The importance of beachgoers as a source of beach litter

Nwaigwe Chukwudi

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FitzPatrick Institute of African Ornithology

Department of Biological Sciences

Faculty of Science

University of Cape Town

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Supervised by Emeritus Professor Peter Ryan

Declaration

This thesis reports original research that I conducted under the auspices of the FitzPatrick Institute of African Ornithology, University of Cape Town. All assistance received has been fully acknowledged. This work has not been submitted in any form for a degree at another university.

Nwaigwe Chukwudi

Plagiarism declaration

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2. I have used the same style as that of the journal, *Marine Pollution* for citation and referencing. Each contribution to and quotation in this thesis from the work(s) of other people has been attributed, cited and referenced.
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Abstract

The increasing prevalence of anthropogenic litter on beaches is a significant environmental concern. Various waste materials, including plastics, wood, metal, and paper, often enter coastal environments through direct disposal or indirect pathways such as rivers, storm drains, and beach and ocean users. This pollution poses serious threats to the aesthetic and recreational value of beaches, local economies, and the well-being of beachgoers. Additionally, it has detrimental impacts on terrestrial and marine ecosystems. Reducing litter on beaches requires an understanding of key pollution sources to implement effective mitigation actions and strategies.

Beach litter could originate from various sources, including beachgoers. When attributing sources to beach litter, various approaches have been applied but all have shortcomings. This study evaluates the dry and wet sand methodology, which was devised by Barnardo and Ribbink (2020) and Ryan et al. (2020b) and has since been used by Barnardo et al. (2021) and Okuku et al. (2020) to identify beach litter originating from beachgoers, although it has not been validated. I compared litter accumulation at two urban beaches in False Bay, South Africa: Muizenberg, a popular recreational beach, and Sunrise Beach, a nearby, less utilised beach. Data from April 2023, when beaches were open to visitors, were compared to April 2020, when beaches were closed during the COVID-19 pandemic. Findings examined whether the dry sand component reflected differences between years with and without visitors, providing insight into the method's effectiveness.

I recorded greater litter loads at Muizenberg than at Sunrise Beach during both sampling years. Between sampling years, more litter was collected during 2020 than 2023 at both beaches. More onshore winds in 2020 likely contributed to litter deposition, while in 2023, when visitors were present, informal beach cleaning would have contributed to the presence of less litter. Litter composition varied by sampling years and beaches. At Muizenberg in 2023, dry sand items were dominated by smoking-related items (mainly cigarette butts) and items made from paper. At Sunrise, single use plastics (such as food and packaging items) dominated in both sampling years. In 2023, dry sand litter accounted for 23% of items and 43% of litter mass at Muizenberg, compared to 6% and 12% at Sunrise, respectively. The amount and composition of the dry sand litter at Muizenberg suggests a correlation with the number of beachgoers the day before, which indicates the potential to use the dry and wet sand method as a proxy for litter generated by beachgoers.

I applied the dry and wet sand daily accumulation method to infer the relative contribution of beachgoers to litter loads seasonally at both beaches. The proportion of dry sand litter was higher in summer (when the number of beachgoers was greater) at both beaches compared to other seasons, especially at Muizenberg. Items made from paper and smoking-related items (mainly cigarette butts) dominated by number and mass on the dry sand, especially in summer. On the wet sand, smoking-related items predominated by number and large non-plastic items (such as a car tyre, processed wood, etc.) by mass, mainly in the winter rainy season. These findings suggest that more effective mitigation measures are needed, particularly during summer. These could include increased educational awareness campaigns, the installation of additional waste bins, and increased beach clean-up efforts.

I also investigated whether beachgoer litter is a major source of litter in the surf zone. I compared the composition of litter in the surf zone to that on the sandy beach over 50-days in 2022/23, repeating a previous study performed in 2013/14. Daily net tows in the surf zone revealed that litter abundance had decreased since 2013/14. A negative correlation between surf zone litter and the number of beachgoers the previous day suggests that little of the surf zone litter derives directly from beachgoer activity. It is more likely that weather conditions influence both the amount of surf zone litter and beach attendance. Most litter sampled in the surf zone was smaller than that collected on beaches because the 5 mm-mesh net used to sample in the surf zone collected smaller items than items collected by hand on the beach > 10 mm. During offshore winds, small amounts of litter typically found on the dry sand were collected from the surf zone on a few of the sampling days. Findings suggest that only a small fraction of beach litter migrates offshore via the surf zone. In addition, 35% of the litter collected in the surf zone in 2022/23 and 18% in 2013/14 showed signs of weathering, indicating a prolonged time in the sea.

In summary, this study validates the use of the dry and wet sand daily accumulation methodology for assessing beach litter contributions from beach users. It also highlights seasonal variations in litter accumulation, particularly on urban beaches. Dry sand litter was most prevalent in summer, linked to an increase in the number of visitors and their tendency to leave waste behind However, there was no strong evidence linking beachgoer litter to the amount in the adjacent surf zone. While findings suggest that only a small proportion of sandy beach litter generated by beachgoers migrates into the nearby sea, interventions to manage beach littering, such as more waste bins, public awareness campaigns, and stricter enforcement policies would be beneficial.

Chapter 1: General Introduction

Marine litter and its impact

Along with global issues such as climate change, biodiversity loss, and overpopulation, marine litter is regarded as a major environmental challenge (Derraik 2002; Thompson et al., 2009; Jambeck et al, 2015). Anthropogenic litter in the marine environment can have detrimental effects, such as ingestion by wildlife (Nam et al., 2021), entanglement and ghost fishing (Baulch and Perry, 2014), spreading invasive species (Gracia et al., 2018), habitat damage (Consoli et al., 2020), and the reduction of revenue from fishing and tourism activities (Mouat et al., 2010). Anthropogenic litter finds its way into the marine environment either unintentionally or deliberately (Ryan et al., 2009; Jambeck et al, 2015). Understanding the source of marine litter is challenging but crucial to devise mitigation measures that will reduce its detrimental effects on natural ecosystems.

Sources of marine litter

Marine litter is mismanaged waste originating from either land or ocean-based sources (Veiga et al., 2016; Falk-Andersson, 2021). Annex V of the International Convention for the Prevention of Pollution from Ships (MARPOL) came into force in 1989, banning the dumping of plastics and other persistent waste material at sea. Since then, it has been widely assumed that approximately 80% of marine litter stems from land-based sources, especially densely populated urban centres (Ryan et al., 2019). These sources include solid waste disposal, sewage disposal, urban storm-water runoff, and agricultural waste discharge (Jambeck et al, 2015; Veiga et al., 2016). Litter can enter the marine environment from land-based sources by being windblown, or as run-off from rivers (Ryan et al., 2009; Veiga et al., 2016). Once in the ocean, currents, tides, wind and waves can transport buoyant plastic waste over vast distances (Ryan et al., 2009; Thompson et al., 2009; van Sebille et al., 2020). Buoyant plastics could either remain afloat for extended periods of time and be washed ashore, or sink to the sea-floor due to biofouling (Fazey and Ryan , 2016; Okuku et al., 2020; van Sebille et al., 2020). As a result, plastic waste has been reported all over the world (Pieper et al., 2019; Kaviarasan et al., 2020). Waste plastics are a major concern because of their wide dispersal and long lifespan in the marine environment (Thompson et al., 2009). Beaches are significantly impacted by and are important sinks for plastic waste (Ryan et al., 2009).

