence of predominantly fibres at 0.17 particles per litre.[19]

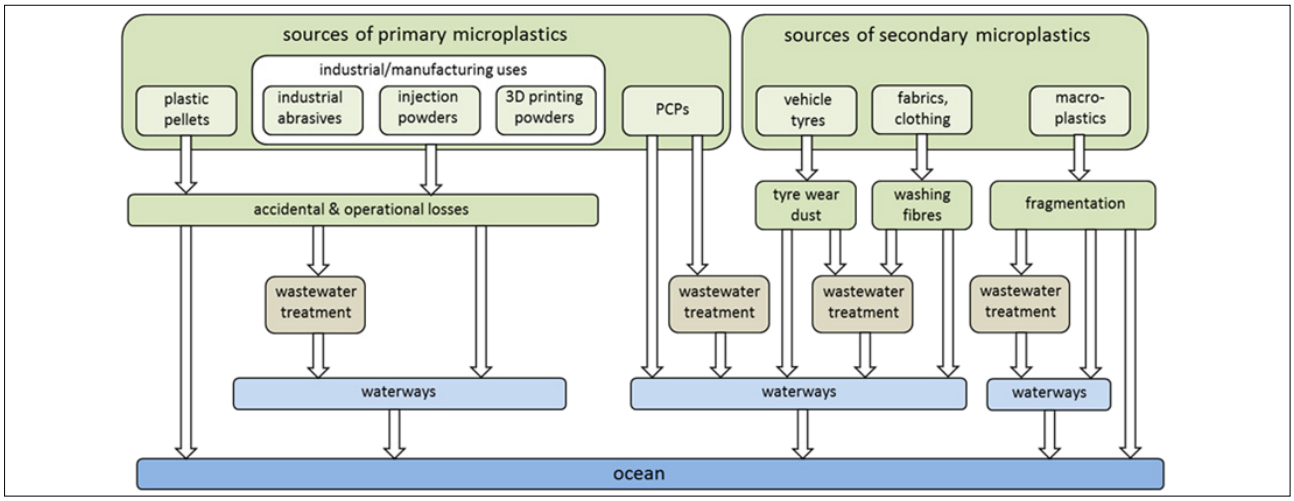
Airborne

Microplastic fibres have been found all over the globe in the remotest of environments.[53] It is assumed that these fibres are deposited via air (Figures 4 and 5). Although the study of microplastic pollution in air is in its infancy, significant numbers of plastic, especially fibres, have been found in settled dust and atmospheric fallout.[53] It is estimated that between 1600 and 11 000 fibres/m^2/day can be deposited in urban areas.[7] Most are natural fibres like cellulose and an estimated 29% are petrochemical-based synthetic fibres.[6] There is a strong correlation between anthropogenic activity in an area and the amount of fibres found in the air.[6] Although a novel field of enquiry[19], microplastics have been shown to travel more than 95 km from point sources[54]. An estimated 7% of the number of ocean plastic may be deposited



Source: Peter Kershaw[15], with permission; adapted to South African conditions.

Figure 4: Schematic representation of generic land-based pathways of representative macroplastics reaching the ocean.



Source: Peter Kershaw[15], with permission; adapted to South African conditions.

PCPs, personal care products

Figure 5: Schematic representation of generic land-based pathways of representative primary and secondary microplastics reaching the ocean.

through atmospheric fallout.[5] Although no data have been published for airborne plastic settling in South Africa, preliminary results indicate the presence of fibres in remote arid areas in the country, suggesting deposition of plastic much further than the 95 km suggested by Bank and Hansson[54]. Plastic fibres were found in dry run-off sediments (up to 315 particles/m^2; Louw J 2019 October, personal communication, and H.B. personal observations) in the Nama Karoo near Brandvlei where it had not rained for many years.

Lightweight macro- and microplastics are also transported by wind. Distances travelled might not be as far as those of smaller particles and fibres, but Jambeck et al.[55] suggest that areas downwind from sources act as plastic sinks. Especially in rural areas without proper waste disposal infrastructure, plastic debris can spread quickly outside the bounds of informal dumps, contaminating large areas of rural land. Plastic debris can thus be directly transported to the ocean, carried by wind or blown into rivers that carry debris to the ocean (Figures 4 and 5).

Sinks

Riverine sediments can act as a sink for plastics released into the environment, containing 40 times more microplastic than in surface waters.[56] Sediments in weirs had increased levels of plastic because particles settle in these slower flowing parts of rivers.[43] Some 16–38% of microplastic denser than water settles out into sediments.[50] Particles larger than 200 μm are also retained in riverine sediment with possible resuspension during high flow periods.[48] From 0 to 567 fibres/dm^3 was found in sediments of lower reaches of water catchments along the South African coast.[38] Although no data are available, this is likely to be the case for macro-debris as well. Microfibre content in river sediments of KwaZulu-Natal and the Eastern Cape also show a very strong association with socio-economic development indicators like access to water.[38]

Elevated levels of micro-litter are found in rivers associated with densely populated areas.[43] There are some conflicting findings in the literature as to how far plastic will flow down a river before it becomes stuck in sediment or vegetation. Mani et al.[43] claim that plastic loads increase immediately downstream of sources, while Jambeck et al.[55] states that downstream areas of high plastic input in rivers act as plastic sinks. Bouwman et al.[19] suggest that in the Gauteng study area, microplastics show little pattern in terms of population or downstream accumulation. Larger fragments were slightly more common upstream closer to the Vaal Dam, while smaller particles dominated downstream sites of presumed sources, which suggest that larger particles do not stay suspended in the water column as long, and sites downstream of sources most likely act as sinks for larger plastic pieces. This is in accordance with findings by Nel et al.[49] in the Bloukrans River system in the Eastern Cape where low-flow winter periods yielded higher sediment microplastic concentrations (160 particles per kilogram dry mass) when compared with high-flow periods (6.3 particles per kilogram dry mass). There are indications of very high microplastic loadings in sediment from rivers flowing through the Kruger National Park (Shikwambana P 2018, personal communication). Although not conclusive, flow rate seems to be an important hydrodynamic factor with the greatest effect on the plastic load in rivers of South Africa due to settling out in low-flow areas and seasons.

Soil

Although images of land-based environmental macro-debris are common, scant data are available in a South African context on amounts and distribution. The largest data sets available in this regard report amounts and composition of plastic on beaches[42], which indicate a recent increase in disposable nappies on beaches close to informal settlements. Interaction with biota on land is also less reported on, but examples include reports of cattle eating plastic in grazing areas.[32]

Current uncertainties

Compared with marine plastic debris research, information and data on inland sources and pathways in South Africa are scarce. To some extent, data, findings and models can be extrapolated from research done elsewhere. However, as pointed out by Jambeck et al.[55], South Africa faces distinct socio-economic challenges and unique environmental and ecological dynamics affecting the load and movement of land-based plastic. Wrong assumptions may lead to wrong conclusions that may adversely affect policy and interventions. Here we discuss some of these uncertainties in terms of difficulties to extrapolate global findings to a South African context.

- Although visibly an issue, volumes and hotspots of illegal dumping and informal dumps are still unknown and need to be quantified in order to motivate mitigation.
- Considering the unique socio-economic issues faced by South Africa when compared with countries with more complete data sets for sources and pathways of plastic, plastic management and regulations implemented in other parts of the world might not be as effective here or have unintended consequences.[57] In order to tailor a plastic policy for South Africa, more spatial and temporal data are needed for freshwater bodies to determine areas in need of protection, areas of highest threat, and processes that may be targeted for intervention.
- The deposition of plastic in riverine sediment as a possible plastic sink[49] correlates with global findings. Deposition or transport of plastic in or by rivers in these different regions need to be better understood and might be part of the answer to the missing plastic problem.[2] If rivers do act as a temporary sink for plastic, more emphasis will have to be placed on determining the amounts and impacts of plastic in freshwater systems.
- Freshwater and estuarine sediments may act as a long-term secondary source of plastics to the oceans, possibly long after effective mitigation on plastic releases has been achieved.
- Preliminary results[19] show low microbead counts in South African rivers compared with those of developed countries. Although surface water microplastic concentrations in the Gauteng and North West Province rivers ranged between 0.33 and 56 particles per litre, microbeads were found at only two of the sites, and in very low concentrations (<0.01 particle per litre). Microbead data from South Africa's freshwater sediments are yet to be reported but can be expected to be higher than that of surface water – international data range up to 103 beads per litre of sediment.[11] Global estimates show microbeads originating from cosmetics make up only 2% of the marine plastic load by number.[5] It would be beneficial to consider import, production, application and distribution of plastic microbeads as it attracts much international attention. South Africa needs to determine whether banning microbeads is a realistic and achievable national priority, and an easy first action to reduce the release of manufactured microplastics.
- A lack of data about polymer and pollutant composition of plastic debris in the environment is another area of study that will help refine, identify and mitigate the greatest threats.
- Recently it has been suggested that antimicrobial resistance genes are associated with microplastic biofilms. These microplastic particles act as vectors for these genes, especially in plastics released by WWTPs.[58] This will possibly translate to agricultural sludge applications as media in which antimicrobial resistance genes spread through the environment. The movement of antimicrobial genes from land-based sources to the sea is a threat that needs further investigation.

Evidence gaps

- Plastic debris from land-based sources reaches the ocean largely by means of rivers and rivers could act as sinks for plastic. When considering that many out-lying communities in South Africa source water, often untreated, directly from these systems and the country has limited freshwater resources, several concerns arise. Knowledge gaps in this regard include the volume of plastic trapped in freshwater systems and the retention time of plastic in freshwater sediment acting as a temporary sink and possible secondary source of plastic debris.

- Due to the diverse marine and freshwater aquatic biodiversity of South Africa, very little is known about specific ecosystem health risks of plastic debris in South Africa. To our knowledge, no published toxicity tests or ecological risk assessments have been conducted on freshwater organisms. Because it is evident that plastic is present in South African aquatic systems, we need to know its effect on freshwater ecosystems.
- Factors affecting the breakdown of plastic in terrestrial and freshwater ecosystems are inadequately quantified in South African conditions. There are many physical and biological factors that play a role and the effects on eventual microplastic and nanoplastic (<100 nm in longest dimension) formation remains unknown.
- Global estimates show that WWTPs remove more than 99% of microplastic from waste water.[59] Sludge from the waste-water treatment process is often applied as fertiliser to agricultural soils, transferring microplastics to agricultural soil.[48] However, the retention rate of South Africa's WWTPs has not been tested, and the extent of sludge addition is not well documented. It is thus necessary to determine the amount of plastic in sludge. Sludge is also a secondary source via wind and run-off. Therefore, more information is needed on how sludge is managed in South Africa, to determine whether intervention is needed.
- Vehicle tyre wear could be a significant source of microplastics in developed countries. The South African transportation system relies heavily on road transport. One can therefore expect notable additions to the freshwater and marine environments. This topic has not yet been considered in South Africa.
- Preliminary results indicate the cosmopolitan distribution of microplastic fibres.[60] The extent to which this is true in South Africa is worth examining. Certain aspects of dust models are available for South Africa and may be adapted, but this will require additional information on the plastic content of dust in air. Long-range transport of plastic is an issue of concern as it can lead to contamination of remote environments, including marine ecosystems.

Implications and actions

Municipalities should prioritise improvements in waste removal and management – especially in informal settlements, for hygienic and environmental reasons. Systems must be designed and/or implemented for the needs and conditions of communities[5] to improve recycle supply chains, and lose less plastic to the environment.

We encourage the development of a standardised solid waste monitoring programme to monitor high risk areas.[61] Issues such as illegal dumping need to be monitored and enforced.

Further public and private sector incentives, awareness raising, and civil society pressures are needed to improve the situation to reduce land-based sources to both freshwater and marine environments. Risk communication and education efforts about the environmental and possible health effects of plastic are of great importance if public participation is to be expected.[19] Public realisation of the value of plastic as an economic resource could motivate public participation in recycling and clean-up efforts.[28] Public sector assistance in extended producer responsibility programmes will assist industry mediators, e.g. PETCO[62], to encourage and administer producer responsibility and contribute to the circular economy concept.

In moving towards a circular economy, research and development resources must be applied to develop alternatives for difficult-to-recycle plastics, e.g. polystyrene.[28] As certain polymers and polymer compositions are less economically rewarding to recycle, much of these are sent to landfill. However, it should be noted that landfill space is limited and so diversion from landfill is ideal.[30]

However, it is clear that maintaining the status quo in the face of increasing population growth, industry, consumerism and wealth, will increase the land-based plastic loadings to the sea. Urgent interventions, awareness, voluntary actions, and regulations are needed to stem the flow of plastics to our oceans. An understanding of the underpinning factors and knowledge gaps is necessary to inform effective and integrated land-based remediation and intervention options and policies.

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Authors' contributions

C.V.: Writing – the initial draft; writing – revisions; project management. H.B.: Writing – revisions; student supervision; funding acquisition; project leadership.

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The transport and fate of marine plastics in South Africa and adjacent oceans

South Africa is thought to be one of the worst contributors of plastic into the sea globally. Although some plastic items derive from offshore sources (mainly fishing and other maritime activities, but also long-distance transport), the importance of local, land-based sources is indicated by the composition of beach debris and the concentration of macro-, meso- and microplastics close to urban source areas. Some 60–90% of plastic from land-based sources is expected to strand on beaches, but plastic standing stocks on beaches are much lower than global model predictions of land-based pollution. Burial in beaches and transport into backshore vegetation are significant sinks, although this plastic is likely to be released as the climate crisis leads to rising sea levels and more extreme storms. Most buried items are fairly small, while many larger items, which account for most of the mass of plastic, are removed from beaches by cleaning efforts. However, even daily accumulation rate estimates – which exclude the effects of cleaning – fall well short of model predictions of plastic leakage from land-based sources. Oceanographic models predict that plastics entering the sea from South Africa are exported to the South Atlantic and Indian Oceans, with the proportion depending on source location and item density. At sea, floating macroplastic is concentrated close to urban centres. Farther offshore, plastic items tend to be large and buoyant because biofouling causes small, low buoyancy items to sink. Size-selective removal of plastics by biota might also contribute to the paucity of floating microplastics (<1 mm). The seabed is likely to be the main long-term sink for waste plastics, but the limited data available indicate low levels of plastics on the seabed off South Africa. Only a small proportion of plastic predicted to leak into the sea from South Africa can be accounted for. However, this should not delay the implementation of effective mitigation measures to limit plastic leakage.

Significance:

- High densities of waste plastic around urban centres indicate that most macro- and microplastics come from local, land-based sources and do not disperse far at sea.
- Beach clean-ups remove up to 90% of the mass of stranded plastic, largely found in macroplastic items (>25 mm).
- The seabed is a long-term sink for marine plastics, but densities of plastic on the seabed around South Africa are still modest.
- The global model prediction of plastic leakage from South Africa into the sea probably is a gross overestimate.

Introduction

South Africa is predicted to be the 11th worst global offender in terms of leaking land-based plastic into the ocean, ranking third in Africa after Egypt and Nigeria.[1] Although the projected growth in plastic from South African land-based sources is more modest than most other African countries, without significant interventions South Africa is likely to remain a significant polluter for at least the next decade.[2] Verster and Bouwman[3] report the sources and pathways by which plastics reach the South African marine environment from land-based sources. Here the relative importance of land- and offshore-based plastic sources are assessed and the fate of plastic items once they enter the seas around South Africa is discussed.

Land or sea? Inferring the origins of marine plastics

Most marine plastics are assumed to derive from land-based sources.[4] If this is the case, we might expect the composition of marine debris to be broadly similar to terrestrial litter, at least close to urban sources. There are differences in the proportions of macro-debris types on South African beaches and in urban litter (Table 1), but most of these discrepancies can be explained in terms of differential transport and environmental lifespans. For example, paper and cardboard comprises 25% of street litter, but <1% of beach litter (Table 1), presumably because it is less likely to disperse and is less long-lasting than plastic. Dense materials, such as glass and metal, are also under-represented on beaches, with only floating items made from these materials regularly washing up on beaches (e.g. sealed glass bottles, lightbulbs, aerosols, gas bottles). Amongst plastic categories, cotton bud sticks are disproportionately abundant on beaches as most come from waste-water treatment facilities rather than street litter. Lids and hard plastic fragments are also more common on beaches, probably because they disperse well and have long lifespans (in part because they are small, and thus less likely to be removed by cleaning efforts than larger items such as bottles and bags, and in part because their greater thickness than flexible packaging makes them more resistant to UV and/or mechanical degradation). Bottles have similar properties, but are more common in street litter because of differential cleaning of large items from most South African beaches.[5] Polystyrene trays are the most common macroplastic item on beaches, greatly outnumbering their occurrence in urban litter, largely because they tend to break up in the environment, thus inflating the number (but not mass) of items.[6] Mass is a better currency to track changes in debris composition, and there is a steady increase in the proportion of plastic

by mass as one moves away from continental source areas (Figure 1), reflecting the differential dispersal and persistence of plastics compared to other debris types.

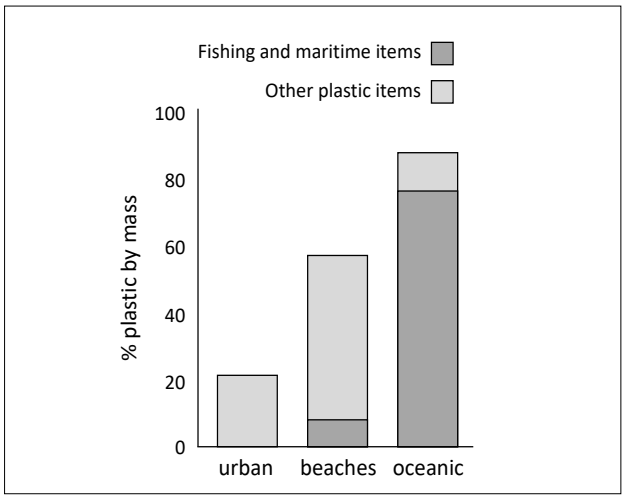

Figure 1: A comparison of the proportion of macro-debris by mass comprising plastic of urban terrestrial litter with that on South African beaches and on a remote oceanic island (Inaccessible Island) in the central South Atlantic Ocean (FitzPatrick Institute unpublished data).

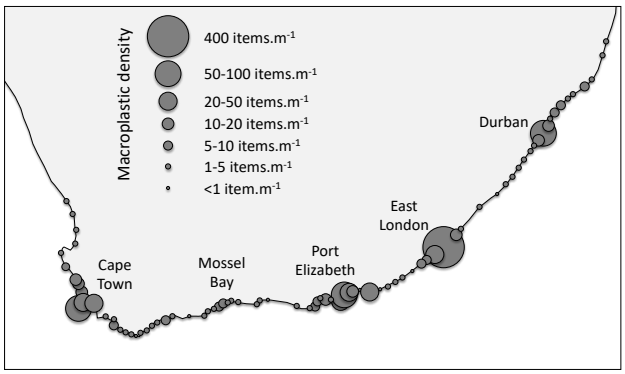

Figure 2: The density of macro-debris (>90% plastic items) at 82 South African beaches in 2015 showing concentrations around urban source areas despite the greater cleaning efforts on urban beaches (FitzPatrick Institute unpublished data).

The dumping of plastic and other persistent wastes at sea was banned in 1989, when Annex V of MARPOL, the International Convention for the Prevention of Pollution from Ships, came into force. However, fishing and other marine activities are still responsible for a substantial amount of marine debris, often accounting for a large proportion of the mass of marine plastic at sites far from land-based sources (Figure 1).[7-9] It is hard to assess how much of this 'maritime' debris is lost at sea accidentally (e.g. as a result of damage to fishing gear or washing overboard during storms) and how much is dumped deliberately. However, in South Africa, fishery-related debris accounts for less than 5% of beach debris by number (12% by mass), much less than food packaging and other single-use plastics typical of street litter (Table 1, Figure 1). Other marine plastics may result from shipping accidents (e.g. 49 tonnes of plastic pellets lost from containers that fell off a ship into Durban harbour in 2017).[10] More problematic to assess, however, is the potential contribution of general waste plastic still dumped at sea in contravention of MARPOL Annex V.[6,11] In this regard, the relative importance of land-based versus offshore sources (fishing, shipping and long-distance drift) can be inferred by examining the distribution and composition of plastic along the coastline.

Table 1: Proportions of macro-debris types at 82 South African beaches sampled in 2015 (n=54 488), in descending order of abundance, compared to Cape Town street and river litter (n=2257). See Figure 2 for the distribution of beaches sampled.

Debris type	Beach	Urban
Polystyrene trays	17.5%	3.5%
Plastic lids and caps (including lid sealing rings)	17.5%	4.0%
Hard plastic fragments	14.4%	1.2%
Cotton buds (earbuds)	8.9%	0.8%
Snack food wrappers (chips, sweets, ice-cream, etc.)	6.6%	12.8%
Plastic straws	5.1%	2.0%
Commercial fishing gear (ropes, netting, floats, light-sticks, etc.)	3.5%	0.0%
Plastic bags (HDPE carrier bags, LDPE bags, mesh bags, etc.)	3.4%	3.9%
Plastic lolly sticks	3.2%	0.2%
Other plastic food wrappers	3.2%	3.9%
Cigarette butts	2.4%	20.5%
Plastic user items (toys, pipes, buckets, etc.)	2.0%	1.8%
Plastic bottles and tubs	1.8%	4.1%
Other packaging (bubble wrap, packing foam, packing strips, etc.)	1.6%	1.3%
Polystyrene lumps	1.6%	0.3%
Disposable plastic items (cutlery, lighters, pens, toothbrushes, etc.)	1.3%	4.2%
Glass items (bottles, lightbulbs, etc.)	1.2%	2.7%
Recreational fishing gear (including monofilament line)	1.2%	<0.1%
Metal items (cans, tins, metal lids, ring pulls, etc.)	0.8%	5.4%
Medical/sewage waste (syringes, condoms, nappies, etc.)	0.6%	0.4%
Shoes, hats, gloves, etc.	0.6%	<0.1%
Paper and cardboard	0.6%	25.5%
Wood (worked timber)	0.5%	0.8%
Other non-plastic items	0.4%	1.7%
All plastic and related synthetic items	**96.5%**	**63.9%**

Regular surveys of debris on sandy beaches around the South African coast, since the 1980s, show that densities of both macro- and mesoplastic items are consistently greater close to urban centres than at more remote beaches (Figure 2).[12,13] This pattern is found among macroplastics even though urban beaches are subject to much greater beach cleaning efforts than remote beaches.[5,14] The distribution of small microplastics (mainly microfibres <1 mm) reported from sandy beaches around the South African coast have differed to some extent between studies[15-17] but the most comprehensive survey to date also found a strong correlation with local urban source areas.[18]

The higher densities of plastics close to urban areas (typically two to three orders of magnitude greater than remote beaches[13,17]; Figure 2) suggest that most plastic on the South African coast derives from local, land-based sources. This is not to say that physical factors do not play a role in the distribution of plastic items along the coast.[19] At a local scale, beach structure and nearshore currents tend to concentrate plastics at some beaches more than at others[10], as evidenced by the correlation between plastic and pumice, a neutral marker of oceanic floating debris[12]. The distribution of plastic standing stocks also is determined by the turnover rate at beaches.[20,21] However, if most plastics were dumped from ships or had drifted from distant sources, we would observe a more uniform distribution of plastic around the coast[13,17] (Figure 2). This conclusion is supported by the greater proportion of locally versus foreign-manufactured items on beaches close to urban source areas than on more remote beaches.[12] Similarly, the proportion of newly stranded plastics carrying bryozoans and goose barnacles (*Lepas* spp.), which is indicative of items that have drifted at sea for some time, increases with distance from urban centres.[22]

All these indicators show that plastics from offshore sources become relatively more abundant with distance from urban centres, which is

consistent with land-based litter being responsible for most of the plastic on beaches close to urban centres. Surveys of stranded bottles are currently being conducted to provide a better indication of the relative proportion of land- and ship-based plastics around the South African coast.[6,11] Preliminary results show that most soft-drink bottles derive from local sources, but that many water bottles are from offshore sources, with the proportion of foreign-manufactured water bottles ranging from 15% at urban beaches to nearly 90% at remote beaches (compared to <2% in street litter). The recent manufacture dates and lack of epibionts (organisms that live on the surface of other organisms) on foreign water bottles suggests that they mainly come from shipping passing around the Cape,[6] whereas many of the HDPE bottles manufactured in South East Asia that are found all along the east African coast from Kenya to Cape Agulhas may have drifted across the Indian Ocean because they typically are colonised by bryozoans and often have bite marks from fish (FitzPatrick Institute unpublished data).

Lost at sea – where is all the plastic?

Due to their low density and long lifespan in the environment, plastics can disperse vast distances.[23,24] About two thirds of plastics produced by mass are polymers less dense than seawater[25], and even items made from more dense polymers can float large distances if they contain trapped air pockets (e.g. sealed PET bottles)[6]. Oceanographic models, drifter tracks and observations of debris at sea all indicate that plastic floating at the ocean surface tends to accumulate in the centre of ocean gyres in so-called 'garbage patches'.[26-29] However, there is a large mismatch between estimates of the amount of plastic entering the sea each year from land-based sources (5–12 million tonnes in 2010)[1] and the amount floating at the sea surface (~250 000 tonnes)[29]. Even allowing for the fact that this estimate of floating plastic is conservative[8] and that Jambeck et al.[1] probably overestimated land-based inputs, the amount of plastic entering the sea each year is at least an order of magnitude greater than the amount floating at sea.[25] This discrepancy adds a new twist to the question 'Where is all the plastic?' posed by the seminal paper highlighting concerns about marine microplastics.[30]

Koelmans et al.[31] suggested that rapid fragmentation and sedimentation of floating plastic could account for the relatively small amount of plastic floating at sea. Their model of global plastic flux, fitted by matching known production figures to the observed amount of plastic floating at sea,[29] suggests that more than 99% of plastic that has entered the sea since the 1950s has already sunk to the seabed, with a mean surface retention period of only 3 years. If correct, this means that the sea surface will lose floating plastic fairly rapidly if leakage into the environment ceases.[8] However, only 1 of 50 dated items found in the North Pacific garbage patch in 2015 was less than 5 years old[8], which is consistent with the long travel times predicted from surface drifter models for floating items to reach the accumulation zones in ocean gyres[25,28]. The Koelmans et al.[31] model excludes stranded items from the global mass balance of marine plastics, treating beach plastic as still on land. Lebreton et al.[25] adopted a more realistic three-compartment model for floating macroplastic that tracks items in beaches, as well as floating at sea in coastal and oceanic waters. Using a Lagrangian drift model, with the amount of plastic released from coastal areas related to human population density and waste mismanagement, 96% of particles (or 98% if wind-induced forcing is added to the model) are predicted to strand within 1 year of release.[25] Stranded items can be resuspended and transported offshore, but in order for the model to match observed estimates of floating plastics, only 1% of stranded/seabed macroplastic is resuspended and returned to coastal surface waters each year, and 33% of floating plastic disperses from coastal to oceanic surface waters each year.[25] These estimates appear to be modest, but they depend in part on the assumed degradation rate from macro- to microplastics of 3% per year across all three compartments, which may be slow for plastic on beaches and fast for plastic floating at sea.[24,32] We need better estimates of the fluxes between the main environmental compartments (beaches, sea surface, water column, seabed and biota), as well as plastic degradation rates within each compartment. However, Lebreton et al.'s[25] model predicts that coastlines are important short- to medium-term sinks for marine plastics irrespective of the exact parameter values, which concurs with oceanographic model predictions for the fate of plastics entering the sea from South African urban areas.[19]

Are beaches major sinks for marine plastics?

In a South African context, the fact that plastic densities are greatest close to major urban centres not only indicates that most marine plastic comes from local sources, it also suggests that a large proportion of land-based plastic does not disperse far from source areas. This is consistent with the rapid decrease in the density of floating macroplastic at sea moving away from urban source areas, although sedimentation to the seabed might also contribute to this pattern.[33] Oceanographic models predict that more than 60% of buoyant items entering the sea from South Africa wash up on beaches[19] (Figure 3). The proportion is expected to be much greater for plastic emanating from urban centres along the country's east coast (>90%) than Cape Town (19%, but all Cape Town litter was simplistically assumed to release into Table Bay; litter entering the semi-enclosed False Bay is less likely to be transported offshore). Fewer plastics with densities greater than seawater are predicted to strand, but even this proportion (35% overall[19]) appears to be rather high given the general paucity of items that sink stranded on South African beaches. Empirical support is needed for these estimates, because the oceanographic model used fails to account for the complex physical dynamics in nearshore environments (waves and tides).[19] In fact, it is likely that the proportion stranding close to major emission points (river mouths and storm drain outfalls) depends on the nature of the receiving environment (e.g. exposure and wave action) as well as the size and buoyancy of the items. Microplastics and low-buoyancy macroplastics (such as bags and flexible packaging, Figure 4a) tend to be transported offshore through surf zones more easily than more buoyant macroplastics (such as bottles and expanded polystyrene, Figure 4b) because they are more prone to be carried offshore in the undertow.[34,35]

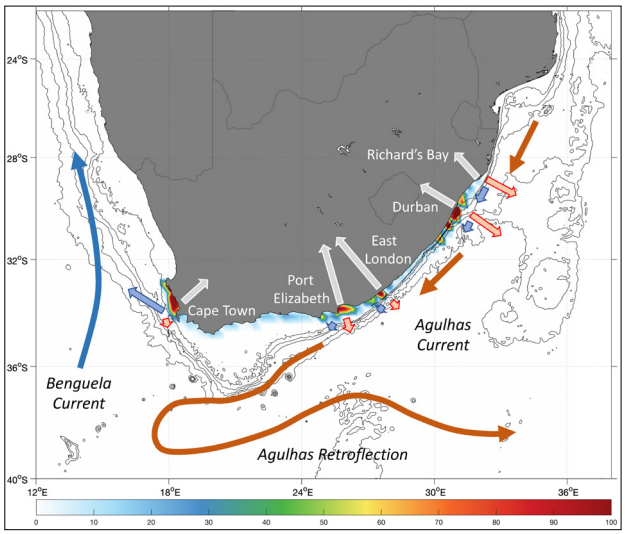

Figure 3: The proportion of plastic items (buoyant and sinking combined) predicted to be exported to the Atlantic or Indian Oceans, or stranded ashore, from the five major urban areas along the South African coast, in relation to ocean currents. Arrow length indicates the relative importance of each pathway. The heat map shading along the coast shows where most debris is predicted to strand (= tracer accumulation factor, adapted from Collins and Hermes[19] with thanks to C. Collins). Cape Town litter was all released off Table Bay (none in False Bay).

Plastic items have been predicted to accumulate along specific areas of the South African coast, mostly downstream from the major urban source areas.[19] However, at a local scale, the predicted zones do not closely match observed hotspots for macro- (Figure 2) or meso/microplastics.[13] These discrepancies probably reflect at least in part differences in shoreline type and associated plastic residence times. For example, concentrations of plastic along the south-central KwaZulu-Natal

coast are lower than expected given the high human population densities and large plastic industry in the Durban area[13] (Figure 2). This is not because of reduced plastic input in this area – the amounts of litter stranding on Durban beaches after rain events are quite shocking and regularly attract media attention. A more likely explanation is that the steep, coarse beaches in this area, together with clean-up efforts, result in fast turnover rates for plastic items.[21]

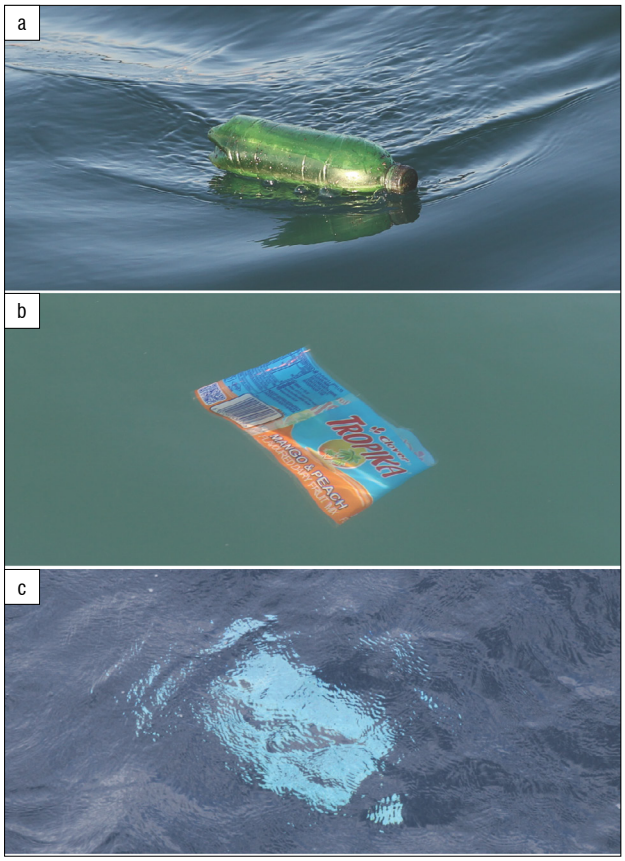

Figure 4: Plastic transport at sea differs between buoyant items with significant windage such as bottles which are blown faster than surface currents even at low wind speeds (a), whereas flexible packaging is close to neutrally buoyant and travels with surface currents (b). After some time at sea, biofouling can cause even large plastic items made from polymers less dense than seawater to sink (c).

One way to test predictions about the proportion of plastic washing ashore is through a mass balance exercise. At least 10^5 tonnes of waste plastic is estimated to reach the sea from land-based sources in South Africa each year.[1-3] How does this figure compare to the amount of plastic stranded on beaches? The average plastic standing stock on South African sandy beaches is <0.1 kg/m, with even the most heavily polluted beaches having 1–2 kg/m (FitzPatrick Institute unpublished data). Extrapolating this estimate along the entire South African coast (3000 km, not all of which is sandy beach) gives a total of $\sim 10^3$ tonnes, appreciably less than the estimated land-based sources. If some 50% of all plastic washes ashore,[19] why do we not see more plastic on our beaches? Several factors might explain this discrepancy: (1) the estimated amount of plastic entering the sea from land-based sources is inflated, (2) the proportion of plastic entering the sea from land-based sources that strands on beaches is lower than expected, and/or (3) turnover rates of plastic items on sandy beaches are rapid, and thus standing stocks underestimate the amount of plastic washing ashore. To resolve the relative importance of these factors, we need direct estimates of the amounts of litter entering the sea,[3] and of the proportion that strands on beaches, but we can make some inferences about how representative standing stocks of beach plastic are of the amount washing ashore.

Burial, export and the impact of beach cleaning

Beaches are dynamic environments, with numerous processes influencing the amount of visible macroplastic.[5,21] Traditional surveys of beach macroplastics only sample superficial items, ignoring buried items.[36,37] In order to estimate the contribution of buried macroplastics, 50-m transects for superficial macroplastics were combined with 1-m wide transects (8-mm sieve) to sample buried macroplastics to a depth of 15 cm. Sampling was conducted at two beaches that are seldom if ever cleaned: a remote beach in the West Coast National Park and at a beach in a restricted area on the False Bay coast. Most macroplastic items were buried at both beaches, but buried items tend to be smaller than surface items because small items are much more readily buried by windblown sand. As a result, buried macroplastics accounted for only 6–34% of the mass of beach plastics (FitzPatrick Institute unpublished data). These estimates suggest that burial is not a major factor in terms of the mass of plastics on beaches. However, they exclude deeply buried plastic items. For example, industrial pellets can occur up to 2 m deep in heavily polluted beaches.[38] Also, sampling did not go far above the storm strand line; substantial amounts of stranded plastic may become trapped particularly on prograding shorelines, which are common locally in southern Africa. Unfortunately, the rapid post-industrial increase in atmospheric greenhouse gases means that we are already committed to substantial sea-level increases (5–10 m) in the near future.[39] Coupled with increasingly severe storm events, it is likely that not only plastic trapped in beaches will be released into the sea through beach erosion, but landfills close to the coast also will be at risk of being washed away (e.g. Coastal Park on the False Bay coast of Cape Town).

There is little information on plastic turnover rates on South African beaches, but they could be fairly rapid, especially for lightweight items given the windy conditions prevalent along the coast. Daily sampling collects 2–5 times more macroplastics by number and 1.3–2.3 times more by mass than weekly sampling, with faster turnover rates for low density items such as expanded polystyrene.[40] The fate of windblown plastic is not well understood; onshore winds blow plastic inland, where much of it is trapped in vegetation along the back shore,[20] whereas offshore winds blow it into the sea. In the surf zone, its fate once again depends on size and buoyancy, with low density items such as sealed bottles and expanded polystyrene being carried back to shore by waves despite their high windage, whereas items such as bags and other flexible packaging, which are much less buoyant, are more likely to be carried offshore.

Beach cleaning efforts likely play a more significant role in removing plastics from marine systems. In South Africa, it is becoming increasingly difficult to find beaches that are not cleaned at least once or twice a year. 'Working for the Coast', part of the government's Expanded Public Works Programme[41], employs teams of people to inter alia clean much of the coastline, augmenting the already substantial municipal cleaning efforts[18] and the ever-growing volunteer cleaning effort. The impact of beach cleaning on plastic standing stocks depends on the frequency and intensity of cleaning, with the intensity largely dependent on the number of cleaners and their level of motivation. There tends to be a strong size bias in cleaning efforts, with larger items more likely to be collected by cleaning teams than small items[5] (Table 2). For example, the beach with the highest macroplastic density sampled along the South African coast in a survey of 82 beaches in 2015 (Figure 2) was an urban beach with daily municipal-funded cleaning. This beach had an average density of 399 items/m of beach, including 66 bottle lids and caps, 52 earbuds, 39 straws and 124 pieces of polystyrene food trays/cups. However, most of the mass of plastic resides in large items. This is illustrated by the comparison of two adjacent beaches on the False Bay coast: one open-access beach that is cleaned regularly by the municipality, and an adjacent beach in a restricted-access area that is seldom, if ever, cleaned. The uncleaned beach has about twice the number of macroplastic items than does the cleaned beach, but the mass of plastic is almost 20 times greater at the uncleaned beach (and 80 times greater if only surface plastic is considered; Table 2). Interestingly, there is more non-plastic debris at the cleaned beach (Table 2), due to littering by beachgoers. This comparison of two adjacent beaches suggests that beach cleaning could account for the removal of over 90% of the mass of plastic stranding

Table 2: The abundance and mass of superficial and buried (to 15 cm deep) macro-debris per metre of beach at two adjacent False Bay beaches with different cleaning histories

Debris type	Uncleaned beach			Cleaned beach			%Cleaned
	Surface	Buried	%Buried	Surface	Buried	%Buried	
All plastic items	35	414	92%	22	268	92%	35%
Bottles	4	7	64%	0	0	–	100%
Lids	9	73	89%	2	21	91%	72%
Straws	3	11	79%	2	6	75%	43%
Bags, wrappers	6	58	91%	4	20	83%	63%
Polystyrene	2	131	98%	3	13	81%	88%
Other packaging	3	15	83%	1	11	92%	33%
User items	5	22	81%	1	5	83%	78%
Plastic fragments	2	69	97%	3	106	97%	**–54%**
Cigarette butts	1	25	96%	6	85	93%	**–250%**
Non-plastic items	2	9	82%	14	118	89%	**–992%**
%Plastic	95%	98%		61%	69%		
Plastic mass (g)	905	472	34%	11	70	86%	94%
Non-plastic mass	41	69	63%	32	126	80%	**–44%**
%Plastic by mass	96%	87%		26%	36%		

%Cleaned shows the proportion removed by regular cleaning, assuming equal inputs.