The impact of beach litter on the value of beach services

Globally, beaches offer various services that are socially and economically beneficial to humans (Mouat et al., 2010). One of the ways beaches are economically beneficial is through tourism. Beaches play an important role in the socio-economic growth of coastal communities around the world, as they attract tourists and generate substantial foreign exchange revenue and job opportunities for coastal communities (Mouat et al., 2010). In South Africa, tourism (which includes beach tourism) contributes 9.8% of the country's total employment and 2.9% of the national GDP (Ballance et al., 2000; Arabi and Nahman, 2020).

Beach litter has a negative impact on the income generated by beach tourism. According to Ballance et al. (2000), a key consideration for foreign tourists when selecting a beach on the Cape Peninsula is cleanliness. Their findings suggest that 97% of potential beach visitors would avoid beaches with more than 10 litter items per square metre. Beach litter therefore discourages recreational users from visiting beaches and reduces their socio-economic value (Ballance et al., 2000; Santos et al., 2009; Mouat et al., 2010; Gall and Thompson , 2015). It is therefore essential to address the issue of beach litter, not only for environmental conservation, but also for sustaining the socio-economic value of beaches.

Monitoring beach litter

Devising appropriate mitigation strategies to reduce the amount of beach litter requires the identification of the origins of litter items (Veiga et al., 2016; Falk-Andersson, 2021). Assigning sources to beach litter is challenging because it can originate from multiple avenues. It can be discarded by beachgoers or blown onto the beach from adjacent terrestrial areas (Ryan 2023). Litter from illegal dumping by ships, or local, land-based litter that has been transported through rivers into the sea can also be washed ashore (Rech et al., 2014; Ryan and Perold, 2021). Some litter can drift long distances before washing ashore (Ryan 2023). Differentiating between the multiplicity of sources of beach litter is central to focussing mitigation efforts.

Beach surveys are useful for detecting and tracking plastic pollution sources and they provide data for coastal management and mitigation purposes (Ryan et al., 2009; Meakins et al., 2022). Beach surveys can either assess standing stocks of accumulated litter or estimate litter accumulation rates (Cheshire et al., 2009; Ryan et al., 2009; Meakins et al., 2022). Standing stock surveys are useful to determine litter hotspots and to track changes in macro-litter composition over time, but they are not well suited for tracking changes in macro-litter abundance or inferring the relative importance of different litter sources (Ryan et al., 2009;

Meakins et al., 2022). Standing stocks depend not only on the amount of litter arriving on a beach, but also on litter turnover rates, which are influenced by factors such as beach dynamics, recent weather conditions, local currents, clean-up efforts, which differentially remove litter items from beaches, and other human activities (Barnardo and Ribbink., 2020; Ryan et al., 2020b). In particular, standing stock surveys do not reflect long-term changes in the abundance of litter in the environment because clean-up efforts have typically increased over time (Ryan and Swanepoel, 1996; Meakins et al., 2022). Accumulation surveys are recommended over standing stock surveys when the objectives are to assess the amount, fluctuations in the amount, and potential sources of macro-litter (Barnardo and Ribbink., 2020; Ryan et al., 2020b). Macro-litter accumulation surveys measure the amount (by number and weight) and the kinds of litter collecting on a shoreline over a given period. Frequent, daily sampling is preferable, as it reduces biases owing to rapid litter turnover rates, including burial and exhumation of items (Ryan et al., 2014; Meakins et al., 2022). Data from accumulation studies can be used to estimate litter flux and variations in litter loads both onshore and offshore (Cheshire et al., 2009; UNEP, 2009; Barnardo and Ribbink, 2020; Meakins et al., 2022). Therefore, beach surveys are critical to estimate the input from various sources to implement appropriate mitigation measures.

Identifying sources of beach litter: An overview of methods employed

Various methods have been applied to ascribe sources to litter on beaches, the main ones being the ‘attribution by litter type’ method or use of indicator items (Tudor and Williams, 2004; Veiga et al., 2016), the matrix scoring technique (Tudor and Williams, 2004), and the dry and wet sand method (Barnardo and Ribbink, 2020; Ryan et al., 2020b). The dry and wet sand method can only be used to differentiate between beachgoer litter and other sources. Another approach must be applied to infer the sources of litter on wet sand (Table 1). The most commonly used approach to identifying sources of litter on beaches is the attribution by litter item type or by indicator items (Table 2). Developed by the Marine Conservation Society during beach clean ups, this method assumes that items of a certain type derive from a specific source (Tudor and Williams, 2004; Veiga et al., 2016) and it has been applied in numerous studies to determine beach litter sources (Prevenios et al., 2018; Mokos et al., 2020). A weakness of this method is that items that are difficult to classify, because they could come from more than one source, tend to be placed in a sizable category known as ‘non-sourced’ or ‘unknown source’ (Tudor and Williams, 2004; Veiga et al., 2016).

The indicator item method is similar to the attribution by litter type method in that both consider potential sources for each item. The key difference is that specific litter items are used as indicators of particular sources (Tudor and Williams, 2004; Veiga et al., 2016). This method has been adopted by the Convention for the Protection of the Marine Environment of the Northeast Atlantic (OSPAR) as well as other beach litter studies (Tudor and Williams, 2004; Veiga et al., 2016). The limitations of both methods are similar: ascribing a single source to a litter item excludes the possibility that other sources and pathways might play a role in its origin. As a result, some studies using these approaches include the category 'unknown source' (Table 2), highlighting the challenges of inferring beach litter sources (Tudor and Williams, 2004; Veiga et al., 2016; Prevenios et al., 2018; Vlachogianni et al., 2018). Differentiating between sources using these approach remains problematic.

The matrix scoring method improves on the indicator item and attribution methods, as most studies using the matrix scoring method do not include a "mixed" or "unknown" source category (Tudor and Williams, 2004; Prevenios et al., 2018). This method uses a probability-based scoring system to determine the likelihood of the item originating from a source by considering its identity or function, the beach location in terms of influence of activities and potential sources of litter, the mix of litter items found, and the abundance of items that unequivocally indicate a given source. Potential sources are identified in advance and then each litter item is assigned a qualitative likelihood (rather than a statistical likelihood), such as "very likely" and "very unlikely", of originating from a particular source (Veiga et al., 2016). This is converted to a scoring system by assigning weighted or scaled values (Tudor and Williams, 2004; Veiga et al., 2016). The matrix scoring approach requires extensive knowledge about local usage and behaviours, which can be difficult to obtain (Tudor and Williams, 2004; Veiga et al., 2016). When using this method, both source identification and the assigning of likelihood scores can be subjective (Schernewski et al., 2017).

Another approach designed specifically to identify litter from beachgoers is to differentiate litter accumulating at short intervals (daily sampling) on dry and wet sand (Barnardo and Ribbink, 2020; Ryan et al., 2020b). For this method, litter found on the dry sand (above the most recent high-tide line to the backshore) is assumed to originate from beach visitors and litter found on or below the latest high-tide strandline is assumed to have washed ashore from nearby rivers and storm drains or from out at sea (Barnardo et al. 2021). This method is more objective than other methods but does not attempt to identify the sources of litter found on wet sand. There is some risk of litter items moving between the wet and dry sand zones: on windy days, dry sand litter can be blown onto wet sand, and wet sand litter that dries out can be blown onto dry sand. This issue can be minimised by frequent (at least daily) sampling. The dry and wet sand method has not been tested for validity, but it has the potential for differentiating litter originating from beachgoers from litter from other sources.