Debris types which are more abundant at the cleaned beach, despite cleaning effort, presumably due to input from beach users, are shown in bold.

on South African beaches (Table 2). No accurate statistics are kept on the amount of plastic collected; most municipal teams also collect seaweed and other natural marine debris, and even volunteer groups that record the mass of different debris types collected have inflated estimates because they do not clean or dry items prior to weighing. It remains to be answered whether the amount of plastic removed through burial, natural turnover and clean-ups is sufficient to close the gap between the modest superficial standing stocks (~10^3 tonnes) and the amount estimated to strand along the coast (~10^5 tonnes/year), bearing in mind that this latter estimate might be grossly inflated.

Dispersal of floating plastic

What happens to plastic that does not strand on beaches? The drift tracks of plastic items floating at sea can be predicted directly from the trajectories of satellite-tracked weather buoys[26,28] or simulated in oceanographic models[27,42]. The former approach makes no assumptions about oceanographic processes; it simply uses the observed movement of tracked buoys to estimate movement probabilities between grid cells. The website www.plasticadrift.org illustrates global drift patterns and the timescales over which they operate.[28] Plastic items are assumed to have the same drift characteristics as the buoys, which are drogued to track water movements 10–15 m subsurface. Comparisons of drift trajectories of buoys with and without drogues show marked differences due to the effect of Stokes drift (linked to wind and wave action), which decreases rapidly with depth.[43] As a result, these models are best suited for plastics drifting below the water surface (Figure 4c).

Oceanographic circulation models (OCMs) simulate water movements based on forcing mechanisms (wind, Coriolis force, etc.). They can provide a finer-scale prediction of plastic movements than empirical models based on drifter tracks, especially when implemented at a regional[19] rather than a global level.[42] However, even in the open ocean, where OCMs should best simulate water movements, OCM predictions tend to underestimate drifter movements[44] and there are mismatches between distributions of floating microplastics[45]. The models typically do not account for fine-scale features such as drift rows, which result from Langmuir circulation and account for much of the fine-scale heterogeneity in the distribution of floating plastics at sea.[5,21]

OCMs have two advantages compared to drifter-based models. First, drift trajectories can be programmed to account for windage, which typically allows buoyant items to travel faster than prevailing currents (Figure 4b). For example, there was generally good agreement between the observed and predicted dispersal speeds and stranding locations of items with different levels of windage released into the sea by the 2011 Japanese tsunami.[46] Adding windage and stochastic motion improves estimates of stranding probability and the trajectory of objects lost at sea around South Africa.[44] This is particularly important for understanding the dispersal of buoyant items, which dominate floating macroplastics away from land-based source areas.[33] Collins and Hermes[19] did not include windage in their model of plastic dispersal around South Africa because they were interested in microplastics, which generally drift at or just below the water surface.

OCMs also can explore the dispersal of plastics suspended in the water column, and thus simulate the effects of vertical as well as horizontal movement (i.e. accommodate changes in movement trajectories with depth, such as those associated with the thermohaline circulation).[19,47] Elsewhere, suspended plastic has been found to aggregate at the salinity front where large rivers enter the sea,[48] but this is unlikely for the relatively small rivers in South Africa. For plastic items released from the south and east coasts of South Africa, floating items are predicted to be more likely to travel into the Atlantic Ocean, whereas dense plastics which sink towards the seabed are more likely to be entrained in the Agulhas Retroflection and travel into the Indian Ocean.[19] However, like drifter models, OCMs struggle to simulate currents and current-wave interactions in the immediate near-shore environment. For example, the recent study to predict plastic movements around South Africa avoided this issue by releasing tracked particles 8–10 km offshore.[19] We need a better understanding of the movement of plastic items in the surf zone and adjacent nearshore environments to understand the movement of plastic released from South African land-based sources. And although the model produced broadly plausible simulations of currents around South Africa[19], it failed to predict known accumulation zones for plastic drift cards (and oil pollution) along the south coast of South Africa[49].

Drifter-based models and OCMs both predict that most floating plastic items that travel offshore from the South African coast mainly enter the South Atlantic gyre, or drift east into the Indian Ocean.[19,42,44] Only small amounts of plastic from South Africa are predicted to travel south[19], which is consistent with the low densities of plastics observed in the Southern Ocean south of Africa[50]. The accumulation of floating plastic in the South Atlantic gyre has been shown empirically for both micro- and macroplastics.[29,51,52] By comparison, the concentration of floating plastic in the Indian Ocean gyre is less well defined[29,51], with greater leakage predicted to occur into the Pacific Ocean[26,28,53]. However, the absolute amount of plastic entrained in the Indian Ocean is extrapolated to be 4–5 times greater than in the Atlantic Ocean, both in terms of the numbers and mass of items.[29] This difference is driven by greater

amounts of macroplastics floating in the Indian Ocean, linked to the much larger input of plastics from South East Asia than from regions bordering the South Atlantic Ocean.[1,53]

Sedimentation of floating plastic and transport by biota

Until recently, models of plastic drifting at sea typically assumed that items less dense than seawater remain at the water surface for protracted periods.[28] However, items drifting at the sea surface tend to lose buoyancy as they become fouled by epibionts, resulting in them sinking.[54] Because fouling occurs on the surface of plastic items, and buoyancy is a function of volume, plastic items with large surface area to volume ratios are expected to sink more quickly.[33] This has been demonstrated experimentally with tethered polyethylene pieces in South African coastal waters, with small (5x5 mm), thin (0.1 mm) pieces sinking within 2–3 weeks, whereas larger (50x50 mm), thicker (4 mm) pieces take more than 2 months to sink.[55] However, it is unclear what impact tethering has on fouling rates and whether fouling in inshore waters is typical of rates experienced farther offshore; fouling rates probably vary seasonally.[56]

Despite these uncertainties, sedimentation probably accounts for the increase in the size and buoyancy of macroplastic items with distance from urban source areas.[33,57] However, there is debate as to the fate of items that sink in this way. In shallow waters, they probably sink to the seabed, where they become fouled by benthic organisms and weighed down by sediment and thus remain trapped on the seabed.[25] This is demonstrated by the fact that most plastic items (77%) collected in trawls on the South African continental shelf are made from polymers less dense than seawater and float once cleaned.[58] Sinking times are of the same order as predicted from the tethered experiments, with a bread bag bearing pelagic goose barnacles (*Lepas anserifera*) trawled up from the seabed within 3 months of being manufactured.[58] In deeper waters, it has been suggested that such items 'yo-yo' up and down in the water column as they start to lose epibionts once they sink below the photic zone.[54,59] Lebreton et al.[25] assumed that this occurred in waters more than 200 m deep. However, the South African trawl survey found a polypropylene margarine tub still bearing pelagic goose barnacles at 685 m.[58] The tub might have travelled down the continental slope after sinking, but it was already colonised by a diverse array of benthic biota, and thus appeared to be unlikely to float again.

Biofouling is not the only process that facilitates the sedimentation of plastics from the sea surface. Microplastics frequently adhere to marine 'snow' (particles of organic detritus[60]), which increases the likelihood of sinking out of surface waters.[61] Sinking is also promoted for microplastics incorporated into zooplankton faecal pellets and larvacean mucous filters[62,63], although microplastics can reduce the sink rate of faecal pellets[64]. Zooplankton may also export plastics directly to deeper waters. Many species forage near the sea surface at night and then migrate vertically to deeper waters during the day, where ingested plastic could be entrained if the zooplankton is eaten in the deep.[65-67] Recent studies suggest that many planktonic organisms now contain ingested microplastics.[65-68] This is particularly true in heavily polluted areas such as the North Pacific 'garbage patch'[68] and near the mouth of the Yangtze River in the Yellow Sea[65], but high incidences of microplastics have been found in mesopelagic fish even in oceanic waters far from the subtropical gyres[66]. Most small pelagic fish off South Africa also contain microfibres (44–80% of individuals of five species contained at least some fibres[69]), but it is not known what proportion of these fibres are synthetic. However, it is questionable whether these items account for a significant proportion of the mass of plastics at sea because they are typically very small fragments and fibres. For example, even in the Yellow Sea, where microplastics are estimated to be almost two orders of magnitude more abundant in zooplankton than in the water column,[65] the mass of ingested plastic is <1 mg/m^2, even if we assume zooplankton occurs to 300 m deep.

Animals might also transport plastics among other environmental compartments. Marine predators, such as seabirds and seals, that come ashore to breed or moult import some plastics to land (e.g. seabirds using plastics collected at sea as nest material).[70] This is probably most significant for ingested plastic in seabirds, which can be released on land through mortality, regurgitation or excretion.[71-73] Off South Africa, petrels in particular often contain large amounts of ingested plastic[74], with adults transferring much of their accumulated plastics to their chicks[75]. However, this is only likely to account for a relatively small amount of plastic, even given the large populations of some species (10^6–10^7 individuals),[76] given average plastic loads of <0.1 g per bird.

The seabed as a long-term sink

The sedimentation of floating plastics, together with the direct sinking of about one third of all polymers that are more dense than seawater, suggests that the seabed is likely to be the ultimate long-term sink for most plastics that enter the marine environment.[77,78] However, very little is published on the composition and abundance of seabed debris in South Africa.[79-81] A recent study of macro-debris in 235 demersal trawls made across the continental shelf (30–900 m deep) between the Orange River and Port Alfred found that plastic was most common in the area north of Cape Town and that densities increased with water depth.[58] Most plastic debris was packaging and other single use items (77%) but these items accounted for only 16% of the mass of plastics.[58] Fishing gear was the next most common category of plastic items (21% by number and 48% by mass). The proportion of fishing gear on the seabed likely increases with distance from land-based sources, particularly on favoured fishing areas such as sea mounts.[82] Overall, the densities of plastics (3 items/km^2 and 0.3 kg/km^2) were markedly lower than in other trawl surveys around the world (typically 20–500 items/km^2 and 2–20 kg/km^2).[58,78] This might be related in part to the nature of the trawl gear used, but examination of remotely operated vehicle camera footage collected for biodiversity surveys across a range of habitats from the continental shelf and slope all suggest very low densities of debris on the seabed around South Africa (Sink K, SANBI, personal communication).

Closer to shore, occasional mass strandings of seabed debris indicate the presence of a pool of plastics on the seabed at least close to urban source areas.[80] For example, monthly spring-low clean-ups of a stretch of rocky intertidal shoreline in False Bay collected an average of 1.65 ± 1.30 plastic items/m (12 ± 10 g/m, $n=36$ months), except one month when more than 65 items (72 g/m) were recorded (FitzPatrick Institute unpublished data). Many items were made of polymers denser than seawater (polyamide cable ties, polystyrene cutlery, etc.). The conditions driving such events have not been studied in South Africa, but probably are related to intense wind-driven upwelling.[83] However, the location of this plastic on the seabed remains unknown, with no plastic items seen in any of 421 images of the False Bay seabed taken to classify benthic communities (FitzPatrick Institute unpublished data).

Current uncertainties and evidence gaps

The gross discrepancy between estimates of the amount of plastic in marine environments around South Africa and the amount thought to be released from local, land-based sources mirrors our inability to produce a plausible mass balance for waste plastics globally.[25,31] Either we are greatly overestimating the amounts of plastic entering the sea, or we are failing to measure a major sink for marine plastics. To solve this dilemma, we need a better understanding of the origins, transport and fates of macroplastics, because they account for almost all of the mass of plastics in marine ecosystems.[8,29]

Although much remains to be learned about the distribution and abundance of plastics on the seabed, all indications are that macroplastic items are scarce on the seabed off South Africa, especially when compared to other densely populated continental margins. As a result, it is unlikely that seabed plastic will fill the deficit in the mass budget. We know even less about plastics suspended in the water column, including how they move vertically with biotic-induced changes in buoyancy.[47,59] Sampling macroplastics in mid-water trawls is perhaps the most practical way to gain useful data in this regard. However, anecdotal reports from fishers and fishery biologists indicate that this compartment is unlikely to explain the thousands of tonnes of 'missing' plastic. Better estimates of plastics removed from beaches might partly

explain the deficit, but estimates of daily arrival rates of macroplastics at urban beaches[84-86] are modest relative to the global model prediction. Paradoxically, the biggest knowledge gap pertains to estimates of land-based plastics entering the sea. This should be one of the easiest fluxes to measure, but it is symptomatic of the history of the plastic pollution problem, which started in marine ecosystems and has only recently started to focus on plastics in freshwater and terrestrial ecosystems.[87]

Implications for tackling the plastics problem

The fact that we cannot account for much of the mass of plastic estimated to be leaking from South Africa into the ocean has little bearing on how we go about tackling the plastics problem. Although the exact amounts are poorly known, it is clear that the country is responsible for a significant amount of plastic waste entering the sea, and that this situation needs to be addressed. There are many ways to reduce plastic wastes, including incentives to reuse or recycle plastics; improved product design to reduce plastic use and facilitate recycling; adopting extended producer responsibility for packaging beyond the point of sale; material substitution; and even banning plastics in high-risk applications. However, the ultimate goal is to reduce the amount of plastic and other solid wastes entering the sea. Here, the biggest short-term gains will be made by improving solid waste management on land and intercepting debris in run-off, particularly from urban areas. Installing and servicing effective litter traps in urban rivers will go a long way towards reducing plastic leakage into the sea. However, there is also a need to ensure better compliance with legislation prohibiting the dumping of plastics and other persistent wastes by ships at sea.

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Impacts of plastic debris on biota and implications for human health: A South African perspective

Entanglement and ingestion of plastics are the main ecological impacts of marine plastic debris on marine biota, but indirect effects such as the transport of alien species and benthic smothering are also important to note. Entanglement of invertebrates, sharks, turtles, birds and marine mammals is mainly caused by macroplastics (>5 mm), and leads to reduced mobility, ineffective foraging and subsequent mortality. The main plastic types associated with entanglement are improperly discarded fishing nets, lines, ropes and straps. In South Africa and surrounding waters, plastic ingestion has been reported in a number of marine species: sharks (n=10), fish (n=7), turtles (n=1) and birds (n=36). Lethal (macroplastic) and sub-lethal effects (microplastic ≤5 mm) of marine debris on biota have been noted, but at the time of this review there were no published reports on impacts at the population level. Consumed shellfish are possible vectors for the introduction of microplastics into humans. The specific impacts of microplastic ingestion on human health are largely unknown, but additives associated with plastics represent a threat. The research infrastructure in South Africa is insufficient to monitor and characterise marine plastic debris and, in many cases, not in line with global standards. More research effort is needed to understand the impacts of marine plastic debris on humans and marine biota in South Africa, particularly at the population level.

Significance

- Macroplastics affect marine biota mainly via entanglement and microplastics largely through ingestion.
- Macro- and microplastic interactions with biota can result in sub-lethal effects and mortality but no population effects have been reported for South Africa.
- Consumed shellfish are a potential source of microplastics for humans but their potential effects in humans remain unknown.
- Better infrastructure is needed for improved monitoring and research on the effects of marine debris in South Africa.

Status of the ecological impact of plastics in South Africa

Global records of the number of organisms that interact with plastic debris indicate an increase from 265 species in 1997[1] to 557 in 2015[2]. Records were initially detailed in higher order organisms such as mammals, birds and reptiles; however, more recently fish and invertebrates have become research interests, especially in terms of their interaction with microplastics.[2] 'Microplastics' is now a globally relevant theme that has received increased attention in South Africa over the last decade. Ryan and Moloney[3] provided the first account of these smaller plastics around the South African coastline in 1984 and 1989 and offshore in the 1970s,[4] but there are still many gaps in our understanding of the prevalence and typology of marine plastic debris in general in South Africa. The widespread bioavailability of microplastics to marine organisms, their potential to act as vectors for both chemicals and microflora, and the resultant impacts on humans and other biota that consume them also represent many unknowns, both in South Africa and globally. This lack of data has hindered the design and implementation of appropriate mitigation strategies.

The marine environment around South Africa supports over 13 000 species, many of which (up to 33%) are endemic[5], necessitating focused research on the impact of plastic debris on marine biota in the country's waters. The South African coastline has unique currents, bioregions and coastal geomorphological features.[5] Early research on marine debris in South African coastal environments focused on the impacts on seabirds and began in the mid-1980s[6,7], although incidental reports of plastic ingestion in turtles were made in the 1970s[8]. Since then, a number of fish, sea turtle, bird and mammal species in South African oceans have been found to be affected by plastics (Table 1 and Supplementary table 1)[9,10]; the effects on these species are expanded on below. However, a comprehensive assessment of the variety and degree to which South African biota are affected is lacking. While the World Health Organization rates the risk of plastics to humans as low, there is still a need to evaluate the potential effects of microplastics on the South African human population given the country's reliance on many edible marine species. This need provided the motivation for this review, which assesses the impact of marine plastic debris on biota and the potential implications on human health in South Africa, by drawing on data available for organisms sampled from waters extending from South Africa to more southerly regions, up to the Prince Edward Islands. Where South African data on these aspects were lacking, examples from international studies were used to draw parallels. The objectives of this review were to: (1) review South African literature on marine biota impacted by plastic debris, through entanglement, ingestion, benthic smothering and alien transport; (2) determine the potential for, pathways of and potential impacts of microplastic ingestion on human health, particularly in relation to species of commercial value; and (3) identify the gaps in our understanding of the impacts of marine plastic debris on South African marine biota and human health. This review also comments on how South African literature on marine plastic debris (and its impacts) contributes to the global understanding of the phenomenon.

The impacts of plastic debris on marine biota

Entanglement

A major impact of discarded macroplastics is the potential to physically trap marine organisms.[10] Kühn et al.[2] provided the most comprehensive global assessment on entanglement in 2015, which lists 344 species including invertebrates, sharks, fish, sea turtles, birds and mammals. This assessment expands on the previous effort by Laist in 1997 of 136 species, which focused on higher order organisms.[1] In general, most entanglement occurs with improperly discarded or accidentally lost fishing gear such as nets, lines, ropes and straps from bait boxes.[11,12] This impact has received the most public attention, partly driven by social media, especially when organisms are physically injured for long periods before mortality. South African entanglement records prior to 1990 include 6 shark, 2 turtle, 13 seabird and 5 marine mammal species.[9] A brief overview of the prevalence of entanglement in South African marine species is presented herein, together with recommendations for future research. It must be noted that in many cases of entanglement by fishing gear, it is often challenging to discriminate between active and ghost gear.[10]

Invertebrates

Published entanglement records for South African invertebrate species were not available at the time of this review. Globally, an assessment in 2015 lists 25 mollusc, 21 echinoderm and 46 crustacean species affected by entanglement.[2] These numbers are higher than those of the assessment in 1997 which lists 8 species, most of which were crustaceans, and probably reflects an increase in research effort.[1] Based on the global literature, pelagic invertebrates are usually smaller and therefore possibly more susceptible to plastic ingestion than entanglement. However, sessile taxa are also at risk; for example, Lamb et al.[13] estimated that 11.1 billion plastic items are currently entangled on corals in the Asia-Pacific. This entanglement will likely affect feeding and gaseous exchange in these coral systems.[14]

Sharks and other fish

South African literature identified plastic straps, from bait boxes and land-based packaging, to be the main plastic types associated with sharks caught in gill nets (or shark nets).[11] Shark nets are put in place by government agencies to protect bathers.[11] Between 1978 and 2000, 53 of the 28 000 sharks (0.18%) caught were found to be entangled by marine debris, and although a wide variety of species was observed, only the dusky shark, *Carcharhinus obscurus*, showed an increase in entanglement over time.[11] Shark fins are not retractable, increasing their vulnerability to entanglement.[11] Discarded fishing nets can also entangle and capture fish and other marine biota, a phenomenon known as ghost fishing.[14] There were no South African studies that provided quantitative data on this phenomenon, possibly because it is difficult to distinguish between active and ghost gear. However, discarded fishing gill nets are removed daily from estuaries around South Africa, some of which appear to have been abandoned. For example, on the Mlalazi Estuary, conservation officers recovered 51 monofilament gill nets, holding 195 fish of 12 species, from 21 April 2018 to 28 March 2019 (Buthelezi T, Ezemvelo KZN Wildlife, 2020, personal communication, February 27). Globally, lost or discarded fishing gear continue to capture fish, which could affect fish populations.[14] The United Nations Environment Programme estimated that 640 000 tons of discarded fishing gear is added to the oceans annually, which captures a wide variety of both commercial and non-target species.[15] As marine organisms trapped in these nets decompose, they attract and entangle scavengers in a cyclic manner, making it difficult to acquire a reliable global estimate of mortalities, but localised international monitoring has seen high mortality rates in some places. For example, Good et al.[16] reported that from 2002 to 2010, 32 000 marine organisms, mainly fish and invertebrates, were recovered from abandoned fishing gear in inland waters of Washington (USA).

Sea turtles

Most reports on entanglement of turtles in South Africa have been made by aquariums along the coastline (Prof. Nel R, Nelson Mandela University, 2019, personal communication, October 17). In addition to this, Ryan[9] has reported two South African turtle species that have been entangled by rope. Drawing from global literature, the impact of turtle entanglement involves the restriction of movement, which compromises their ability to surface for air.[12] Tightly wound lines can also restrict blood flow, causing decreased mobility and the potential loss of limbs.[12] Plastic rings around turtles' necks can also asphyxiate them as they grow, eventually leading to mortality.[14] The impact on sea turtles is therefore partially dependent on the plastic types they encounter. As turtles are particularly vulnerable to many other anthropogenic perturbations[17], plastics represent an additional factor that can lead to population declines. Although plastics left on beaches may not necessarily contribute to entanglement, they can result in a decrease in the number of turtles nesting on beaches. Fujisaki and Lamont[18] found a 200% increase in nests when beaches in Florida were cleared of natural and anthropogenic debris. As the sex of turtle hatchlings is dependent on nest temperature, any temperature anomalies caused by plastic debris in the sediment could also affect the sex distribution of turtle populations.[19]

Birds

An extensive review of entanglement of birds by plastic and other marine debris is provided in Ryan[10]. As many as 265 bird species, many of which are found in South Africa, were found entangled in plastic or similar types of debris. Fishing line seems to be the major plastic type affecting seabirds and virtually all bird species associated with the marine environment appear to be at risk.[10] However, there are some differences in the risk posed to seabirds by different plastic types. For example, plunge diving birds get entangled more often by plastic bags as they dive for juvenile fish, that shelter under the bags, than do other birds.[10] Birds that frequent mangroves may be more at risk to fishing line entanglement as these plastics get caught up in aerial mangrove roots.[10] Self-removal of plastics is difficult in species that have backward serrations on their beaks.[10] Entangled birds often get injured, have reduced feeding efficiency and become startled, which can sometimes attract unaffected birds that then also get trapped.[10] Birds that use plastic debris to build their nest can also be at risk of entanglement.[10]

Mammals

Research in South Africa on entanglement of marine mammals has largely focused on Cape fur seals (*Arctocephalus pusillus*) and whales.[20,21] In the case of seals, a study that dates back to 1979 indicated that marine debris was encountered in generally less than 1% per colony of seals that were harvested from locations in the Western Cape; harvesters recorded removing rope, string, fishing line and plastic straps from seals.[20] Of the 72 000 seals observed, 84 were found to be entangled by plastics, suggesting that this was not a major impact on their population numbers at the time. Debris was mostly observed around the neck and was seen to cut into flesh as individuals grew. However, on Marion Island, a territory of South Africa, entanglement was recorded in 101 sub-Antarctic (*Arctocephalus tropicalis*) and Antarctic (*A. gazella*) fur seals and 5 elephant seals (*Mirounga leonina*) over a 10-year period (1991–2001).[22] These numbers imply that only 0.24% of the seal population on this island were observed to be affected over this period, but both entanglement and increase in debris types closely coincided with a longline fishery that was implemented around Marion in 1996. This fishery has since ceased; however, it should be noted that seals are generally inquisitive, and the prevalence of marine debris has escalated globally, which may increase their risk of entanglement.[14] In the case of whales along the South African coastline, most cases of entanglement have been attributed to fishing gear (associated with a lobster fishery) or shark nets.[21] Humpback whales (*Megaptera novaeangliae*) and southern right whales (*Eubalaena australis*) are the species that are commonly entangled, but it was concluded that the entanglement rates of 9.5–21.6% were not affecting populations.[21]

Although the possibility of population-level effects by entanglement of organisms appears to be low, in general, reducing the disposal of items such as packing rings associated with canned and bottled drinks, monofilament line and bait box straps will decrease the risk of entanglement.[10] This was the reasoning behind banning packaging rings and ring pulls on drink cans in South Africa, in the 1980s. Measures

such as introducing discard bins near popular fishing spots with accompanying sign posts may also reduce the line and plastic straps from bait boxes entering the marine environment.[10]

Smothering

Benthic invertebrates can be smothered by macroplastics that have settled out of the water column, on the seabed, reefs or on beaches.[14] While the diversity of South African coral reefs and that of sediments have been well characterised[5], it is unclear how susceptible these systems are to disruption of species assemblages by debris. Smothering could affect filter feeding in sessile species or food location in mobile organisms. For example, beached plastic debris decreased the foraging efficiency of the gastropod *Nassarius pullus*[23], and in the same way may affect benthic species in South Africa. Alteration of physical characteristics of these benthic habitats by debris (e.g. porosity of the sediment and its heat transfer capacity[9]) has also not been assessed in South Africa. The global literature indicates that plastic accumulation may alter temperature, water permeability and gaseous exchange in marine sediments, which could cause physiological stress to meiofaunal communities.[14,19] Plastic debris on beaches may lead to anoxic conditions, altering infaunal communities.[24]

Transport

Plastics have the potential to transport alien species.[14] Bacteria, cyanobacteria, dinoflagellates, coccolithophores, corals, bryozoans, hydroids, and others have all been found on plastics in marine environments globally.[25] While marine debris can assist invasions of alien species[26], the prevalence of this phenomenon in South African systems has not been well characterised, with the exception of a record from gooseneck barnacles[27]. Nevertheless, the epiplastic community, now termed the 'plastisphere'[25,28], can potentially impact marine biota through transfer by ingestion if pathogenic bacteria are transferred from the environment to biota via plastics. This possibility is concerning for South African marine species, as high levels of pathogenic bacteria, like *Escherichia coli*, can be present in urban estuaries.[29] Coral reefs can also suffer from diseases vectored by plastics, as Lamb et al.[13] found that plastics on corals increased the likelihood of disease from 4% to 89% in the Asia-Pacific.

Ingestion

To date, ingestion of plastics has been recorded for more species than has entanglement.[2,30] Globally, plastic ingestion has been recorded in many taxa, ranging from annelids to mammals, but South African research has focused on fewer groups (Table 1). Factors influencing plastic ingestion by organisms that actively ingest plastic, include the abundance, type, size and colour of plastics, as well as feeding strategy.[31] Plastic shape and chemical factors such as chemical additives, and external pollutants that are associated with plastics, determine the risk(s) posed to specific organisms.[32] In addition, exposure and gut retention time also determine the impacts of different plastics on specific species.[30] Organisms can be classed as those that (1) regurgitate plastics after ingestion, (2) excrete most plastics or (3) retain much of the ingested plastics for long periods.[30] These differences need to be considered when investigating plastic ingestion in organisms, especially when investigating the effects of persistent organic pollutant (POP) transfer via plastics. For instance, organisms that regurgitate plastics after ingestion may have limited digestive transfer of POPs compared with organisms that retain plastics.[30] Mortalities have been noted mainly from macro/mesoplastic ingestion and can be caused by gut blockage and subsequent starvation, as shown for some South African bird and turtle species.[9,33] However, it must be noted that mortality is a rare phenomenon for most taxa.

Smaller particles usually have sub-lethal effects, primarily caused by the chemicals associated with plastics.[32] An investigation of 55 different plastic polymers found that polyurethanes, polyacrylonitriles, polyvinyl chloride, epoxy resins and styrenes were likely to be the most hazardous, due to the mutagenic and carcinogenic monomers they contain.[34] Fortunately these are not the dominant plastic types recorded in South African systems.[4,35,36] Plastic additives such as phthalates, bisphenol A, polybrominated diphenyl ethers and tetrabromobisphenol A can leach out from plastics and may affect reproduction as well as increase the risk of genetic aberrations and hormonal imbalances.[37,38] Coupled with this, metals and POPs such as polychlorinated biphenyls, dichloro-diphenyl-trichloroethanes, polycyclic aromatic hydrocarbons, aliphatic hydrocarbons and hexachlorocyclohexanes have been found to adhere to the surface of plastics.[38-40] POPs are of particular concern as they can act as endocrine disruptors or carcinogens in organisms[41]; however, assesments of pellets show that POPs have decreased over the last few decades in South Africa[42].

Plastics ingested by marine organisms can also release associated pollutants, as some simulated desorption experiments have shown.[43] This can depend on stomach conditions, such as the type of oil present in the stomach and also the retention time of particles.[44] If this is the case, organisms around urban centres in South Africa may be at a higher risk of exposure to pollutants associated with plastics, as urban harbours and other estuaries in South Africa have been shown to exhibit elevated levels of metals[45] and organic pollutants[46,47]. These areas are therefore ideal sites for ecotoxicological investigations on plastics. However, it must be noted that coal and wood can also transport equally high, if not higher, amounts of external pollutants to biota than microplastics[48], and if these sites exhibit both plastic and non-plastic debris, this should be factored into the sampling framework.

Invertebrates

Microplastics are generally the bioavailable size class to marine invertebrates such as filter-feeding mussels and barnacles.[49,50] The South African brown mussel (*Perna perna*) for example, has been shown to ingest fibres[51], although the polymer identity was not confirmed. Ingestion in brown mussels ranged from 4 fibres/g tissue (wet weight, ww) (collected near an estuarine mouth) to 1 fibre/g tissue (ww) (collected 2 km away).[51] However, this trend was not consistent across estuaries[51], suggesting that catchment activities and possibly biogeomorphology, play a role in determining microplastic ingestion levels in rocky shore invertebrates within estuarine systems.

Fibrous microplastics have the potential to form bundles, which can increase their gut residence time, as found in Norwegian lobsters, *Nephrops norvegicus*.[52] Active feeding invertebrates such as fiddler crabs, *Uca rapax*, were also shown to consume microplastics in experiments by Brennecke et al.[53] These authors showed that fragments of polystyrene pellets (180–250 μm) can transfer to the stomach, hepatopancreas and gills of crabs; however, no harmful effects were observed, at least for a period of up to 2 months.

Fish

Global observations of plastic ingestion by fish were made soon after mainstream plastic production commenced in the 1950s.[54,55] The limited South African literature on the phenomenon focuses almost exclusively on plastic ingestion in estuarine environments.[56,57] These environments are the pathways for plastics to the ocean, as storm-water drains, canals and treated waste-water effluent often flow into these estuaries in South Africa. Estuaries are also nursery areas for fish fry, and up to 160 South African fish species are dependent on estuaries at some stage of their life cycle.[58] Chronic exposure of the estuarine glassfish (*Ambassis dussumieri*) to virgin and harbour-collected microplastics compromised their growth and survival in experimental tanks, possibly due to energy normally used for growth being redirected to ridding the body of plastics and their associated pollutants.[59] Juvenile fish fed virgin and harbour-collected microplastics grew shorter on average, in standard length, than control fish, after a 3-month exposure period.[59] Kaplan–Meier curves showed significant reductions in survival probability in fish fed plastic relative to the control, mainly after 50 days of exposure.[59] Importantly, four species of juvenile fish (*Oreochromis mossambicus*, *Terapon jarbua*, *Ambassis dussumieri* and *Mugil* sp.), collected from four mangrove forests in KwaZulu-Natal, were shown to have ingested fibres and fragments of rayon, polyester, nylon and polyvinylchloride in proportions of 70.4%, 10.4%, 5.2% and 3.0% of the total particles consumed, respectively.[60] Generalist feeding fish such as mullet may consume larger numbers of particles than fish that feed on specific prey[61]; however, particles seem to pass through the gastrointestinal tract without physical influence[56]. In this regard, it is important to consider

the residence time of particles in fish, as some fish, such as herbivores, tend to have longer guts and therefore particles may remain in the gut for longer periods. Mullet that were force-fed plastic fibres showed gut residence times of up to five-fold longer than those of control fish that were fed food only.[62] Increased residence time allows for surface contaminants (e.g. POPs) and inherent additives to dissociate from particles and enter the organism. However, the global literature reveals no clear trend of net influx of pollutants adhering to plastics transferring to organisms by dissociation in the gut, compared with natural routes, such as ingesting wood.[48] Currently there are also no published estimates of microplastic concentrations in the commercially important South African species.

Sea turtles

Kühn et al.[2] observed plastic ingestion in all seven sea turtle species; this observation is concerning as, in addition to plastic ingestion often being fatal to turtles, their conservation status is either threatened or data deficient. A global review on this phenomenon is provided by Schuyler et al.[17], who found that green turtles (*Chelonia mydas*) and leatherback turtles (*Dermochelys coriacea*) were the most prone to consuming plastic debris, with an increase in ingestion probability from 1985. Turtles are particularly prone to plastic ingestion and the effects of ingesting mesoplastics can be fatal.[33] Possibly the earliest report of plastic ingestion in turtles from South Africa was made by Hughes in 1974[8], who reported plastic pellets in the digestive system of stranded loggerhead (*Caretta caretta*) hatchlings. In the South African context, Ryan et al.[33] noted that mesoplastics could block and rupture the digestive tract of turtles, and subsequently break into the bladder with peristaltic movement, which may lead to death. Post-hatchlings are at risk because they drift on the surface along drift lines that accumulate marine debris.[33] A variety of plastic types are ingested with a high incidence of ingestion (Supplementary table 1). Those authors noted that post-hatchling loggerhead turtles off South Africa mainly consumed white and blue mesoplastics.

Birds

As with entanglement, records of plastic ingestion by South African seabirds has been well documented.[6,30,63] Ryan[6] recorded plastic ingestion in 36 of 60 seabird species in South Africa and the African sector of the Southern Ocean, noting that birds consume mesoplastics based on colour and foraging strategy. Birds with a mixed or omnivorous diet had a higher incidence of ingested plastic and consumed darker-coloured plastics. Ingestion by members of the Procellariiformes, such as petrels, albatrosses and shearwaters (Supplementary table 1), is of concern, as they forage at the sea surface, consume a wide range of prey items and many members do not usually regurgitate indigestible material. Bird size and plastic size also influence ingestion, with smaller birds having a higher incidence of ingestion, ingesting smaller plastics and being less colour selective than larger birds. These birds could possibly also be consuming microplastic fibres, as observed in freshwater duck species from South Africa.[64] Reynolds and Ryan[64] found that duck faecal samples from areas near a sewage facility had higher (1–17%) numbers of microplastic fibres than faecal pellets collected from a site without this facility (1–3%). This supports the suggestion that these facilities are a potential source of plastic fibres to marine environments.[65]

Pellets, fragments, fibres and foams are the major plastic types consumed by seabirds.[6] Consumption of these particles can potentially have negative impacts on birds, as experiments on chickens fed polyethylene pellets resulted in decreased appetite and growth.[7] However, it must be noted that this did not hold true during short exposure times in similar experiments on white-chinned petrels.[66] Ogata et al.[67] showed that pre-production pellets collected from South Africa also contained high concentrations of hexachlorocyclohexanes, and this is a concern near the main industrial hubs where plastics can accumulate and concentrate chemical pollutants.[42] However, the incidence of pellets being ingested by seabirds in South Africa has decreased relative to other plastic types.[63] This suggests that the concentration of pellets in the environment may have decreased over time, which may be attributed to increased education and awareness, resulting in less spillage from industry.[63]

Mammals

Published literature on the ingestion of plastics in South African mammals is scarce compared with that for the rest of the world. However, seals and whales are a common feature of the South African coastline, and plastics can be unintentionally ingested by filter-feeding whales, or enter via primary and secondary ingestion in toothed species.[30] These larger organisms are thought to ingest larger fragments of plastic and possibly, in the case of baleen whales, a higher abundance of microplastics than other groups of organisms, although this supposition has yet to be confirmed.[68] An analysis of the scat from fur seals on Macquarie Island suggests that they mainly consume plastic fragments through their diet of small pelagic fish[69], yet this is not common in South African species[30]. In a similar way, dolphins and other species feeding on filter-feeding pelagic fish may ingest plastics. No population responses that were directly linked to plastic ingestion had been published at the time of this review.