Table 1. Main methods used to attribute sources to beach litter items

Method	Reference	Description	Sources
Attribution by litter type	Veiga et al., 2016	Assumes certain items are widely used by a particular sector.	Public litter (shoreline and recreational activities), fishing litter, sewage related, shipping activities, fly-tipped, medical, and non-sourced.
Use of indicator items	Veiga et al., 2016	Uses a single item as an indicator that the litter originates from a particular source.	Fishing activities, galley litter, sanitary and sewage -related litter, shipping activities, and tourism activities.
Matrix scoring technique	Tudor and Williams, 2004	Uses a probability-based scoring system to ascertain the likelihood of an item originating from a given source.	Tourism activities, sewage, river run-off, shipping activities, offshore installations, fishing activities, improper waste disposal.
Dry and wet sand comparison	Barnardo et al., 2021	Dry sand = items from the most recent high-tide line to backshore, whereas Wet sand = items on or below the latest high-tide strandline	Dry sand = beachgoers/tourism activities, wet sand = offshore sources (river run-off, shipping, fishing, etc).

Identifying sources of beach litter: contribution from recreational activities

Most beach litter studies have focused on urban beaches and were carried out in the global north. Of the 28 studies in Table 2, five were carried out in Africa. Some studies sampled one type of beach exclusively: 16 studies sampled urban beaches, three sampled village beaches, and two sampled remote beaches. Seven of the nine studies that sampled a variety of beach types did not distinguish between beach types when reporting results on the proportion of litter emanating from recreational activities. Only two studies, marked with an asterisk in Table 2, compared beach type and the proportion of litter from recreational activities (Prevenios et al., 2018; Barnardo. et al., 2021). The total number of beaches by type investigated by these studies was 118 urban, 43 village, 24 remote, and 8 resort beaches (Table 2).

Most studies used the attribution by litter type or indicator item method rather than the matrix scoring approach (Table 2). Results from studies using the attribution or indicator item method vary widely, with the proportion of items categorised as 'unknown' or 'non-sourced' ranging from 5% to 69% (Table 2). It is unclear how some studies using this method arrive at the proportion of litter from each source. Additionally, some items in the unknown category could come from various sources, so there may be inaccuracies in the categorisation of items. Studies using the matrix scoring method have produced similar ranges of results (Table 2). From the literature reviewed, recreational activities of beach visitors have been identified as one of the major sources of litter on beaches, particularly on urban beaches (Arun et al., 2016; Munari et al., 2016; Nachite et al., 2019; Okuku et al., 2020) (Table 2).

The reported contribution from recreational activities (including beachgoers) varies according to the methodology (Table 2). Estimates from the 23 studies using the attribution by litter type or indicator items methods vary significantly, with the proportion from recreational activities ranging from 18% to 94% by number (Table 2). This is mainly due to differences in the type of beaches studied, but also because of differences in research design. The majority of these studies sampled urban beaches exclusively and only five sampled a variety of beach types. Four of those did not distinguish between beach types when reporting the proportion generated from recreational activities. Studies using the matrix scoring approach suggest that the proportion of litter (by number) from tourism activities ranges from 4% to 68%. In this case, most studies were conducted in Turkey and have produced similar results ranging from 15% to 17% (Table 2). A South African study that applied the dry and wet sand method estimated that the proportion from beachgoers was 39% at an urban beach compared to 18% at a more remote, secluded beach (Barnardo et al., 2021). The only other study to implement this approach found that, across six (6) Kenyan beaches, dry sand contributed 50% of litter items by number (Okuku et al., 2020) (Table 2). The variation in findings might be due in part to differing numbers and behaviours of beachgoers across beach types as well as differing methods applied across studies.

Table 2. Studies reporting the contribution of beachgoers to beach litter, arranged by methodology. Each study includes location (country or region), beach type (urban, resort, remote or village), and the number of beaches investigated. The proportions of other sources in square brackets are inferred values.

Reference	Location	Beach type and number investigated	Litter source	
			Beachgoers	**Other sources**
		Attribution by litter type		
de Ramos et al., 2021	Brazil	Urban: 4	Beach users = 37%	Unknown (36%), fisheries (10%)
Gjyli et al., 2020	Albania	Urban: 5	Recreational/shoreline activities = 59%	Fishing and shipping (2%)
Kaviarasan et al., 2020	India	Remote: 3	Recreational/shoreline activities = 32%	Fishing (47%)
Mghili et al., 2020	Morocco	Urban: 3 Village: 2	Recreational/shoreline activities = 70%	Smoking activities (14%), dumping (6%), ocean/waterway activities (3%), medical/physical hygiene (1%)
Mokos et al., 2020	Croatia	Village: 1	Recreational/shoreline activities = 34%	Fishing (12%), sanitary/sewage (6%), shipping (1%), fly-tipping (1%), medical waste (1%)

Nachite et al., 2019	Morocco	Urban: 6 Resort: 2 Village: 6	Recreational and smoking activities = 61%	[39%]
Rangel-Buitrago et al., 2021	Colombia	Urban: 4 Resort: 6 Remote: 5 Village: 11	Recreational/shoreline activities = 38%	Dumping activities (54%), sea activities (4%), medical/personal hygiene (3%), smoking activities (<1%)
Araújo et al., 2018	Brazil	Urban: 9	Beach users = 89%	[11%]
*Prevenios et al., 2018	Greece	Urban: 1	Recreational/shoreline activities = 62%	Non-sourced (27%), fishing (5%), sanitary/sewage (4%), shipping (1%), medical (1%), fly-tipped (<1%), agric. waste (<1%)
*Prevenios et al., 2018	Greece	Village: 1	Recreational/shoreline activities = 49%	Non-sourced (37%), fishing (8%), sanitary/sewage (5%), shipping (1%), medical (1%), fly-tipped (<1%), agric. waste (<1%)
*Prevenios et al., 2018	Greece	Remote A: 1	Recreational/shoreline activities = 37%	Non-sourced (42%), fishing (9%), sanitary/sewage (9%), shipping (2%), medical (1%), fly-tipped (<1%), agric. waste (<1%).
*Prevenios et al., 2018	Greece	Remote B: 1	Recreational/shoreline activities = 40%	Non-sourced (41%), fishing (10%), sanitary/sewage (5%), shipping (2%), medical (<1%), fly-tipped (1%), agric. waste (<1%)

Vlachogianni et al., 2018	Ionian Sea	Urban: 17 Remote: 5 Village: 8	Recreational/shoreline activities = 33%	Sanitary/sewage (10%), fisheries (5%), fly-tipping (1%), shipping (1%), medical (1%)
Arun et al., 2016	India	Urban: 1	Recreational/shoreline activities = 75%	Dumping Activities (21%), smoking activities (3%), sea activities (1%), others (1%), medical/personal hygiene (<1%)
Munari et al., 2016	Italy	Urban: 5	Recreational/shoreline activities = 38%	Smoking activities (26%), dumping (19%), fishing activities (17%), Medical (1%)
Zhou et al., 2015	China	Urban: 5	Recreational activities = 61%	Smoking (7%), fishing (14%), sanitary (1%), other disposal (17%)
Topcu et al., 2013	Turkey	Village: 10	Recreational activities = 2%	Unknown sources (52%), beverage packaging (19%), foam/sponge (9%), ropes (5%), nylon packaging (4%), Fisheries (1%)
Portz et al., 2011	Brazil	Urban: 10	Beach users = 68%	Unknown (25%), non-Local (4%), fishing activities (3%)
Santos et al., 2009	Brazil	Urban: 15	Beach users = 8%	Unknown (54%), non-local (23%), fishing (16%)