Potential impacts on human health

Fish consumption in South Africa grew by more than 26% between 1994 and 2009. This figure poses a potential threat to human health, as the consumption of some marine species (such as invertebrates and fish) can result in the transfer of microplastics and associated chemicals and microbes to humans.[70] It must be noted, however, that the World Health Organization regards the threat of microplastics to humans as minor.[71] While current literature focuses on the fate and movement of microplastics, nanoplastics ($<1\ \mu$m) also pose a threat to human health.[50] Countries in Europe, the Persian Gulf and China have quantified the amount of plastics humans consumed from specific food groups (mussels, shrimp)[70]; these amounts vary across different regions and are subject to the dependence of the population on seafood. Additionally, these organisms are consumed whole, unlike fish which in most cases are usually gutted first, which removes microplastics in the gastrointestinal tract. As mentioned earlier, edible marine organisms in South Africa that have been investigated for microplastics are brown mussels[51] and four species of estuarine fish[60]. At the time of this review, data on levels of transferral of microplastics from edible aquatic species

Table 1: Summary of records of South African vertebrates found to be entangled or to have ingested plastics

Organisms*	Entanglement		Ingestion	
	Number of species	Main plastic type	Number of species	Main plastic type
Sharks	8	Plastic bands/straps	10	Plastic bags and sheets
Bony fish	Not distinguished from active gear		7	Fragments and fibres
Turtles	2	Rope	1	Fragments, films and pellets
Birds	265	Plastic bags and line	36	Fragments, pellets and foams
Mammals	5	Nets, rope, line and straps	0	–

**Species names and metadata for ingestion are given in Supplementary table 1.*
Note: These figures would be higher if unpublished reports were considered.

to humans were unavailable for South Africa. Nevertheless, there is a possible route of microplastic uptake for people who consume a number of marine species that include filter feeders (e.g. mussels and oysters).[72]

Dried fish may pose a higher threat to consumers than fish that are gutted, because even though the former may have the viscera and gills removed, microplastics may still be present in the gut.[70,73] This is relevant in the South African context, as the production or processing of dried fish or 'bokkoms' traces back to the 17th century, with mullet (*Chelon richardsonii*) being dried and salted in the Western Cape.[74] Unlike dried fish from other parts of the world, these are generally gutted before drying and the microplastics in the gut may therefore be removed, but the danger still exists for the bioaccumulation of other chemicals in fish tissue. Salt is also a source of microplastics that may be directly added to our diets. Salt from more than eight countries, including South Africa, tested positive for microplastics, with 1–3 microplastic particles per kilogram found for the size range of 160–980 μm.[75]

The fate of consumed microplastics may depend on the size of the particle. Some studies have identified microplastics in the faeces of humans, showing that most particles (90%) are excreted.[75,76] Particles that are <150 μm may move from the gut to the lymph and circulatory systems, with particles <20 μm likely to penetrate the organs and those within the smallest fraction likely to move through cell membranes, the blood-brain barrier and the placenta.[70,75] The body responds to the presence of these particles by triggering a number of responses such as immunosuppression, immune activation and abnormal inflammatory responses.[70,77] Unfortunately, at the time of this review no published studies had been conducted in South Africa but given the high dietary seafood content of a considerable proportion of the country's population, future research in this area should be prioritised. However, drinking water and inhalation seem to be the dominant uptake routes for microplastics in humans, with ingestion a secondary route.[71] Microplastics are classified as toxic vectors and may facilitate transfer of chemicals in organisms consumed by humans; associated chemical ingestion may be a more important issue than the consumption of the plastics themselves.

Key uncertainties, existing knowledge gaps and research challenges

Much of our uncertainties around the impacts of marine plastic debris on South African biota stem from the lack of monitoring marine debris in the country's water bodies, more especially microplastics. Additionally, reports of plastic ingestion in a wide range of biota (sharks, fish, turtles, birds and mammals) in South African waters[9] point to the need to monitor trends in the amount and composition of debris ingested by indicator species, as well as those species that are regularly consumed[78]. Indicator species should be studied from different trophic levels and feeding guilds, to determine whether the transfer of plastics and their associated pollutants are an issue. The need for continuous monitoring in the South African context is emphasised by the fact that, while the number of biota recorded with plastics in their guts has increased over time, with a wider diversity of plastic types[33], some types of ingested plastics seem to be decreasing (e.g. pellets in seabirds)[63]. These fluctuations in plastic prevalence are important considerations, as some plastic types are considered to be more toxic than others. The transfer of microplastics into organs of biota has been shown, but the level of toxicity has not been established.[50] Fibres are the most common microplastics in marine organisms (Supplementary table 1), and may be overlooked in some of the larger biota, but many probably are not actually synthetic. Assessing the impacts of fibres is also important, because the width of fibres is usually small and they may therefore be transferred to organs. The impacts of fibres on biota with regard to ingestion, inhalation, assimilation and their ability or inability to carry associated pollutants, remain largely unknown globally.

As alluded to above, data on the transfer of plastics along the food chain is limited in South Africa (and globally). These data are needed to ensure the quality and market acceptance of commercial species, which have the potential to transfer microplastics to humans. Research on plastics in South African biota exists for relatively few focal groups. However, even within a group of organisms there are differences in feeding strategies, gut biology and residence times that can affect their interaction with plastics. A suite of indicator species should therefore be selected to account for this potential variability. South African fisheries are regionally important (fish and invertebrates in particular).[72] While there have been reports of microplastic ingestion in fish and invertebrate species associated with the country's coastline, data for commercially important species are virtually non-existent (Supplementary table 1). Plastic ingestion in commercially important invertebrates in other parts of the world, e.g. Norway lobster in Scotland[52] and brown shrimp in the North Sea[79], suggests the need for South Africa to consider the effects of marine debris on the country's wide variety of commercially important species (e.g. prawns, lobster, mussels and abalone)[80,81]. There is a need to determine if there are harmful effects of consuming these species and if this can be linked to the secondary ingestion of plastics by humans. Pilchards and anchovies are also processed for fish meal and exported to other countries which could make secondary ingestion also important in cultured species.[82]

At the time of this review, an evident knowledge gap was the lack of understanding around the amounts of pollutants that are transferred, dissociated or bioaccumulated in biota as a consequence of plastic ingestion. This gap must be filled in order to make predictive decisions in regard to safety for consumption. Given the short gut retention times of some fish and invertebrates, plastic particles may pass without much interference, but chronic exposure does show changes in organisms[59], and research into these key interactions will help us understand the risk of plastic ingestion to both biota and humans.

Some of South Africa's research challenges with regard to the impacts of marine plastics are, however, similar to those faced globally. This challenge is largely due to the lack of standardised protocols for investigating the uptake and biological effects of plastics on biota. A primary step for efficient monitoring is the development of consolidated protocols for the isolation of plastics from different organisms. Challenges associated with the development of these protocols include directly observing for plastics under the microscope in organisms, while gut contents hamper visualisation. Furthermore, in some instances, chemicals are used to digest organic materials in the hope of leaving microplastics behind[83], but certain polymers can be degraded depending on the chemical(s) used, for example, nitric acid disintegrates polyamides[57]. The lack of access to instrumentation such as micro-Fourier transform infrared spectroscopy, which is used for the characterisation of plastic polymers[84], is a further challenge in developing countries such as South Africa. Given that many studies conducted in South Africa to date have not used these analytical methods[56,85], comparison with global trends is difficult. Contamination also represents a major research challenge in many laboratories in South Africa; plastic microfibres are often airborne and can thus contaminate samples, especially when working with small organisms and small plastics. The lack of sufficient contamination control measures in many of the laboratories involved in plastic research in South Africa must be urgently addressed. Ways to minimise the risk of contamination include the route taken by researchers at the University of Plymouth (United Kingdom) who have designed laboratories dedicated to microplastic work, in which ventilation systems are isolated from the rest of the building and air that enters the working area is filtered.

Implications if the gaps are not addressed

Despite the research gaps and challenges described above, South Africa has been at the forefront of research on marine plastics. For example, studies by Ryan[4] and Ryan and Moloney[3], both of which quantified microplastics in South African marine systems, are regarded as seminal research in this field of research. However, microplastic pollution is fast becoming a 'hot topic' globally, and South African research is falling behind in terms of its coverage, depth and methodological approach. This is largely because some of South Africa's health (HIV/Aids) and developmental challenges (large-scale unemployment and lack of adequate water and sanitation) are considered research priorities[86] by the government and funders alike. Greater investment in human capacity and infrastructure for marine plastic research needs to be made by all

stakeholders within governmental, research and environmental sectors. The lack of evidence-based research on marine plastic pollution will also hamper the development of policies and practices to mitigate its effects in the country. For instance, no published data on declining biota populations due to interaction with plastics were found for South Africa. Also, the potential effects of plastic ingestion on humans as a consequence of consuming marine biota have yet to be confirmed. Many of the impacts, particularly in relation to microplastic ingestion, are sub-lethal, but the consequence of not continuously monitoring these products is that the sub-lethal impacts may go unnoticed, which could directly impact consumers both locally and abroad. Major efforts also need to be made to encourage and upskill researchers presently working in the area to transition from empirical to more interpretative, predictive and systems-based science. However, given the paucity of data on many research topics related to marine plastic pollution in South Africa, it is essential (at least in the short to medium term) to draw on the international literature to predict possible impacts of this type of pollution on organisms (including humans), to design policy to mitigate its effects, and to drive the research agenda on the topic.

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Authors' contributions

T.N. undertook the literature review and the write-up of the draft manuscript. S. helped develop ideas and was involved in the write-up and editing of the manuscript. A.R. helped develop ideas and was involved in the write-up and editing of the manuscript.

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Impacts of marine plastic on ecosystem services and economy: State of South African research

In addition to its direct impacts on marine ecology and biota, marine plastic debris can affect the delivery of ecosystem services, with resulting impacts on human well-being, society and the economy. It is important to quantify these impacts in economic terms, so as to be able to provide evidence-based support for an appropriate policy response. We review the South African literature on the impacts of marine plastic debris on ecosystem services and on the economy, in order to identify relevant knowledge gaps. The gaps are found to be significant. Some research has been conducted in terms of impacts relating to recreation, aesthetics and tourism and the costs of beach and harbour clean-ups. However, there is a significant lack of research regarding impacts on ecosystem services relating to fisheries and aquaculture, heritage, habitat provision, biodiversity, and nutrient cycles. There is also a significant lack of research regarding direct economic impacts on the transport/shipping and fisheries industries, indirect economic impacts (such as costs associated with health-related impacts), and non-market costs (e.g. impacts on scenic, cultural and spiritual values). More research is needed in South Africa to address these gaps, in order to inform policy aimed at addressing plastic waste and marine plastic debris.

Significance:

- This review highlights the knowledge gaps in terms of the impacts of marine plastics on ecosystem services and on the economy in South Africa, which are important to understand in order to be able to direct funding for future research in this domain. Without better knowledge of the economic impacts of marine plastic debris, it is difficult to assess the costs of inaction, and therefore to inform an appropriate policy response for tackling the problem of marine plastic debris.

Introduction

Globally, the impacts of plastic debris on the marine environment have received increasing attention over the past decade. Jambeck et al.[1] estimated that between 4.8 and 12.7 million metric tons of plastic waste entered the ocean from land-based sources in 2010, and that flows of plastic waste to the marine environment are likely to increase significantly in the absence of improved management. In Africa, the estimated total mismanaged waste in 2010 was 4.4 million metric tons, which is projected to increase to 10.5 million metric tons by 2025 if no significant changes are implemented.[2]

In South Africa, plastic recycling rates are relatively high (46.3% in 2018), exceeding the average for Europe,[3] with 70% of the recycled tonnages coming from landfill and other post-consumer sources. Plastics recycling provided 7892 formal jobs in 2018[3], as well as livelihoods for 58 470 informal waste pickers and smaller entrepreneurial collectors[3]. The procurement of plastic recyclables in 2018 contributed ZAR2.3 billion to the South African economy at primary sourcing level.[3]

However, generally speaking, the state of waste management in South Africa is poor, with significant leakage of plastic debris to the environment, largely as a result of inadequate waste collection and disposal. Although Jambeck et al.'s[1] oft-cited figures (suggesting that South Africa ranks 11th in the world in regard to the amount of plastic waste leaking into the ocean) are subject to debate[4], there is evidence of an upward trend in marine plastic debris from land-based sources in South Africa[5]. For example, plastic items make up a higher proportion of macro-debris found on South African beaches in more recent studies as compared to older studies.[5]

Naidoo et al.[6] provide an overview of the impacts of plastic debris on marine ecology and biota. In addition, however, to the extent that marine plastic debris can affect the structure and functioning of ecosystems more broadly, the increasing volume of plastics in the ocean could potentially have negative impacts on the delivery of marine ecosystem services, and in turn, on human well-being, society and the economy.

Ecosystem services refer to the valuable goods and services provided by ecosystems to human societies. While classification systems vary, they are generally understood as including supporting services (such as habitat provision and biodiversity), provisioning services (such as food, water and other resources), regulating services (such as climate regulation and nutrient cycles), and cultural services (such as recreation and education).[7] The provision of such services to humankind is vital to human livelihoods and to sustained economic activity, and therefore has an intrinsic (although typically unaccounted for) economic value.[7]

However, the by-products of human activities, such as pollution and waste, can have a negative impact on ecosystem structure and functioning, and therefore on the continued ability of ecosystems to provide these services.[7] In turn, this can have a negative impact on the economic value derived from such services. For example, to the extent that marine plastic debris has a negative impact on marine habitats and biodiversity, fishing stocks for commercial and recreational fishers may be negatively affected, which in turn has a negative economic impact. These negative impacts are referred to as externalities, that is, the side-effects of human activities which are not internalised in market prices. To the extent that these impacts are not quantified in economic terms, the benefits of a policy response (in terms of avoided damages) are difficult for policymakers to assess. It is therefore vital to be able to quantify the

impacts of marine plastic debris on the economy, so as to be able to provide evidence-based support for an appropriate policy response.

We review the South African literature on the impacts of marine plastic debris on ecosystem services and on the economy, in order to be able to identify gaps. Research on ecological impacts is specifically excluded; for a review of this research, see Naidoo et al.[6] in this issue. The following section provides a brief overview of the typical impacts of marine plastic debris on ecosystem services and on the economy as identified in international literature. The intention is to provide a framework against which to assess the current state of South African literature on each of these impacts, in order to identify gaps.

Ecosystem service and economic impacts of marine plastic debris identified in international literature

Impacts on ecosystem services

According to the Millennium Ecosystem Assessment (MA)[7] and The Economics of Ecosystems and Biodiversity (TEEB)[8] frameworks, ecosystem services can be classified into four categories: supporting services, provisioning services, regulating services, and cultural services. While some classification systems (such as the Common International Classification of Ecosystem Services, CICES)[9] differ slightly, for the purposes of this paper, the MA and TEEB systems provide a useful framework for structuring the discussion.

The main impacts of marine plastics on ecosystem services relate to provisioning services (fisheries and aquaculture), cultural services (recreation, aesthetics and heritage), and supporting services (e.g. impacts on habitat provision and biodiversity).[10,11] There are also some suggestions of potential impacts on regulating services (e.g. nutrient cycles).[10] In this section, we briefly review the typical expected impacts of marine plastic debris on each of these categories of ecosystem services.

Impacts on provisioning services: Fisheries and aquaculture

Seafood is an important food and protein source, making up 20% of the food intake (by weight) of 1.4 billion people worldwide.[11] Naidoo et al.[6] provide an overview of the impacts of marine plastic debris on individual organisms, through ingestion, entanglement, etc. Although there is currently a lack of knowledge regarding the resulting impacts on populations, to the extent that fish stocks could be impacted by marine plastic debris, the efficiency of commercial fisheries and aquaculture farms could potentially be negatively affected.

Ingestion can take place directly from the marine environment, or through the food chain.[11-13] Studies have shown uptake of microplastics by mussels, which are filter-feeding organisms. Mussels are not only ecologically important, they are also important for subsistence and commercial harvesting.[14] Impacts of exposure via the food chain can be detrimental due to possible accumulation and bio-magnification of microbial pathogens and toxic persistent organic pollutants in higher predators, although there is a lack of conclusive evidence in current research.[15] The impacts of marine plastic debris on ecosystems – together with the cumulative impacts of climate change, ocean acidification and over-exploitation of marine resources – could potentially put the fishing and aquaculture industries at risk.[15]

Finally, there is potential for marine plastics to affect human health when entire contaminated organisms are ingested. This is further impacted by the accumulation of synthetic microfibres, toxic chemicals and persistent organic pollutants in shellfish and fish tissue, which have the potential to cause birth defects, cancer, and compromised immune systems, although there is currently a lack of scientific evidence regarding these health-related impacts.[11,12] While some studies suggest that the risks for human health due to ingestion of plastic in contaminated species are minimal[11,12], the high dependency on seafood by a large part of the world's population suggests that further research is required to clarify the extent of these risks[11].

Impacts on cultural services: Recreation, aesthetics and heritage

In many parts of the world, visitors to coastal areas are frequently exposed to plastic debris.[11] The presence of plastic debris has been found to be a key reason for visitors to the coastline to shorten their visits to a particular beach and sometimes even avoid a specific area.[11] Furthermore, the presence of debris can impact both physical and mental health. Visitors and workers on the coastline can incur physical injuries such as cuts due to sharp debris, entanglement in nets, as well as exposure to unsanitary items.[11] Exposure to polluted coastlines has also been shown to have a negative impact on individual's mental well-being and mood.[11] Visiting beaches has important health benefits, such as promoting physical activity and social interactions, thereby improving physical and mental well-being.[11] As such, in attempting to avoid the risks associated with polluted coastlines by not visiting beaches, health and well-being is likely to be negatively impacted.[11] In addition, marine debris can negatively affect peoples' quality of life by reducing the aesthetic appeal of the marine environment.[15]

The presence of marine plastics can also have negative impacts on the heritage of communities and individuals. People tend to have an emotional and/or cultural attachment to marine organisms such as turtles, seabirds and cetaceans. According to Beaumont et al.[11], the expectation that these marine organisms exist and will continue to exist in future has an impact on the well-being of humans, irrespective of whether they ever get to see or interact with these animals. The potential loss of these animals (e.g. through ingestion, entanglement, or reduced reproductive success), which has gained significant public attention in recent years, could therefore have a negative impact on the well-being of humans.[11]

Impacts on supporting services: Habitat provision, biodiversity and invasive species transport

According to Mouat et al.[15], approximately 70% of marine debris accumulates on the ocean floor, where it can significantly impact benthic organisms and habitats. In particular, such debris can prevent gas exchanges and reduce the amount of oxygen in sediments, which impacts negatively on ecosystem functioning, benthic organisms and the composition of biota on the ocean floor. It can also physically damage benthic habitats through abrasion, scouring, and breaking; while derelict fishing gear has the potential to translocate organisms and sea-bed features.[15]

In addition, marine plastic debris has the potential to significantly impact marine ecology and biodiversity, which could in turn severely impact the resilience of such ecosystems in the face of global change.[11] However, there is currently a lack of understanding regarding the extent to which impacts associated with ingestion, entanglement, damage to benthic environments and loss of biodiversity will interact to cause deterioration of marine ecosystems in the long term.[15]

Finally, marine plastic provides a habitat on which invasive species can become attached and be transported over long distances (see also Naidoo et al.[6]). Floating plastics allow for the attachment and transport of alien species and disease, thereby potentially modifying pelagic ecosystems.[11,13,16,17] Plastic, unlike natural flotsam, is able to withstand UV exposure and wave action, and is able to remain buoyant for extended periods, thereby travelling great distances with the colonised species attached.[11] For example, a study along the Catalan coast showed primarily benthic diatoms and small flagellates ($<20\ \mu$m) attached to plastic debris. Potentially harmful dinoflagellates, resting cysts of unidentified dinoflagellates and both temporary cysts and vegetative cells of the harmful algal bloom species, *Alexandrium taylori*, were also found.[18]

Impacts on regulating services: Nutrient cycles

While there is less information regarding the impacts of marine plastic debris on regulating services compared with the other categories of ecosystem services, there are some suggestions of a potential impact on nutrient cycles. For example, plastic could affect the buoyancy of faecal matter discharged from marine outfalls, thereby affecting the movement of nutrients and carbon into the deep ocean, potentially disrupting nutrient

cycles,[10] although the small volumes involved relative to global nutrient and carbon cycles implies that this impact is likely to be negligible.

Economic impacts

In 2011, marine ecosystem services were estimated to contribute USD49.7 trillion per year in terms of benefits to global society.[11] These values were calculated based on actual or hypothetical maximum sustainable use of natural or semi-natural systems with minimal anthropogenic impacts. Although there are limitations to the accuracy of the method, the figure above has been acknowledged for its use in global analysis and to determine the decline in value of marine ecosystem services due to the impacts of marine plastics. This figure can therefore be used as a baseline to provide an order of magnitude estimate of the costs of marine plastic debris, in terms of various levels of decline in ecosystem service delivery.[11] While it is difficult to accurately quantify the loss of ecosystem services due to marine plastic debris, Beaumont et al.[11] estimated a 1–5% decline in ecosystem services as a result of marine plastics in 2011. Based on the value of marine services to society of USD49.7 trillion per year, this equates to a loss of USD0.5–2.5 trillion in the value of benefits derived from marine ecosystem services annually, as a result of marine plastic debris. Based on a 2011 estimate of 75–150 million tonnes of plastic in the marine environment, the annual cost in terms of reduced marine natural capital is between USD3300 and USD33 000 per tonne of plastic. It is important to note that this calculated cost covers only the impact on marine natural capital, and is therefore lower than the full economic cost of marine plastic debris.[11]

Mouat et al.[15] identified a number of specific economic impacts associated with marine debris, including cleaning costs; losses to tourism; losses to fisheries; losses to aquaculture; costs to shipping; costs of control and eradication of invasive non-native species; costs to coastal agriculture; costs to power stations; and costs of environmental damage and ecosystem degradation. These impacts are also for the most part discussed in McIlgorm et al.[19] who distinguish three broad categories of costs resulting from marine debris:

1. direct economic costs, arising from damage to an industry or economic activity, e.g. impacts on the fishing, transportation/shipping and tourism industries (relatively straightforward to quantify);
2. indirect economic costs, e.g. the impacts on human health resulting from marine life ingesting plastic and contaminating the food chain (more difficult to quantify); and
3. 'non-market' costs, which impact the value that humans place on the marine environment over and above the value associated with the actual use of marine resources, such as scenic value, cultural value, and spiritual value (most difficult to quantify).

These categories are briefly discussed in turn below.

Direct economic costs

McIlgorm et al.[19] estimated the direct economic costs of marine debris on the Asia-Pacific Economic Cooperation region. They found that the main impacts were on the fishing industry (USD364 million in 2008), transportation/shipping (USD279 million), and the tourism industry (USD622 million), with a combined impact of USD1.265 billion in 2008.[19]

These results suggest that the main economic impact of marine plastics is on tourism revenue. This is particularly significant in areas that rely heavily on tourism. For example, researchers in Florida (USA) have found that debris is considered undesirable for a popular tourist destination, and highlighted the importance to Florida's economy of ensuring that an attractive environment is maintained.[20] A study of marine debris on the US East Coast in 1987–1988 estimated a loss of between USD379 and USD1 598 million.[21] In South Korea, a heavy rainfall event which increased coastal waste resulted in a 63% drop in tourism, and an associated loss in revenue of USD33 million.[21]

Leggett et al.[22] found that marine debris impacted on residents of Orange County in California (USA) in terms of additional costs spent to avoid degraded areas. Residents were willing to travel to clean beaches even it if meant more time and money being spent, costing locals millions of dollars per year. It was found that a 50% reduction in marine debris would save residents USD67 million in total over a period of 3 months.

In order to avoid losses in terms of tourism revenue, some municipalities incur high costs for clean-up operations to remove debris from beaches and public use areas.[21] For example, municipalities in Belgium, the Netherlands and the UK spend between EUR10–20 million (USD10.7–21.5 million) per year to clean up debris affecting coastal tourism.[21,23] Funding requirements for clean-ups and implementation of litter prevention strategies increased in the archipelago of Svalbard from NOK20 million in 2016 to NOK280 million in 2018 (USD2.15–30.1 million).[24]

Marine plastic debris can negatively impact the shipping industry, e.g. due to fouling of propellers, damage to drive shafts, fouled anchors, clogging of intake pipes, and increasing maintenance and repair costs.[19,23,25] McIlgorm et al.[19] found that marine debris causes approximately USD19 000 worth of damage per vessel per year to Hong Kong's high-speed ferry network. Like the clean-up operations undertaken by municipalities to reduce tourism-related impacts, some harbours incur clean-up costs to reduce impacts on the shipping industry. For example, harbours in the UK spend approximately EUR2.4 million (USD2.6 million) annually on marine waste removal.[23] Werner et al.[23] reported that the Spanish Port of Barcelona carries out daily clean-ups of floating debris, collecting over 117 tonnes in 2012 at a cost of approximately EUR300 000 (USD330 000).

In addition, marine plastic debris has negative impacts on the fishing industry. For example, marine debris has been found to result in restricted catch due to litter in nets for 86% of Scottish fishing vessels, costing these fleets on average EUR11.7–13 million (USD12.8–14.2 million) per year. This equates to approximately 5% of the total revenue of affected fisheries.[26]

Finally, both the shipping and fisheries industries can be affected by derelict fishing gear through damage to vessels (e.g. fouled propellers), the costs of replacing lost gear, as well as the potential loss of catch (reduced fishing time and contaminated catch), resulting in reduced revenue.[15] In 2002, losses of approximately USD21 000 in fishing gear and USD38 000 in fishing time were experienced by a single trap fisher in the Scottish Clyde fishery.[15] An estimated USD250 million worth of marketable lobster is lost to 'ghost' fishing annually in the USA, and between 4–10 million blue crabs are trapped in ghost fishing gear annually in Louisiana, USA.[15]

Indirect and non-market economic costs

Indirect costs associated with marine plastic debris include human health and safety costs (from consumption of contaminated species, navigational hazards, injuries to recreational users, leaching of poisonous chemicals, etc.).[15] Current literature does not provide clarity on the health risks associated with marine plastic[11,12,27], although some research suggests that it is minimal[11]. It is therefore difficult to quantify the associated economic impacts.

Non-market costs associated with marine plastic debris, such as impacts on scenic value, heritage value, and spiritual value, have not been assessed in any great depth, based on our brief review of the international literature.

Status quo: South African research on ecosystem service and economic impacts of marine plastic debris

In this section, we review the South African research that has been undertaken in assessing the impacts of marine plastic debris on ecosystem services and on the economy, under each of the categories identified above, in order to identify gaps. A comprehensive review was undertaken using a wide range of databases (Scopus, ScienceDirect, Taylor and Francis, SpringerLink, and Google Scholar) and various combinations of all relevant keywords, as identified based on the framework established from the international review. The keywords were: economic, marine litter, South Africa, socio-economic, human health, agriculture, fisheries, commercial fisheries, recreational fishing, aquaculture, harbours, ports, shipping, marine plastic litter, marine plastic debris, ecosystem service, ecosystem service impact, plastic, ecosystem services, Africa, food contamination, pollutant accumulation, litter, nutrient

cycles, marine debris, pollution, plastic pollution, marine plastic pollution, economic cost, economic impact, coastal communities, livelihoods, food security, microplastics, human health, human safety, recreation impacts, cultural impacts, shipping hazards, ghost gear, subsistence fishing, beach clean-ups, beach aesthetics, beach cleanliness, biodiversity, habitats destruction, invasive species, species transport, tourism costs, and port clean-up costs. We also consulted with a number of South African experts to identify any other relevant literature that had been missed.

Impacts on ecosystem services

Very little research could be found that specifically assessed the impacts of marine plastic debris on ecosystem services in South Africa. The following sub-sections provide an overview of South African research on each of the specific categories of ecosystem services identified in the previous section.

Impacts on provisioning services: Fisheries and aquaculture

Over 12 million people engage in the fisheries sector in Africa. In addition, subsistence fishing in Africa is practised by multiple communities, and plastic pollution could potentially have a significant impact on their livelihoods and food security.[2] However, no research could be found specifically assessing the impacts of marine plastic debris on fisheries and aquaculture in South Africa.

Impacts on cultural services: Recreation, aesthetics and heritage

There has been some research in South Africa on the impacts of marine debris on tourism, which includes aspects related to recreation and aesthetics. All of this research is focused on identifying the economic impacts on the tourism industry, or the costs of beach clean-ups to mitigate such impacts. As such, this research is discussed in the section below on economic impacts. No research could be found regarding impacts on ecosystem services associated with heritage.

Impacts on supporting services: Habitat provision, biodiversity and invasive species transport

While a fair amount of research has been conducted on the impacts of plastic pollution on marine biota in South Africa (see Naidoo et al.[6]), much less literature is available on supporting ecosystem services such as habitat provision and biodiversity.

A number of studies have, however, examined the issue of marine plastics acting as a substrate for the attachment and transport of species, although not for invasive alien species specifically. Whitehead et al.[28] sampled 22 beaches in South Africa for debris that had been colonised by goose barnacles (*Lepas* spp). It was found that plastic was one of the two most colonised substrate types, at 29% of all colonised items; second only to kelp at 33% (although given that significantly more kelp is stranded on beaches than plastic, plastic appears to have a higher likelihood of being colonised). All species identified were found to colonise plastic debris, thereby impacting the abundance and distribution of goose barnacles, where large, natural substrata are not commonly available.[28] Similarly, Fazey and Ryan[17] found a range of epibionts on marine plastic debris, including red and green algae, bryozoans, barnacles, polychaetes and mussels.

Although the above studies found evidence of the attachment and transport of species on plastic, there is little evidence of plastic serving as a substrate for alien species entering South African waters. Robinson et al.[29] found that the main vectors of transport for these species included attachment to shipping vessels, via ballast water and through mariculture operations. Marine plastic debris was not identified as a possible vector of invasive species transport in their 2005 review, although it would be interesting to see whether this may have changed more recently.

Impacts on regulating services: Nutrient cycles

No South African research was found relating to the impacts of marine plastic debris on regulating services, such as nutrient cycles.

Economic impacts

Direct economic costs

As a popular tourist destination, South Africa's tourism industry is a significant contributor to the economy, employing 1.5 million workers (9.8% of total employment) and contributing ZAR125 billion (USD8.2 billion) directly to GDP in 2016 (2.9% of GDP), or ZAR422.6 billion (USD27.7 billion) including indirect and induced effects (9.2% of GDP).[30] Marine ecotourism specifically contributed approximately ZAR400 million (USD26 million) directly, and over ZAR2 billion (USD130 million) indirectly, to the South African economy in 2014.[31] In Cape Town, for example, visiting the beach makes up 12% of foreign visitors' activities in the city.[31]

There has been some research in South Africa on the impacts of marine debris on tourism. To the extent that marine debris impacts on the aesthetic value of the coast, and decreases the number of visitors to polluted beaches, increasing quantities of marine plastic debris can be expected to negatively affect the tourism industry, and therefore the economy.[32-34] Ballance et al.[32] found that cleanliness was the primary factor influencing visitors to the Cape Peninsula when choosing a beach, particularly for international tourists. Almost 50% of residents would be prepared to spend more to visit clean beaches further away; while litter densities of more than 10 large items per metre of beach would deter 40% of foreign tourists, and 60% of domestic tourists, from returning to Cape Town, with a significant potential impact on the local economy.[32] If beaches had more than 10 large debris items per metre, 97% of visitors would not visit them, leading to a decline in total recreational value of approximately ZAR300 000 (USD19 600) per year, and a loss of ZAR8 million (USD520 000) for the regional economy (based on 1996 values; equivalent to approximately ZAR1 million and ZAR27 million, respectively, in current values).[32]

A number of studies have also assessed the costs of beach clean-ups aimed at mitigating negative impacts on the tourism industry, although most were undertaken in the mid-1990s. According to Swanepoel[35], the Cape Town City Council spent ZAR2.7 million (USD176 000) on beach clean-ups in 1992–1993; equivalent to approximately ZAR12 million in current values. Compared to the domestic refuse removal cost of approximately ZAR75 (USD4.9) per tonne, the cost for removal of beach debris amounted to ZAR3000 (USD190) per tonne.[35] According to Ballance et al.[32], given the large amount of expenditure on beach cleaning in Cape Town (ZAR3 million / USD196 000 during 1994–1995), alternative means of reducing debris at source are required.

Ryan and Swanepoel[34] carried out a study in 1994–1995 of 63 coastal authorities in South Africa to assess the amount of effort spent on cleaning beaches. A total of 34 authorities estimated their annual costs for beach cleaning to be ZAR5.5 million (USD360 000), with the Cape Town metropolitan region alone spending in excess of R3.5 million (USD229 000) annually. Costs varied depending on the location of the beaches, with west coast beaches (ZAR397/km) costing more than those on the east coast (ZAR68/km) due to larger volumes of kelp. When the data were extrapolated for areas that did not provide estimates, the total cost for cleaning in 1994–1995 across the 63 authorities exceeded ZAR8 million (USD520 0000) – equivalent to approximately ZAR31 million in current terms.[34]

Finally, one of the projects under the South African Department of Environment, Forestry and Fisheries' national Working for the Coast programme involves beach clean-ups, although the costs of such clean-ups could not be found in published sources.

In terms of damage to the shipping industry, debris (including plastic) in and around the Port of Durban can become a shipping hazard, particularly after periods of rainfall. However, there has been little assessment of the associated economic impacts. The Port incurs costs in debris clearing operations, while there are also public volunteer clean-ups of plastic from the Port. There are also public clean-ups of estuaries and beaches in eThekwini, although the costs of these operations have not been quantified in published sources. Based on information received from the Port through personal communication, clean up-costs due to storm events in April/May 2019 ranged between ZAR52 800 (USD3400) and

ZAR1 046 000 (USD68 400), and totalled ZAR4 350 000 (USD284 800) in that period alone (Transnet 2019, written communication, August 22).

There is a lack of research regarding the impacts of marine plastics on the fishing industry in South Africa. In 2012, the commercial fisheries sector produced ZAR5.8 billion (USD370 million) in output, while the estimated economic value of the recreational fishing sector in 2017 was ZAR1.6 billion (USD104 million).[31] The aquaculture sector contributed approximately 0.8% to South Africa's fish production in 2012.[31] However, there is a significant lack of information regarding the impacts of marine plastics on these sectors.

Finally, no South African research could be found regarding the impacts of ghost fishing gear on the shipping or fisheries industries.

Indirect and non-market economic costs

No South African research could be found on indirect costs associated with marine plastic debris, e.g. costs associated with impacts on human health and safety; or on non-market costs, such as impacts on scenic value, cultural value, or spiritual value.

Current uncertainties

Globally, there is generally a lack of evidence regarding the overall effects of marine plastics on populations of marine species, or on ecosystem structure and functioning, and, therefore, on the provision of ecosystem services, as well as on human health, society and the economy. There are some studies that provide insight into the impacts of plastics on ecosystem services and the economy at a local level, but it is difficult to extrapolate these results more widely. In the South African context, for example, most studies focus on the impacts on tourism and the costs of beach clean-ups in the Cape Town area. There is a clear need to quantify the impacts of marine plastics on ecosystem services and on the South African economy more broadly.

Even in the international literature, there is a lack of evidence with regard to the impacts of marine plastics on ecosystem services, human health and on the economy, with much of the research seemingly focused instead on impacts on marine biota. Globally, it remains challenging to accurately quantify the loss of ecosystem services due to marine plastic debris. In addition, there are uncertainties around the long-term impacts of plastic pollution on marine ecosystems, that is, regarding how impacts such as ingestion, entanglement, damage to benthic environments and loss of biodiversity may interact and affect marine ecosystems over the long term.[15]

More research is also required to assess the risks of marine debris for human health and safety, e.g. in terms of the impact of consuming contaminated seafood, navigational hazards, injuries to recreational users, and the leaching of poisonous chemicals.[15,16] In particular, there is a need for research into the effects of microplastic pollution on aquatic and marine ecosystems, and on human health.[15,36,37] For example, there is a need to assess whether microplastic and microfibre pollution has ecosystem or human health implications such as chemical toxicity or fibre-induced mesothelioma, which would have negative impacts on both river biota and downstream communities as well as marine ecosystems.[36,37]

Finally, there is a need for more research to quantify the environmental and social impacts of marine plastic debris in economic terms, in order to provide an understanding of the costs of inaction.[15] In particular, Beaumont et al.[11] suggest that there is a need to quantify and assess a broader range of social and economic costs, e.g. direct and indirect impacts on the tourism, transport and fisheries sectors, as well as on human health. It is also important to take into account spatial and temporal heterogeneity and non-linearity with respect to the impact of each additional tonne of marine plastic debris entering the marine environment.[11]

Evidence gaps

From an economic and ecosystem services perspective, there is very little research that has been done in South Africa regarding the impacts of marine plastics, and therefore the gaps in local knowledge are significant. Table 1 provides a summary of the key impacts that have been identified in the international literature. The last column summarises the state of current South African research on each impact. Some research has been conducted regarding impacts on recreation, aesthetics and tourism, and the costs of beach and harbour clean-ups. However, there is a significant lack of research regarding impacts on ecosystem services relating to fisheries and aquaculture, heritage, habitat provision, biodiversity, and nutrient cycles. There is also a significant lack of research regarding direct economic impacts on the transport/shipping and fisheries industries, indirect economic impacts (such as costs associated with health-related impacts), and non-market costs (e.g. impacts on scenic, cultural and spiritual values). More research is required in South Africa to address these gaps, in order to be able to inform policy decisions.

Implications

Without better knowledge of the economic impacts of marine plastic debris, it is difficult to assess the costs of inaction, and therefore to inform an appropriate policy response. While it is potentially possible to apply the quantified estimates from other countries to South Africa in order to estimate orders of magnitude, those numbers should first be interrogated to ensure that this can be done with confidence, while the South African context needs to be taken into account in adapting these

Table 1: State of South African research on the impacts of marine plastic debris on ecosystem services and the economy

Category	Sub-category	Impacts	South African research
Impacts on ecosystem services	Provisioning services	Impacts on fisheries and aquaculture	–
	Cultural services	Impacts on recreation and aesthetics	Some research on the impacts on tourism (see below)
		Impacts on heritage	–
	Supporting services	Impacts on habitat provision	–
		Impacts on biodiversity	–
		Invasive species transport	Some studies on plastic as a vector for transport of species,[13,14,26] but not for invasive alien species specifically
	Regulating services	Nutrient cycles	–
Economic impacts	Direct costs	Impacts on the tourism industry	Some research conducted on the impacts on tourism and on beach clean-up costs, although fairly dated and largely confined to Cape Town[32,34,35]
		Impacts on the transport/shipping industry	Information on harbour clean-up costs in Durban obtained through personal communication; no published information could be found
		Impacts on the fisheries industry	–
	Indirect and non-market costs	Health costs	–
		Non-market costs	–

Note: – indicates that no relevant South African research was found in this review.

figures. However, primary research conducted in South Africa should be considered preferable.