Walker et al., 2006	Canada	Urban: 1	Recreational activities = 52%	Other (28%), sewage (14%), shipping/fishing (7%)
Cunningham and Wilson, 2003	Australia	Urban: 6	Beachgoers = 20%	Stormwater (63%), unknown (5%), shipping (5%), commercial fishers (4%), recreational fishers (3%)
Indicator items				
Abelouah et al., 2021	Morocco	Urban: 3	Recreational activities >50%	Fishing (25%), galley Litter (9%), shipping (4%), sewage/sanitary (4%)
Sarafraz et al., 2016	Iran	Urban: 1	Recreational activities = 94%	Fishing Activities (2%), shipping (2%)
Silva-Iniguez and Fischer, 2003	Mexico	Urban: 3	Beach users = 18%	Unknown/mixed Sources (69%), sea-based (13%)
Matrix scoring technique by Tudor and Williams, 2004				
Bat et al., 2022	Turkey	Urban: 7 Remote: 2	Recreational activities = 16%	Improper waste disposal (33%), river-runoff (20%), shipping (9%), fishing (17%), sewage (5%)
Terzi et al., 2020	Turkey	Urban: 3 Remote: 5 Village: 3	Recreational activities = 17%	River Transport (22%), landfill/improper disposal (21%), sewage (15%), sea/fishing (14%), offshore (11%)
Tudor and William, 2004	UK	Urban:1	Recreational activities = 68%	Runoff (17%), shipping (4%), fishing (11%).

Aytan et al., 2020	Turkey	Village:1	Recreational activities = 15%	River-runoff (22%), fishing (18%), shipping (13%), landfill/dumping (21%), sewage (4%)
Pieper et al., 2019	Portugal	Remote: 2	Recreational activities = 4%	Ocean/offshore (85%), landfill/improper disposal (8%), stormwater (3%)
Comparison of dry and wet sand litter				
*Barnardo et al., 2021	South Africa	Urban: 1	Beach user = 39%	61%
*Barnardo et al., 2021	South Africa	Urban (secluded): 1	Beach user = 18%	82%
Okuku et al., 2020	Kenya	Urban: 3 Peri-urban: 3	Beach user =49%	51%

Thesis Overview

This study posed three main questions and objectives:

Question 1: Does the dry and wet sand method provide useful insights into the amounts and types of litter left by beachgoers from recreational activities?

Objective: To assess the effectiveness of the dry and wet sand method in identifying and quantifying beach litter associated with beachgoers using 2020 data (in the absence of beachgoers) and 2023 (with the presence of beachgoers).

Question 2: How does the amount and composition of litter left by beachgoers vary seasonally at two urban beaches with different visitation rates?

Objective: To understand the seasonal variation in amount and composition of beach litter associated with beachgoers at two urban beaches using the dry and wet sand method.

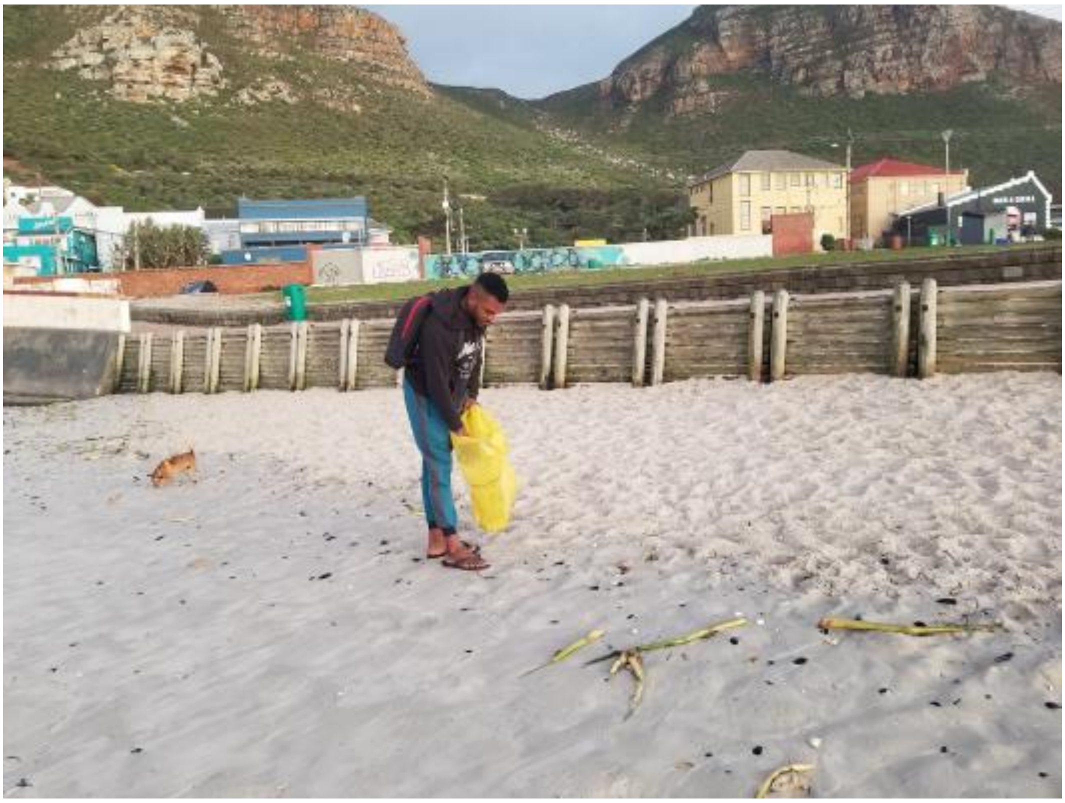
Question 3: Is there a link between the amount of beach litter left by beachgoers and litter in the adjacent surf zone (to test whether beachgoer litter is likely to disperse offshore and impact plastic at sea)?

Objective: To assess the relationship between beachgoer-generated litter and litter accumulation in the adjacent surf zone, in order to evaluate the potential for land-based litter to disperse offshore and contribute to marine plastic pollution.

All methods used to determine the sources of beach litter have shortcomings. The approach proposed by Barnardo and Ribbink (2020) and Ryan et al. (2020b), which assumes that litter on dry sand comes from beachgoers (recreational activities) and litter on wet sand comes from other sources, only distinguishes the relative contribution of dry sand litter (beachgoers) from other sources (mainly washed ashore). However, this method has not been validated. In this thesis, I assess the efficacy of the dry and wet sand litter method during 2020 (without beachgoers) and 2023 (with beachgoers) at two urban beaches with different visitation rates. In 2023, I compare the amount and composition of litter on dry sand (likely from beachgoers) and wet sand (likely from offshore sources) at both beaches sampled seasonally. I also categorize the litter according to items that could likely be generated by beachgoers based on a modified version of the (UNEP, 2011) classification list.