Finally, a more holistic understanding of the impacts of marine plastics is needed in order to change the way we make, use and reuse plastics, and therefore to reduce its negative impacts. This will also inform changes in behaviour by the public, legislative and governance changes, and changes to the plastic industry, towards the sustainable use, management and disposal of plastics[11], and the development of a circular plastics economy.

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Monitoring marine plastics – will we know if we are making a difference?

In the context of marine anthropogenic debris management, monitoring is essential to assess whether mitigation measures to reduce the amounts of waste plastic entering the environment are being effective. In South Africa, baselines against which changes can be assessed include data from the 1970s to the 1990s on microplastics floating at sea, on macro- and microplastic beach debris, and interactions with biota. However, detecting changes in the abundance of microplastics at sea is complicated by high spatial and temporal heterogeneity in net samples. Beach debris data are easier to gather, but their interpretation is complicated by the dynamic nature of debris fluxes on beaches and the increase in beach cleaning effort over time. Sampling plastic ingested by biota is a powerful approach, because animals that retain ingested plastic for protracted periods integrate plastics over space and time, but there are ethical issues to using biota as bioindicators, particularly for species that require destructive sampling (e.g. turtles, seabirds). Bioindicators could be established among fish and invertebrates, but there are technical challenges with sampling microplastics smaller than 1 mm. Fine-scale debris accumulation on beaches provides an index of macroplastic abundance in coastal waters, and offers a practical way to track changes in the amounts and composition of debris in coastal waters. However, upstream flux measures (i.e. in catchments, rivers and storm-water run-off) provide a more direct assessment of mitigation measures for land-based sources. Similarly, monitoring refuse returned to port by vessels is the best way to ensure compliance with legislation prohibiting the dumping of plastics at sea.

Significance:

- Monitoring is required to assess whether mitigation measures to reduce waste plastics at sea are making a difference.
- Monitoring the leakage of plastic from land-based sources is best addressed on land (e.g. in storm drains and river run-off) before the plastic reaches the sea.
- Illegal dumping from ships is best addressed by monitoring the use of port waste reception facilities.
- Sampling plastic ingested by biota is a powerful approach, using fish and invertebrates as bioindicators for larger microplastic fragments.

Introduction

It has long been recognised that waste plastics in the environment have significant ecological and economic impacts, particularly in marine systems.[1] By the early 1990s, the focus of research shifted from documenting these impacts to devising solutions to the marine debris 'problem'.[2] Monitoring – the repeated measurement of variables to detect change – is a key component of this process, as it forms part of the adaptive management cycle.[3] Only by detecting a change in the amounts and types of debris can we assess the efficacy of mitigation measures designed to reduce the amounts of waste plastic entering the environment.[4] Monitoring can also detect novel threats, e.g. repeated sampling of beach debris around the South African coast has detected the emergence of novel pollutants such as the switch from card to plastic earbud sticks. And monitoring can be used to ensure compliance to standards, e.g. that levels of microplastics in seafood remain within acceptable levels, although there are currently no international standards for plastic contamination levels. The options for monitoring marine plastics in the four marine compartments – at sea, on the seabed, on beaches and in biota – recently have been reviewed in an attempt to harmonise approaches and improve the comparability of data across studies.[5] Here, we summarise existing baseline data that can be used to monitor changes in marine plastics in South Africa (Supplementary table 1), and suggest preferred strategies for monitoring changes in marine debris in the region in relation to some of the most pressing questions regarding marine macro- and microplastics (Table 1).

Monitoring: Why, what and where

Monitoring is a purpose-driven exercise that requires a significant investment in data gathering, analysis and archiving, so the goal needs to be well defined and the process subject to regular review.[3] It is thus essential to decide *why* we want to monitor marine plastics and the extent of the change we want to be able to detect, as this determines the amount of sampling needed.[5] We propose five questions pertaining to marine plastic pollution that might justify monitoring programmes in South Africa (Table 1). This list is not exhaustive, and not all of these questions need monitoring programmes.

Once the goal has been identified, the *what* to monitor can be decided. The key questions in Table 1 are divided into those pertaining to macro- and microplastics. The divisions between plastic size categories are arbitrary,[5] and the recognition of three size classes (macro, meso and micro) makes sense in as much as these classes mirror different sampling approaches: macroplastic items are large enough to be recorded visually at sea, or collected by hand on beaches; mesoplastics are caught in neuston nets or sieved from beach sand; and microplastics can be filtered from bulk water samples or separated from sediment samples using density gradient extractions.[5] However, there remains debate about the boundaries between these size classes (Figure 1).

Table 1: Recommended research approaches for key questions in monitoring of plastics in marine ecosystems

Monitoring questions	Recommended research approaches
Macroplastics	
Is the amount/composition of debris from local land-based sources changing?	1. Monitor inputs in storm drains and rivers 2. Beach accumulation studies (frequency depending on level of beach use)
Is the amount/composition of debris from offshore sources changing?	1. Monitor origins of beach debris 2. Monitor use of port reception facilities*
Is the amount/composition of debris on the seabed changing?	1. Monitor debris in benthic fish trawls 2. ROV surveys of accumulation zones
Microplastics	
Is the amount/composition changing?	1. Monitor ingestion by biota 2. Sample soft sediment cores from the seabed 3. Beach arrival studies (tidal stranding)
Are marine foodwebs being contaminated?	Monitor microplastics and/or selected contaminants (plastic-specific additives) in biota (mussels, fish, top predators)

**Monitoring at a regional or global level, as many ships round South Africa without calling at a port.*

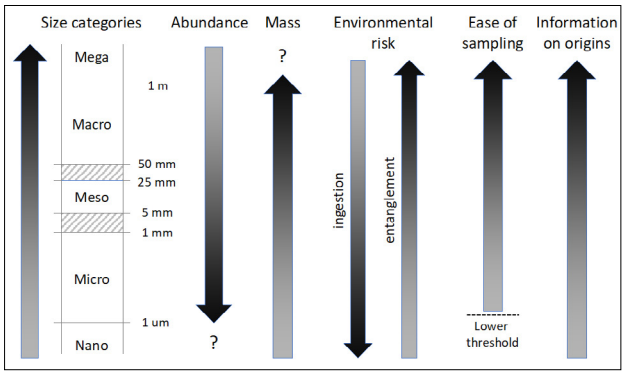

Figure 1: The size categories of plastic debris items in the environment, and their relationship to abundance, mass, environmental risk, ease of sampling and the ability to infer debris origins (and hence target mitigation measures). Hashed areas on the size spectrum indicate where boundaries between size classes are controversial, and ? denotes areas where there are insufficient data to confirm size-based trends. The minimum size threshold below which microplastics cannot be discriminated from organic particles is currently ~5 μm.[5]

The size of items monitored has significant implications, both in terms of sampling constraints as well as what can be learned from their study (Figure 1). Microplastics dominate plastic pollution numerically, and arguably have a greater environmental impact through plastic ingestion, although ingestion by large marine organisms mainly involves meso- and macroplastics. By comparison, macroplastics are responsible for most entanglement and economic impacts of plastic pollution[6,7] and account for the vast majority of marine plastic pollution in terms of mass[8]. Indeed, most leakage of plastics into the environment occurs through macroplastics (with steps being taken to phase out the few sources of primary microplastics, such as in cosmetics). The origins of macroplastics in marine environments are also easier to infer, through manufacturers' labels and the presence of epibionts,[9] and sampling macroplastics does not require sophisticated analytical approaches. Currently there is limited capacity in South Africa to identify particles towards the lower end of the microplastics size spectrum. Even globally, there is as yet no way to identify nanoplastic particles unless they are made with specific tracers.[5] As a result, we suggest that monitoring should focus on macroplastics and larger microplastics (mainly >1 mm), which are easy to sample and identify, and pose little risk of sample contamination.

Other questions that should be considered include the spatial scale of the monitoring exercise (local, national, regional or global), and the suite of items to be monitored.[4] One of the challenges of sampling macroplastics is deciding on the appropriate level of detail to collect on each item. The minimum should be some idea of size/mass, type of material and broad functional group. However, for many debris types it is possible to record additional information (e.g. brand, date produced, production facility), which can help to infer the origins of marine debris[9] but requires considerable effort to collect. If the goal is to track broad trends in debris amounts, it might be better to only record a subset of macro-debris items selected as indicators of specific debris sources.[10] Ultimately, the decision of what to monitor comes down to the question being asked.

Having decided what you want to monitor, and identified the best approach to do so, the next step is to design a statistically robust monitoring programme able to detect the desired level of change in pollution levels. This requires a power analysis to decide how many sites need to be monitored, and the sampling intensity and frequency at each site,[5,11] which needs an estimate of within-sample variance (the greater the variance, the larger the required sample size) and a decision as to the desired level of change to be detected (e.g. a 50% reduction in plastic input per year requires much less sampling effort to detect than a 10% reduction per year). The outcome from this exercise has to be compared with available resources to decide whether it is worth investing in a given monitoring programme. Finally, should monitoring go ahead, it is important to select study sites that will remain accessible and not be subject to undue structural changes over the lifespan of the monitoring programme.[3]

The following sections summarise existing baseline data for marine plastics in the four main environmental compartments off South Africa, and discuss the pros and cons of attempting to use these data sets to monitor changes in the amounts, types and impacts of marine plastics in the region. Additional data sources are listed in Supplementary table 1.

Debris floating at sea and in the water column

Floating plastics at sea typically are sampled by neuston or manta trawls at the sea surface, which target larger micro-plastics (0.5–5 mm).[5] These nets usually are at most 1–2 m wide with a mesh size of 200–500 μm, so they are too small to sample the large macro-debris items that account for most of the mass of plastics at sea[8] and are too coarse to sample the very small microplastics that account for most plastics by number of items[12]. One of the first such surveys globally was conducted off the Western Cape in 1977/1978, when 120 stations were sampled monthly for a year.[13] Although the net used was unusually coarse (900 μm) and tow durations short (2 min), this large sampling effort collected more than 800 plastic fragments at an average density of 3600 plastic items/km^2 (bootstrapped 95% confidence interval [CI] of the mean 2900–4600 items/km^2), similar to the density recorded in oceanic waters of the southeast Atlantic in the 1970s.[14] As is typical of such surveys, variances were large due to marked spatial and temporal heterogeneity in the distribution of floating debris.[4]

The only subsequent surveys of floating microplastics off South Africa have occurred since 2016: 43 manta trawls off KwaZulu-Natal[15] and 30 neuston trawls throughout the South African Exclusive Economic Zone (FitzPatrick Institute unpublished data). Both studies used a finer mesh (200–333 μm), complicating comparisons of the density of floating microplastic items with the samples from the 1970s. Restricting analysis to particles greater than 1 mm, the average density in 2016–2019 is around 11 000 plastic items/km^2 (95% CI 8200–14 600 items/km^2), about three times that in the 1970s. This increase is modest given the seven-fold increase in annual plastic production over the last 40 years,[16] but confidence in this estimate of change is low given the different areas sampled, large variances among net tows and small number of recent samples. The increase has been driven by increases in user plastics (mostly fragments of hard plastic items). The average density of industrial pellets decreased from 850/km^2 (95% CI 545–1020/km^2) in

1977/1978 to 190/km^2 (40–420/km^2) in 2016–2019, and the difference is even more marked when comparing the proportion of pellets now (2%) to that in the 1970s (23%; $\chi^2=79.7$, d.f.$=1$, $p<0.001$). This change in microplastic composition is consistent with the marked decrease in the proportion of pellets ingested by seabirds[17] and juvenile turtles[18] in the region in the last three to four decades, and mirrors the steady decrease in the abundance of pellets in the North Atlantic Gyre from ~1000/km^2 in the mid-1980s to ~250/km^2 by 2010[19].

In comparison to microplastics, there has been less focus on estimating the abundance of floating macroplastic debris at sea, both off South Africa and globally. Most surveys rely on direct observation from vessels or aircraft, although attempts are being made to use remote sensing or camera-based approaches.[5,20] The only published historical data on macroplastic debris floating at sea off South Africa are from an aerial survey in 1985 showing a density of debris items an order of magnitude greater 10 km off the Western Cape coast than 50 km offshore.[13] Subsequent ship-based surveys have confirmed this spatial pattern, with very high debris concentrations close to urban source areas.[21] However, the ship-based observations cannot be compared directly with aerial survey data, so it is not possible to assess whether there has been a change in debris densities over the last three decades.

Very little is known about plastics suspended in the water column around South Africa. The concentration of plastics typically decreases rapidly with water depth, but the pattern depends on item size, buoyancy and the strength of vertical mixing (related to wind stress and other physical processes).[5,22] Generally, smaller and less buoyant items are more dispersed vertically throughout surface waters, whereas larger, more buoyant items tend to remain close to the surface (although buoyancy is reduced by biofouling).[23] However, even among microfibres, which are the most abundant anthropogenic particulate pollutants in seawater[24], the density sampled at 5 m below the surface is 2.5 times lower than at the surface[25]. Current best practice for sampling subsurface microplastic requires specialised underwater pumps to filter large water volumes.[26,27] Macroplastics can be sampled using subsurface trawls[28], and this might be a useful approach given the apparently rapid sinking[23,29,30] and possible mid-water accumulation[31] of near-neutrally buoyant macroplastics such as plastic bags and food wrappers.

Recommendations for monitoring

In terms of future monitoring efforts, three factors argue against using net sampling for monitoring microplastics at sea off South Africa: (1) the very large sample sizes needed to detect changes in plastic concentrations[4]; (2) the need for dedicated ship's time to sample (typically slowing the ship to 2–3 knots); and (3) the generally exposed nature of the coastline and the often windy conditions, which make it hard to sample from small boats and reduce the efficiency of neuston/manta nets to sample floating plastics due to vertical mixing. The same limitations apply to subsurface sampling, with the added complication of lower plastic concentrations reducing the ability to detect change. The only advantage of routine subsurface sampling would be the set-up of automated filter systems on ships' underway water supplies. However, this sampling would require the use of relatively coarse filters to prevent clogging by organic material, and the larger plastic particles that might be captured by such an approach are seldom found 3–5 m beneath the surface, at the depth at which ships' water intakes are located. Continuous plankton recorders have proved useful in tracking long-term changes in microplastics in the North Atlantic[32] and have been deployed on numerous research cruises off South Africa, but have not been examined for plastics. However, most items captured are fibres[32], which are challenging to identify, and recent studies show that most are not synthetic[33,34]. A more promising approach would be to couple plastic sampling with surveys for commercially important fish eggs and other zooplankton.[35,36] Filtering replicate 10-L bulk water samples through a <1-μm fibreglass filter (which requires vacuum filtration) or a 20–25-μm mesh filter (which allows for gravity filtration) is a simple method to assess the abundance of smaller microplastics (<0.5 mm), but sample variance is large, and the risk of sample contamination is high,[25] thus reducing the value of this approach for monitoring.

Recording floating macro-debris at sea provides useful insights into broadscale patterns of debris dispersal,[21,37] and could be used to monitor changes locally (e.g. fine-scale changes in relation to rainfall events in coastal waters). However, given the limited options to use vessels of opportunity for routine sampling around the South African coast (the Robben Island ferry being the only regular ferry service) and the challenges posed by rough sea conditions[37], coupled with the subjective nature of direct debris observations which result in significant inter-observer effects[4], this approach is not well suited for long-term monitoring. We thus do not recommend at sea sampling of plastics as a monitoring approach to address the most pressing questions regarding marine plastics in the region (Table 1).

Debris on the seabed

The seabed is likely to be the long-term sink for most plastics globally[5,38,39], yet it is the compartment about which we know the least in terms of plastic debris off South Africa[40]. Survey approaches depend on water depth, seabed type and size of plastics to be sampled.[5] For macro-debris, observations by divers or remotely operated vehicles (ROVs) are ideal in shallow water (up to 30 m deep), whereas trawls and ROVs can sample in deeper waters.

In South Africa, recreational divers conduct clean-ups, mainly in heavily impacted areas such as harbours. Such initiatives can generate useful monitoring data as well as raise awareness of the marine debris problem.[5,41] The first systematic attempt to assess seabed debris in South Africa, conducted in False Bay in 1991, found low densities of flexible packaging and plastic bottles in shallow subtidal environments.[42,43] Monthly surveys at one site suggested that most debris derived from local, land-based sources. Attempts to repeat this survey in 2014 were shelved when initial sampling failed to locate any macro-debris on soft sediments at the sites studied in 1991. Similarly, examination of 421 images of the False Bay seabed taken to classify benthic communities failed to detect any debris items (FitzPatrick Institute unpublished data). However, occasional upwelling of dense debris onto False Bay beaches[43] indicates a substantial pool of seabed debris somewhere in the Bay.

In deeper waters of the continental shelf, very little debris is seen in video footage of the seabed (Sink K, SANBI, personal communication). Systematic collection of debris caught in hake (*Merluccius* spp.) stock assessment trawls (which use a finer mesh than commercial trawls at a large number of randomly selected sites) offers a pragmatic tool to monitor changes in macro-debris on the seabed in the region, although capture rates are low and sampling is limited to soft bottoms.[30] ROV footage is needed to establish a baseline for debris in deep-water canyons where seabed debris tends to accumulate.[44,45]

Even less is known about microplastics in seabed sediments around South Africa. The only published data on subtidal microplastics are from a single core collected at a polluted site in Durban Bay.[46] Sediment cores can be used to track changes in plastic density over time. For example, the density of microplastics (>300 μm) in the Durban core was four times higher at 2.5–5 cm deep (~1750 particles/kg dry mass) than at 20–22.5 cm deep (~400 particles/kg dry mass).[46] At more remote sites, microplastics were found at relatively low densities (<5 microfibres per 50 mL sediment) in all three sediment grabs collected from seamounts south of Madagascar.[40] Further samples are needed of especially deep-sea sediments to establish a baseline against which future changes in the region can be monitored (Table 1).

Beach debris

Plastic stranded on beaches provides the easiest way to assess marine plastics.[4,5] We have a fairly good understanding of the abundance and composition of beach debris around the South African coast, with information on macroplastics and larger microplastics (mesoplastics) dating back to the 1980s.[47,48] A consistent pattern found in all these surveys has been for higher densities of plastic debris close to urban centres,[40,48] suggesting that most debris derives from local, land-based sources. More recently, surveys of smaller microplastics (mainly microfibres) also report a strong correlation with local urban source areas.[49]

Interpreting standing stock data

Beach debris surveys can be divided into two distinct types: those that sample debris standing stocks and those that measure debris accumulation.[4,10] Both provide useful information on the abundance and distribution of marine plastics, but interpreting changes in standing stocks over time requires a thorough understanding of beach debris dynamics. The amount of debris on a beach is influenced by numerous interacting factors (Figure 2), some of which are episodic (e.g. storm-driven undercutting events). Even if we assume these dynamics are fairly constant, little is known about the turnover rate of debris on South African beaches, and this rate plays a key role in determining long-term trends in standing stocks. For example, a modest increase in standing stocks over 50 years could result from an increase in debris washing ashore, no change or even a decrease in the amount washing ashore, depending on the beach debris turnover rate (Figure 2). To add to the complexity, turnover rates differ between debris types.[50] For example, lightweight items such as expanded polystyrene turn over more quickly than items less prone to being blown off the beach.[51] Similarly, small items are buried more rapidly than larger items and are thus 'lost' from traditional beach surveys that only sample superficial debris.