The thesis contains three substantive chapters, each written as stand-alone papers to facilitate publication in peer-reviewed journals. I have cross-referenced between chapters as much as possible to avoid needless repetition of common topics, such as methods and site description. The aim of the thesis is to estimate the contribution of beachgoers to beach litter. This general introduction (**Chapter 1**) provides the broader context of the study and identifies methods used in previous studies that have attributed sources to beach litter items. **Chapter 2** evaluates the efficacy of the dry and wet sand comparison method utilized by Barnardo et al. (2021) to infer litter inputs from beachgoers by examining spatial differences (comparing two beaches with markedly different visitation rates by beachgoers) and temporal variations (contrasting periods when beaches were open to beachgoers versus when they were closed due to the COVID-19 pandemic). In **Chapter 3** I use the dry and wet sand comparison method to explore how the amount of beachgoer litter changes seasonally at two beaches with different visitation rates and explore the reasons for this seasonal variation. **Chapter 4** assesses whether beachgoer litter is a major source of litter in the surf zone at Muizenberg and thus infers how much beach litter generated by beachgoers migrates to the adjacent ocean. In **Chapter 5**, the synthesis, I summarize the results of my study and discuss their relevance in terms of the broader questions raised in Chapter 1.

Chapter 2: Evaluating the dry sand method as a measure of beachgoer litter on urban beaches



Collecting wet sand litter along the most recent tideline at Muizenberg beach. Photo: Shark Spotters

Abstract

Litter found on beaches originates from various sources, including items littered by beachgoers, blown by the wind, or washed up from rivers and offshore sources. Different methods have been used to determine sources of beach litter, but all have drawbacks. This study tests the dry sand – wet sand daily accumulation method to infer the contributions of beachgoers to beach litter, where litter on the dry sand is assumed to originate from beachgoers, and wet sand litter is assumed to be washed up from the sea. Strict beach closures enforced during the COVID-19 pandemic provided the opportunity to compare daily accumulation rates of beach litter with (2023) and without the presence of beachgoers (2020) at two adjacent beaches characterised by different numbers of visitors in False Bay, South Africa. In 2023, the dry sand – wet sand comparison was used to infer the contribution of beachgoers when the beaches were open to visitors, and to see whether the dry sand component accounted for differences between years with and without visitors. Overall, the number of items collected at Muizenberg Beach, which has a high visitation rate, was double the number recorded at Sunrise Beach, a more remote

beach with less than 5% of the number of visitors at Muizenberg. Greater litter loads were recorded at both beaches in 2020 than in 2023, due at least in part to onshore winds, rainfall, and informal beach cleaning in 2023. Such informal cleaning differentially targets larger items and thus has a greater impact on the mass than the number of litter items. During 2023, dry sand litter items at Muizenberg comprised 23% by number and 43% by mass, whereas at Sunrise, litter on the dry sand comprised 6% by number and 12% by mass. Dry sand litter was mainly paper items (30%), smoking-related items (27%), and plastic food packaging (10%) – all items commonly associated with beachgoers. Items such as sewage and fishing-related litter, on the other hand, contributed more on the wet sand. The findings suggest that daily litter collection from the dry sand zone provides a useful measure of litter from beachgoers.

Introduction

The presence of anthropogenic litter on beaches is a growing concern (Veiga et al., 2016; GESAMP, 2019). The negative effect of beach litter is far reaching, from the economy to physical health. Litter can negatively impact socio-economic activities by causing a decrease in numbers of tourists visiting beaches. In addition, littered beaches require cleaning, which is costly. Both consequences result in a loss of revenue for coastal communities (Ballance et al., 2000; Santos et al., 2005; Ramos et al., 2021). Litter on beaches, such as broken glass, can also injure tourists (Arabi and Nahman, 2020). Plastics are the most frequently recorded type of beach litter. Plastics persist in the natural environment due to their durability and dispersibility (Ryan et al., 2009; Jambeck et al, 2015). Addressing the issue of beach litter requires an understanding of its sources to develop effective mitigation measures (Ryan et al., 2009; Veiga et al., 2016).

Differentiating the sources of beach litter is challenging. Local land-based litter that has been transported via rivers and storm drains may become stranded on beaches shortly after entering the ocean (Rech et al., 2014; Maclean et al., 2021; Ryan and Perold, 2021). Beach litter can also come from littering beachgoers, from blowing onto the beach from inland sources (Ryan et al., 2009; Veiga et al., 2016; Ryan, 2023), illegal dumping by passing ships (e.g. Ryan et al., 2019; Ryan, 2023), or from long-distance drift (Ryan et al., 2024). Devising methods to differentiate the multiplicity of sources of beach litter is crucial for mitigation purposes.

Various methods have been used to assign sources to litter items on beaches (Veiga et al., 2016; Chapter 1). Some studies have applied the attribution by litter type or indicator items approach in identifying sources (Veiga et al., 2016). The former assumes that items of a certain type derive from a specific source, while for the latter, specific litter items are singled out as indicators of particular sources (Tudor and Williams, 2004; Veiga et al., 2016). Other studies use the matrix scoring method, which applies a probability-based scoring system to determine the likelihood of a litter item originating from a source by considering its identity or function, the beach location, the mix of litter items found, and the abundance of items that unequivocally indicate a given source. Chapter 1 provides a more complete explanation of these methods.

The dry and wet sand method applied by Barnardo et al. (2021) differentiates between litter on dry sand and litter on wet sand during daily accumulation studies. This method assumes that litter found on dry sand originates from beach visitors and litter on wet sand has washed ashore from the sea, having originated either from nearby rivers and storm drains or from offshore sources. In trying to differentiate beach litter sources, litter items on the wet sand are collected from the edge of the water to the latest high-tide strandline and items on the dry sand are collected from above the most recent high-tide line to the backshore (Barnardo et al., 2021). This method is more objective than other methods and requires less knowledge of local sources, but it does not inform on the origins of the wet sand litter. The dry and wet sand is quite new (Barnardo and Ribbink, 2020; Ryan et al., 2020b) and has only been used in a few studies to date (Okuku et al., 2020; Barnardo et al., 2021) but it is the proposed method for beach litter monitoring in Africa (Barnardo and Ribbink , 2020).

This chapter tests the efficacy of the dry sand method in differentiating beachgoer litter from other beach litter sources and assesses the contribution of beachgoers to beach litter loads. The COVID-19 pandemic lockdown and associated period of beach closures afforded an opportunity to study the sources of litter on two urban beaches with different visitation rates while they were empty of beachgoers. After the COVID-19 beach closure, I could compare litter composition and amounts on dry sand (likely from beachgoers) and wet sand (likely washed ashore) at the same two beaches. I report litter amounts across space and time, during periods when beachgoers were present and absent, and provide evidence of the validity of a methodology to measure the impact of beachgoer activity on beach litter loads by using the dry sand component to assess the difference in the amount of beach litter between periods with and without beach visitors.

Methods

Site description

Two 400 m stretches of the long northern beach in False Bay were chosen for sampling: Muizenberg corner and east of Sunrise Beach (Fig. 1). False Bay, south of Cape Town, is South Africa's largest bay. These sites were selected based on the availability of data from 2020, which were used in this study to evaluate the impact of the COVID-19 lockdown on litter levels and to assess beach litter loads in the absence of beachgoers. The two study beaches are located in the heart of a densely populated metropolitan area, 27 km from Cape Town’s city centre. Several rivers draining the heavily populated Cape Flats enter the northern shore of False Bay, introducing significant litter loads into the bay (Pfaff et al., 2019; Ryan and Perold, 2021). Muizenberg is a popular recreational beach, used for swimming, surfing and other beach activities. The second study site, Sunrise beach, is 2 km east of Muizenberg beach. It is located near a residential area, but it is less accessible than Muizenberg beach, as a buffer of dune vegetation separates the beach from the residents (Fig. 1). Visitor numbers average 1-5 % of those on Muizenberg Beach and it is mainly used by walkers and joggers. Local drainage is via the seasonal Zandvlei River (Fig. 1) as well as several storm drainage systems along the rocky shore west of Muizenberg corner. The Zandvlei River mouth is open in the winter rainy season but is only opened sporadically at spring tide during summer (Ryan and Perold, 2021). It was closed during both sampling periods in this study. The Zeekoevlei River mouth lies 1 km east of the Sunrise study site and remains open year-round, transporting urban waste into the bay (Pfaff et al., 2019). The Zeekoevlei catchment has an annual run-off of approximately 20 million cubic metres of water (Water Research Commission, 2008).

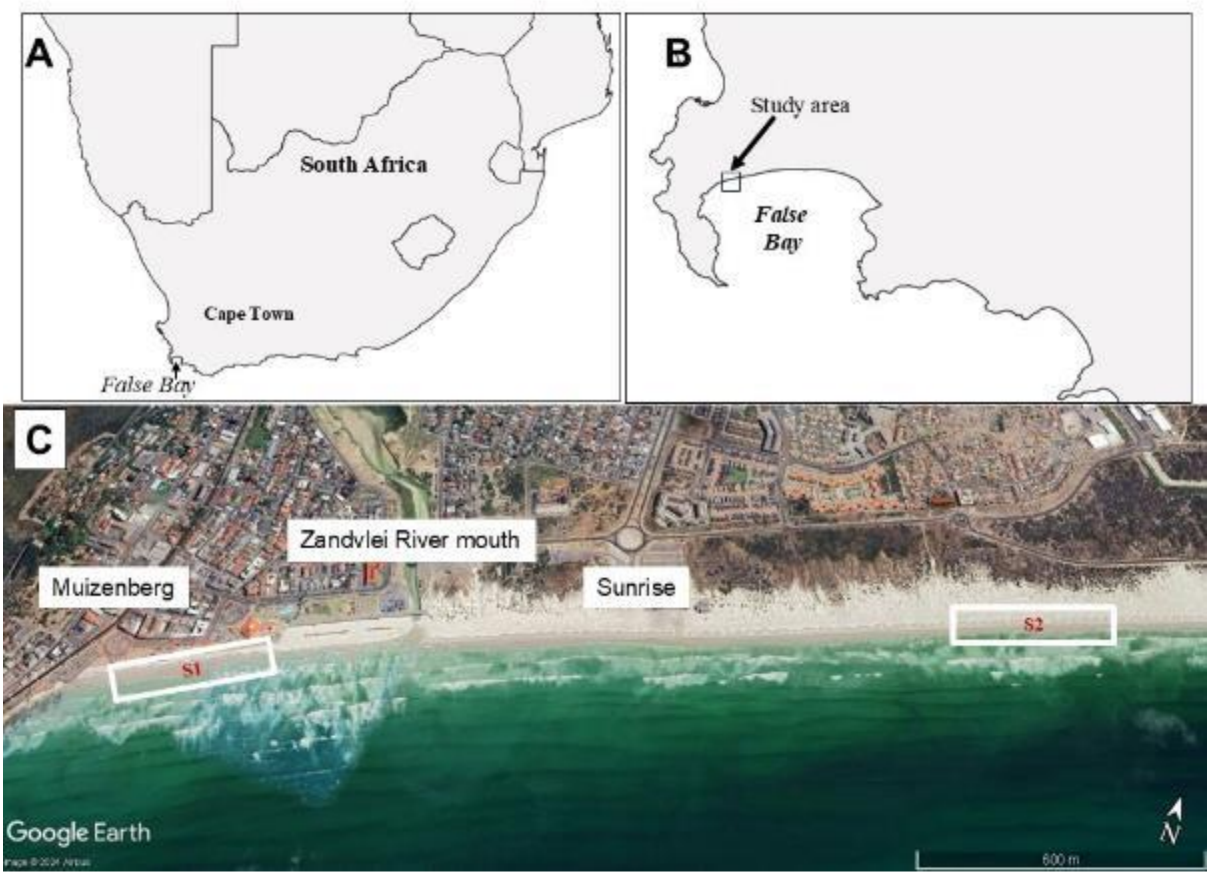


Fig. 2.1. Map showing A) the location of False Bay in South Africa, B) the location of the study area within False Bay, and C) the location of the two beaches sampled: Muizenberg (S1) and Sunrise Beach (S2).

Data collection

Daily litter accumulation was collected for two 10-day periods, from 22 April to 01 May in 2020 and 23 April to 02 May in 2023. Each period was preceded by a comprehensive initial clearing of all visible litter by a team of 3 to 5 people; this litter was discarded. Buffer zones of 50 m were cleared on either end of each transect, and litter was removed daily from these buffer zones to prevent it from drifting into the sampling area from adjacent areas (Barnardo et al., 2021). In 2023, all formal cleaning was suspended during the 10-day sampling. Visitors were informally advised of the beach litter study (10-days data collection) and requested not to clean the beach. After the initial clean-up, all litter items within each 400 m transect were collected every day from the water's edge into the backshore (for Sunrise, the back of the beach is defined by vegetation on the backshore dunes, whereas at Muizenberg there is a wooden or concrete sea-wall). This study used line-based sampling (items·m^{-1}) rather than an area-based method during beach sampling, because litter strands along linear fronts on beaches and, with a tidal range of 1.2–1.8 m (hydrosan@iafrica.com), high tide at the Muizenberg study area leaves very little dry sand available for recreation.

Collection of litter at each beach was on the same day. Sampling times were chosen to avoid spring tides and thus minimise the risk of exhuming old, buried litter (Ryan et al., 2020b). In April 2020, a strict COVID-19 lockdown was enforced, closing all beaches in Cape Town. Permission to collect litter during this time was obtained from the relevant authorities and was carried out across the full beach profile (wet and dry sand combined). The 2020 data were collected by my supervisor, Peter Ryan, assisted by Vonica Perold, Coleen Moloney and Aaniyah Omardien, while Peter and I collected the data in 2023. All litter was assumed to have been washed ashore in 2020. In April 2023, collections were conducted in two zones: the wet sand zone, including the latest high-tide strandline, and the dry sand zone, above the most recent high-tide line (Barnardo et al., 2021). All litter items larger than 10 mm were collected.

Litter items were taken to the University of Cape Town where they were cleaned, dried, counted, and weighed to the nearest 0.1 g (items < 100 g) or 1 g (items > 100 g). They were grouped into 15 broad functional categories, based on the UNEP/MAP MEDPOL (2011) classification list adapted by Falk-Andersson (2021). Since my study focused on the contribution of beachgoers to beach litter, I adapted this classification further by splitting some items classified by Falk-Andersson (2021) as “shoreline and recreational activities” – and which would likely be items littered by beachgoers - into separate categories (Table 2.1).