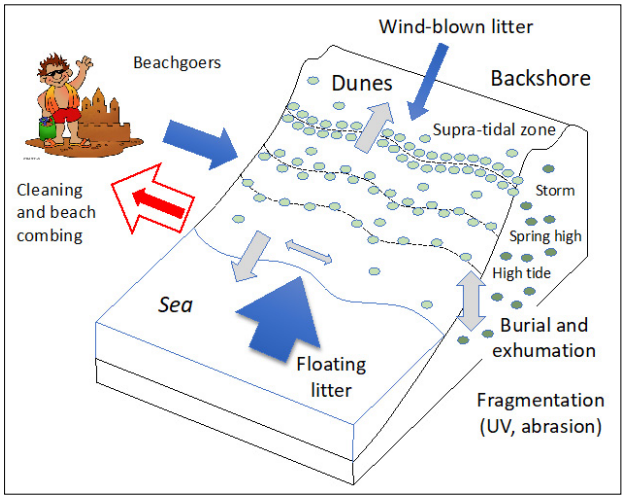

Figure 2: The factors affecting plastic debris standing stocks on sandy beaches. Most debris typically washes ashore, but beach visitors and wind-blown debris from the land also contribute debris inputs (blue arrows). Debris (green circles) tends to accumulate in a series of strand lines linked to wave action, tidal cycles and storm events. Within the beach, debris is moved by the wind, tides and waves (grey arrows), which may carry debris back into the sea, into the backshore where it is often trapped by vegetation, or along the shore, or debris may be buried (darker circles) and can be re-exposed if the beach is cut back by storm seas. Over the long term, items exposed to UV radiation become brittle and break down, aided by mechanical abrasion. Beach cleaning (red arrows), which selectively removes larger debris items from beaches, typically has increased over time.

However, the biggest challenge to interpreting standing stock data for macro-debris on beaches is the systematic change in beach cleaning effort that has occurred over the last 50 years. Beach cleaning effort increased exponentially in South Africa up to 1995[52], and has continued to increase since then thanks to initiatives such as the government-sponsored 'Working for the Coast' Programme[53]. As a result, turnover rates for macro-debris items have changed dramatically over time, confounding attempts to infer changes in debris loads at sea based on beach standing stocks. Such cleaning tends to focus mainly on larger debris items, and thus we see different trajectories in the abundance of large and small debris items recorded during 5-yearly standing stock surveys at South African beaches.[4]

Accumulation surveys

If the goal is to assess changes in the amount of debris at sea, accumulation studies obviate many of the challenges posed by standing stock beach surveys because they estimate the rate of debris arriving at a beach. This requires thoroughly cleaning a section of beach, and then checking the amount of debris arriving over a known period. In most studies to date, sampling has been repeated every 1–3 months[54,55], but can be as seldom as once a year[56]. Such infrequent samples underestimate the actual amount of debris washing ashore, especially for items that turn over rapidly.[51] The magnitude of this effect depends on the frequency of sampling as well as on beach type and local conditions. For example, at two beaches near Cape Town, daily sampling collected 2–5 times more debris by number and 1.3–2.3 times more by mass than weekly sampling.[51] And in the sub-Antarctic, daily sampling collected 10 times more debris than monthly sampling.[57] This is not a problem for monitoring as long as conditions affecting debris turnover rates are more or less constant, and the sampling interval remains the same. However, there are two significant challenges to accumulation studies: one is exhumation of buried debris, and the other is the need to limit beach cleaning. Buried debris can be exposed by beach goers, fossorial animals (e.g. dune mole rats, *Bathyergus* spp.) or by storm seas, which inflates estimates of stranding debris. By comparison, beach cleaning deflates estimates of debris stranding rates, and is increasingly difficult to control at open-access beaches due to growing public awareness of the marine debris problem (Figure 2).

Accumulation surveys could be conducted at remote beaches to assess background debris stranding rates. However, if monitoring is designed to assess changes in local, land-based sources of marine litter and the main goal is to determine the efficacy of mitigation measures to reduce plastic leakage into the environment, surveys should focus on urban beaches (Table 1).[39,47] Unfortunately, it is difficult to prevent informal cleaning at such beaches, particularly over a period of weeks or months. As a result, daily accumulation studies were initiated at two beaches in Table Bay in 1994/1995: one urban beach and one more remote beach.[58] A 500-m stretch of beach was cleaned at each site, and then checked daily for newly arriving debris, for several 10–14-day periods (Box 1). The study was repeated in 2012, but the area sampled at the urban beach was reduced to 250 m due to the marked increase in the amount of debris washing ashore.[59] The results show a consistent difference between the two beaches, with 13 times more debris washing ashore at Milnerton (6 km from central Cape Town, and close to the mouths of the Riet and Black Rivers) than at Koeberg (30 km from central Cape Town). The number of debris items increased three-fold over the 18-year period between surveys, greatly exceeding human population growth in Cape Town over the same period (~50%). However, the increase in the mass of debris was more modest, due to a decrease in the average mass per debris item (driven in part by increased packaging of foodstuffs, such as the introduction of individual sweet wrappers, sports drinks with caps on their lids, etc.). Shorter accumulation studies recently have been completed at other Cape beaches[60] and similar studies have been initiated as part of an integrated marine debris monitoring programme throughout the western Indian Ocean region[61].

Accumulation studies are much harder to perform for microplastics, because it is virtually impossible to clean a beach prior to the start of an accumulation study, or to remove all newly arrived microplastics. Perhaps the only practical option is to monitor the arrival rate of larger microplastic items on successive tidal cycles (i.e. record numbers stranding on fresh swash lines on each tidal cycle,[62] although it is hard to ensure that items are not being recirculated within the beach system). Regular surveys of standing stocks of larger microplastics at 50 South African beaches monitored every 5 years since 1989 show no consistent temporal trend, presumably because beaches differ in turnover rates. User plastics have increased at 12 beaches, decreased at 9 beaches, and show no strong trend at 29 beaches (FitzPatrick Institute unpublished data). By comparison, industrial pellets have decreased at 29 beaches, remained constant at 19 beaches, and increased at only 2 beaches. This difference reflects the apparent decrease in pellets at sea (see above). Both beaches where pellets continue to increase fall within predicted accumulation zones for

BOX 1: Conducting a daily beach debris accumulation study

Repeated daily accumulation studies of macro-debris on sandy beaches provide arguably the best measure of changes in the abundance and composition of plastic debris in coastal waters. To conduct such a study:

- Select sites where the land use is unlikely to change substantially, and long-term access is guaranteed. Restricted areas are ideal, because it is easier to control beach cleaning efforts during data collection periods, but at least some sites should be close to urban source areas. If beach access is not restricted, erect signage and use the media to alert beach users to the study, asking that people do not clean the beach during sampling periods.
- Select study periods of at least 10 days to integrate across a range of weather conditions, with sampling blocks in winter/summer and wet/dry seasons. If possible, select the start and end dates to avoid spring tides, because exhumation of buried debris is most likely during spring tides.
- Mark out the study area. The length of the study area should be sufficient to collect enough debris daily to give a reasonable signal of debris input. The length should be at least 500 m at remote beaches with relatively little debris input, but can be shorter for urban sites with high debris input rates.
- Conduct a thorough initial clean-up, removing all debris from the beach and adjacent dunes/vegetation throughout the study area and an adjacent buffer zone of 50 m on either end of the study area to limit the risk of lateral drift. The initial clean-up is best done with a large group of volunteers, and then followed up to ensure that no old debris remains visible. Record any large items that cannot be removed.
- Each day, collect all washed-up debris along the strand line, keeping it separate from debris dumped by beach visitors (e.g. items collected on the dry sand) or exposed buried debris. Note that lightweight items such as bags, bottles and expanded polystyrene trapped by backshore vegetation could be blown inland, and thus should be included in stranded debris.
- Record the number and mass of all newly arrived debris (wash items to remove sand and dry before weighing), scoring by material (plastic, glass, metal, etc.) and functional groups (packaging, user items, etc.). If possible, record presence of epibionts and country of manufacture to help to infer local vs distant water sources of stranded debris.
- Record environmental conditions (wind strength, direction, sea state and precipitation) throughout the study, and use these data to help interpret fine-scale differences in debris accumulation rates.

A similar approach can be used to estimate daily littering/dumping rates in terrestrial habitats.

local-source microplastics[63] and at least one appears to be a long-term sink (i.e. it has a very low turnover rate, cf. Figure 3), with many of the pellets likely having been there for decades. Turnover rates can be estimated for the largest microplastics using marked debris items,[64] but this seldom has been attempted and the accuracy of such estimates is uncertain (especially given the challenges posed by microplastic burial). As a result, we do not recommend routine monitoring of microplastics on beaches.

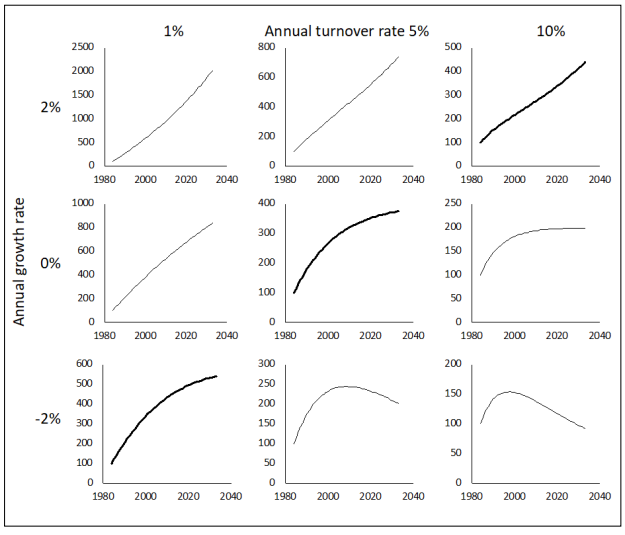

Figure 3: Trends in plastic standing stocks on beaches over 50 years in relation to debris turnover rates, given different trends in arrival rates (growth rates in amounts of litter stranding, in % per year). The three bold curves show that it is difficult to differentiate the debris trend at a beach with increasing input and a fast turnover rate (top right) from one with decreasing input and low turnover rate (bottom left) or one with a constant input and moderate turnover rate (centre). All simulations start with 100 items in 1984 and an initial input rate of 20 items per year. Note different *y*-axis scales among plots.

Bioindicators: Interactions with biota

Monitoring plastic interactions with biota can be a valuable approach, particularly if the interactions integrate exposure to plastics over space and time (e.g. plastic ingestion by species that tend to retain ingested plastic for protracted periods).[65] Parameters that can be monitored include the proportions of biota that contain ingested plastic, that are entangled in marine debris, or use plastic items for construction material or shelter (e.g. seabird nests, hermit crabs, tube-building annelids, echinoderms). It is also feasible to track levels of contaminants associated with plastic ingestion, which can have direct relevance for human health.[5,66] One of the challenges of monitoring through biota is the wide range of potential interactions.

Plastic ingestion

Globally, the incidence of plastic ingestion among marine top predators, and the size of ingested plastic loads, generally increased from the 1960s to the 1980s, but there has been relatively little change since then.[65,67] In South Africa, plastic ingestion was first recorded among turtles in the late 1960s, when 12% of stranded post-hatchling loggerhead turtles (*Caretta caretta*) contained ingested plastic; this figure increased to 60% by 2015.[17] However, there was little change in the amount of plastic in procellariiform seabirds from the 1980s to 2000s,[16,68] and this pattern has largely continued to date (FitzPatrick Institute unpublished data). Similarly, there was no increase in the incidence of plastic ingestion by sharks killed in shark nets off the KwaZulu-Natal coast between 1978 and 2000.[69]

Routine sampling of ingested plastic in seabirds in Europe has led to an Ecological Quality Objective target of less than 10% of northern fulmars (*Fulmarus glacialis*) containing more than 0.1 g of ingested plastic.[18] Similarly, loggerhead turtles have been chosen as an indicator of ingested pollution in the Mediterranean[70], although there is the added complication of changes in the size and type of plastic eaten by turtles as they grow[62]. Unfortunately, monitoring of plastic ingestion in these taxa typically requires dissecting the animal to examine the gut contents, because non-lethal sampling approaches fail to recover all ingested plastics[71] or have serious side effects[72]. Ethical concerns prevent killing these animals for such research, and so monitoring therefore relies on opportunistic sampling from animals found dead (e.g. strandings)

or killed accidentally (e.g. in fishing gear or shark nets). Undertaking regular patrols along the South African coast could provide ingestion and entanglement data for a range of seabirds, turtles and marine mammals. However, caution is needed when extrapolating ingestion data from stranded animals to the entire population, because stranded individuals might have a greater propensity to ingest plastic immediately prior to death[68], which may possibly even contribute to the cause of death[73], although it is very hard to tell whether stranded seabirds die as a result of plastic ingestion[74]. Another approach for seabirds is to score the plastic in regurgitations of brown skuas (*Stercorarius antarcticus*) that prey on petrels, which allows large numbers of petrels to be sampled with minimal human impact.[16] Unfortunately, this is most feasible at islands where petrels dominate the diets of skuas (e.g. Prince Edward Island, Inaccessible Island), and these islands are seldom visited.

Fish offer an easier means to monitor plastic ingestion because there are fewer restrictions on their collection, and it is possible to sample from commercial fish catches. Data on plastic ingestion by bony fish off South Africa have only been collected in the last few years.[75,76] Most mullet (*Mugil cephalus*) sampled in Durban Harbour in 2014 contained plastics, although half of these items were fibres and their synthetic nature was not confirmed.[75] Fibres also were found in most small pelagic fish of five species examined from the Benguela upwelling region, but only two hard plastic fragments were found in the 125 fish examined[76] – a much lower proportion than in mullet from the more polluted Durban Harbour. Any monitoring programme designed to track changes in ingested plastic loads thus needs to be cognisant of regional and local differences in ingestion.[77] Ingested plastic loads also differ in relation to feeding method, habitat, diet and age, given indeterminate growth in fish.[65]

Internationally, there has been a call to use mussels as bioindicators of microplastic pollution.[78] Mussels have been used to monitor other types of marine pollution since the 1970s[79] and are widely distributed, easy to collect, play an important role in the ecology of intertidal and shallow-subtidal habitats, and are often eaten by people. Mussels also have been the subject of numerous studies of plastic ingestion, and can reflect local differences in microplastic densities.[78] However, there are several challenges to using mussels in this regard, and standardised protocols are required to select mussels, extract and identify microplastics, and limit contamination, before monitoring can commence.[78] It is critical to fully understand the turnover rate of ingested plastics of different sizes/types in relation to mussel size and feeding conditions.[65]

Entanglement and other plastic interactions

Entanglement affects a wide range of marine organisms, including sessile species such as corals.[5] Changes in the proportion of entangled individuals within populations can indicate changes in the abundance of the items responsible for entanglement[4], even though entanglement is generally less frequent than ingestion[80]. For example, entanglement of dusky sharks (*Carcharhinus obscurus*) off the KwaZulu-Natal coast increased between 1978 and 2000, with over 1% of individuals entangled in the last 3 years of the study, but there was no increase in the proportion of other sharks entangled over this period.[69] There are baseline data on entanglement rates of Cape fur seals (*Arctocephalus pusillus*) from the 1970s[81], against which more recent data can be compared, although such comparisons need to be made at the same colonies, and consider the possible effects of changes in population size on entanglement rates[82]. Similar data exist for seals breeding at Marion Island.[83]

Tracking the amount of debris that seabirds incorporate in their nests provides another measure of change in the abundance of marine plastics.[84] However, the incidence depends not only on the abundance of plastics in the vicinity of each colony, but also the availability of other nest materials.[85] The occurrence of plastic in a suite of seabird species' nests was recorded at various colonies during the 1990s and early 2000s (Department of Environment, Forestry and Fisheries, personal communication), and these surveys are now being repeated. Spatial and temporal changes in microplastics might also be monitored by measuring their incorporation into polychaete worm tubes.[86]

Finally, it is feasible to monitor plastic-associated compounds in biota (e.g. brominated flame retardants, UV stabilisers), which is particularly relevant given concerns about the impact of these compounds on marine organisms and humans who consume seafood.[66] This is perhaps best done among top predators, which could accumulate toxins through biomagnification. Analysis of preen gland oil from seabirds that regularly ingest plastics is a non-destructive way of monitoring such compounds[87], but they are easier to assay in fat tissue from dead birds (e.g. those killed accidentally by fisheries) which provide larger samples with less risk of contamination[88]. It may also be possible to analyse such compounds in the serum or organs of fish.[89,90] Assays of plastic-associated compounds should be conducted in conjunction with other contaminants (e.g. heavy metals) as they may have synergistic impacts on biota.[91] However, such assays are analytically complex, especially at the very low concentrations typical of most plastic-associated compounds.

Uncertainties, evidence gaps and implications for monitoring

The goal of this review series was to identify key uncertainties and evidence gaps needed to inform policy- and decision-making on marine plastics, and, particularly, the implications of not plugging those knowledge gaps. In South Africa, we have a long history of studying marine plastics, and we already know enough about their impacts on marine systems to justify implementing policies to reduce the leakage of waste plastic into the environment. As a result, the most important monitoring goal should be to assess the efficacy of these mitigation measures. Because most leakage occurs as macroplastics, monitoring should focus on this size class of debris. Monitoring should estimate flows of materials rather than standing stocks, because we lack sufficient understanding of turnover rates in any environmental compartment to interpret changes in input rates from standing stock assessments. Sampling at sea or on beaches is not the most direct way to monitor leakage from either land-based or ship-based sources, and thus is subject to greater uncertainty regarding the link between action and response. Monitoring the efficacy of mitigation measures ideally should occur as close to the leakage as possible.

Most plastic inputs into the sea come from land-based sources, which can be assessed by monitoring debris in rivers, storm-water drains and effluent from waste-water treatment plants. However, water-borne inputs of at least macro-debris tend to be episodic, linked to rainfall events, with little or no leakage occurring during dry spells. With rainfall predicted to become increasingly variable throughout South Africa, monitoring plastics in run-off will be increasingly challenging. A better approach might be to monitor plastic flux on land (through fine-scale accumulation studies similar to daily beach debris surveys) as an index of land-based leakage. For plastics dumped illegally from ships, the best approach probably is to ensure compliance with regulations through monitoring the use of port reception facilities for waste from ships.[92] However, such monitoring needs to be conducted and coordinated at an international level, because many vessels operating in and around South African waters do not call in South African ports.

Finally, there is benefit to monitoring plastic in marine environments by taking advantage of existing surveys (e.g. annual fish stock assessments) and continuing existing long-term studies (e.g. beach litter surveys) if they are cheap to conduct and can serve other useful purposes (e.g. student training). Monitoring interactions with biota (e.g. debris in seabird nests and plastic ingestion in selected taxa) also may form a useful and cost-effective adjunct to track ecological impacts in the region.

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Authors' contributions

P.G.R., V.P. and C.L.M. contributed unpublished data; P.G.R. wrote the first draft; all authors commented on the draft.

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