Weather data were obtained from the South African Weather Services from Cape Town Airport, 18 km NE of the study site. Hourly maximum wind speed and the maximum air temperature per day was used, and rainfall data were summated. There was no rain in the 2020 sampling period, when the wind was predominantly from the south (onshore). In 2023, the wind was predominantly from the north (offshore) and there were rainfall events on six (6) of the 10 sampling days, ranging from 0.2 mm to 24.1 mm.

Table 2.1. The 15 litter categories used to classify the beach litter items collected on Muizenberg and Sunrise Beach with a list of items in each category.

Litter category	Items
Paper/card items	Cardboard, cartons, paper packets, match boxes, newspaper, receipts, serviettes, tissues and paper straw wrappers, etc.
Smoking-related items	Cigarette butts, cigarette packets and wrappers, lighters
Snack food packaging	Biscuit wrappers, chip packets, drink straws, ice-cream and ice-lolly wrappers, yoghurt tubs, etc.
Sweet packaging	Sweet and chocolate wrappers, lollipop sticks and wrappers
Drink bottles and their lids	Soft and fruit drinks, bottled water, alcoholic beverages, drink lids and caps, corks, cooldrink labels, etc.
Fast-food packaging	Fast food cups, fast food lids, polystyrene cups, disposable cutlery
Other food packaging	Polystyrene trays and other food wrappers
Other plastic bottle and lids	Canisters, cooking oil bottles, cosmetic bottles, detergent bottles, food jars, margarine tubs, motor oil bottles, etc.
Other packaging items	Barrier bags, carrier bags, fertilizer bags, woven bags, mesh bags, zip lock bags, clothing tags, packing foam, packing strips, pill blister packs, tape, security tags, etc.
Disposable items	Balloons, wet wipes, razors, syringes, plasters, toothbrushes, etc.
Sewage-related items	Condoms, earbuds, sanitary pads and liners, nappies, etc.
Fishing and shipping items	Angling floats, bait line reels, fishing lures, floats, light sticks, marine crates, monofilament line, polypropylene fibres and ropes, silicon sealant
Other user items	Bike helmets, buckets, footwear, gloves, hair-ties, tile spacers, pens, pegs, rawl-plugs, sunglasses, vinyl pieces, hard hats, clothes hangers, toys, pipes, etc.
Plastic fragments	Unidentifiable plastic items
Non-plastic or paper items	Wax, car parts, ceramic, processed wood, needles, matches, tin foil, etc.

Data analyses

I used Generalized Linear Models (GLMs) to assess which factors best explained the variations in the amount of litter accumulating each day between beaches and sampling years, followed by litter loads at each beach between sampling years, and litter loads on the dry and wet sand during 2023. GLMs were implemented using the *glm* function from the *MASS* and *stats* packages of R (Venables and Ripley, 2002; R Core Team, 2024). I modelled the number and mass of litter items per day as a function of the sampling period, incorporating daily rainfall, wind speed, wind direction, and air temperature, all lagged by one day. I applied negative binomial distribution to model the number of litter items to account for overdispersion in the data. In contrast, I used Gamma distribution in modelling the mass of litter items due to the skewed nature of the semi-continuous data. Only at Sunrise, I applied the hurdle model to analyse the number of litter items, addressing the zero-inflated nature of the data. The count component of the model was specified with a negative binomial distribution to account for overdispersion, while the zero-hurdle component employed a binomial distribution to model the occurrence of zeros. This analysis was conducted using the *pscl* package (R Core Team, 2024). I employed Principal Component Analysis (PCA) to visualize the associations between litter loads across different categories, sampling years, and beaches. The *PCA* and *PCA_biplot* functions were used for this analysis. To standardize the data and ensure consistency in variance, the litter category data were scaled using the scale() function. I presented the data as means ± SD or as medians and IQR ranges where data were strongly skewed. Results were considered significant when $p < 0.05$. All statistical analyses were conducted using R version 4.2.3 (R Core Team, 2024).

Results

Litter-loads

During 2020 and 2023, 9080 litter items weighing 58.97kg were collected. The total number recorded at Muizenberg (6047 items, 78.6 ± 20.0 100 $m^{-1}\cdot day^{-1}$) was significantly more than at Sunrise beach (3033 items, 37.9 ± 21.8 100 $m^{-1}\cdot day^{-1}$; Tables 2.2 and S2.1). However, the mass of litter at Sunrise beach (33.2 kg, 414.7 ± 1500.8 g·100 $m^{-1}\cdot day^{-1}$) was not statistically different from that at Muizenberg (25.8 kg, 322.5 ± 613.2 g·100 $m^{-1}\cdot day^{-1}$; Table S2.2). The increased mass at Sunrise was due to a few large fishing and shipping-related items collected in 2020 that weighed 24 kg (74% of the total mass collected at this beach).

At both beaches, the number of items collected each day was greater in 2020 than in 2023 (Table S2.3). By mass, the number of items measured in 2020 was 7 times higher at Muizenberg and 33 times higher at Sunrise than in 2023 (Table S2.3). At Sunrise, the GLMs showed that greater litter loads were recorded during 2020 than in 2023 by number and mass (Tables 2.2, S2.4 and S2.5) and daily accumulation rates increased during onshore, southerly wind (Tables 2.2 and S2.4) and on cooler days (Tables 2.2 and S2.4). At Muizenberg, more litter items were recorded in 2020 than in 2023 but there were no significant differences between years (Tables S2.6 and S2.7). The number of items increased following rainfall events (Tables 2.2 and S2.6) with greater masses recorded following windy days (Table S2.7).

When litter loads were compared between the dry and wet sand, items on the dry sand accounted for 23% by number and 43% by mass at Muizenberg compared to only 6% by number and 12% by mass at Sunrise (Table S2.8). The GLM failed to detect any factors that significantly influenced the amount of dry sand litter at Muizenberg (Tables S2.9 and S2.10), but the number of items on the wet sand increased following rainfall events (Tables 2.2 and S2.11). At Sunrise, the number of items on the dry sand decreased following rain (Table 2.2, and S2.13).

Table 2.2. GLMs output showing the effects of wind strength and direction (onshore and offshore winds), maximum air temperatures and rainfall on litter loads by number between the beaches (Muizenberg and Sunrise) in both sampling years (2020 and 2023), at each beach over the sampling years (2020 and 2023), and at Muizenberg in 2023 on dry and wet sand. Note – only significant factors are presented here.

Factors affecting litter loads	Estimate (± SE)	Z-value	P-value
All litter at both beaches in both years			
Sunrise (< Muizenberg)	-0.742 ± 0.139	-6.486	0.0001
2023 (< 2020)	-0.575 ± 0.221	-2.606	0.0092
At Muizenberg beach between years			
Air temperature (> on warm days)	0.058 ± 0.026	2.227	0.0259
Rain (> after rain events)	0.021 ± 0.010	2.050	0.0403
At Sunrise beach between years			
2023 (< 2020)	-0.961 ± 0.373	-2.573	0.0101
Onshore (> offshore)	0.579 ± 0.269	2.154	0.0321
Air temperature (< on warm days)	-0.149 ± 0.073	-2.032	0.0422
On wet sand at Muizenberg in 2023			
Onshore (< offshore)	-0.378 ± 0.132	-2.863	0.0042
Rain (> after rain events)	0.046 ± 0.021	2.251	0.0244
On dry sand at Sunrise in 2023			
Rain (< after rain events)	-0.644 ± 0.249	-2.670	0.0076

Composition

The principal component analyses revealed a greater separation in the litter composition between sampling years at Muizenberg than at Sunrise beach (Fig. 2.2A). Muizenberg beach in 2023 was clearly separated from Muizenberg in 2020, whereas Sunrise beach was fairly similar in both sampling years (Fig. 2.2A). If dry sand litter originates from beachgoers, and I exclude litter recorded on dry sand from the analyses in 2023 (Fig. 2.2B), then we would expect to find little difference between the beaches. Although the principal component analysis still revealed some separation in litter composition for Muizenberg between 2020 and 2023 – although less clear for Sunrise between years – it was much less than when dry sand litter was included (Fig. 2.2A).

At Sunrise beach, plastic packaging dominated in terms of number of items but most of the mass of litter came from fishing and shipping related items (Fig. 2.3 and Table S2.17). By number, snack food packaging contributed 10% in 2020 and 15% in 2023, and other food packaging items contributed 13% in 2020 and 32% in 2023 (Fig. 2.3A and Table S2.17). By mass, fishing and shipping related items contributed 78% in 2020 but only 1% in 2023 (Fig. 2.3B and Table S2.17). When the proportion of litter items (by number) between the dry and wet sand were compared in 2023, other food packaging items contributed 4% on dry sand and 33% on wet sand, whereas snack food packaging contributed 7% on dry sand and 16% on wet sand (Fig. 2.4A and Table S2.18). By mass, other food packaging items contributed 2% on dry sand and 30% on wet sand, whereas snack food packaging contributed 4% on dry sand and 13% on wet sand (Fig.2.4B and Table S2.18).

At Muizenberg, the litter composition differed substantially between sampling years (Fig. 2.2A and Table S2.19). By number, smoking-related items (especially cigarette butts) contributed 4% in 2020 and 38% in 2023. Paper and card items contributed <1% in 2020 and 8% in 2023 (Fig. 2.3A and Table S2.19). More than half of the mass in 2020 came from fishing and shipping items (53%), but it only contributed 1% in 2023 (Fig. 2.3B and Table S2.19). In 2020, most items had epibionts (bryozoans). When the proportion of items (by number) between the dry and wet sand in 2023 were compared, smoking related items (especially cigarette butts) contributed 27% on dry sand and 41% on wet sand, whereas paper and card items contributed 30% on dry sand and 1% on wet sand (Fig. 2.4A and Table S2.20). By mass, smoking related items (especially cigarette butts) contributed 4% on dry sand and 16% on wet sand, whereas paper and card items contributed 11% on dry sand and 2% on wet sand (Fig. 2.4 B and Table S2.20).

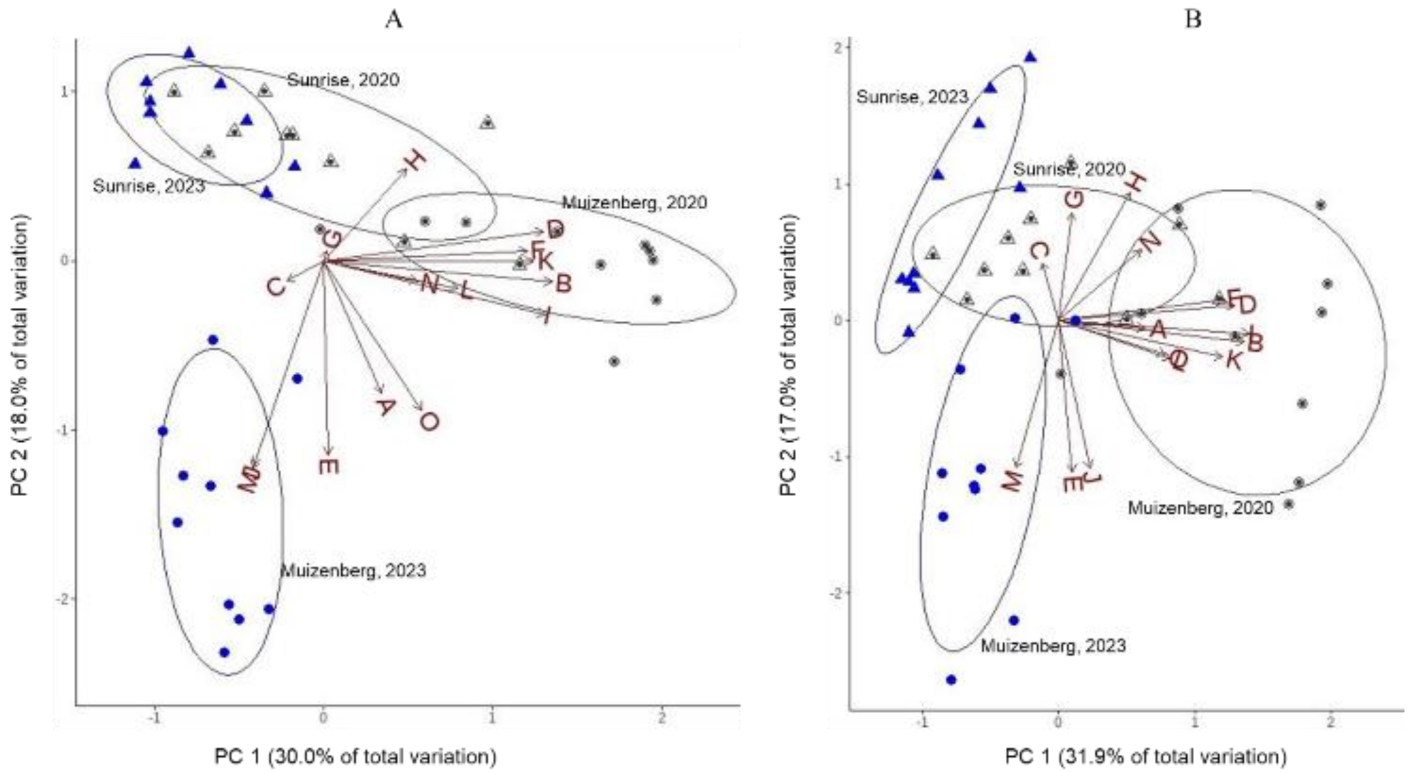


Fig. 2.2. Principal Component Analyses (PCA): PCA (A) includes all data in the sampling years and beaches; PCA (B) excludes the dry sand litter in 2023 at the beaches. Showing the variation between sample days in the number of litter items in each litter category at Muizenberg (circles) and Sunrise (triangles) in 2020 (grey) and 2023 (blue). Ellipse represent beaches and sampling periods. A) includes all data whereas B) excludes litter items collected from dry sand. Arrows indicate litter types driving the spread of sample points: A = Disposable items, B = Drink bottles and lids, C = Fast-food packaging items, D = Fishing and shipping, E = Non-plastic items, F = Other bottles and lids, G = Other food packaging items, H = Other packaging items, I = Other user items, J = Paper and card related items, K = Plastic fragments, L = sewage, M = Smoking related items, N = Snack food packaging items, O = sweet packaging items.

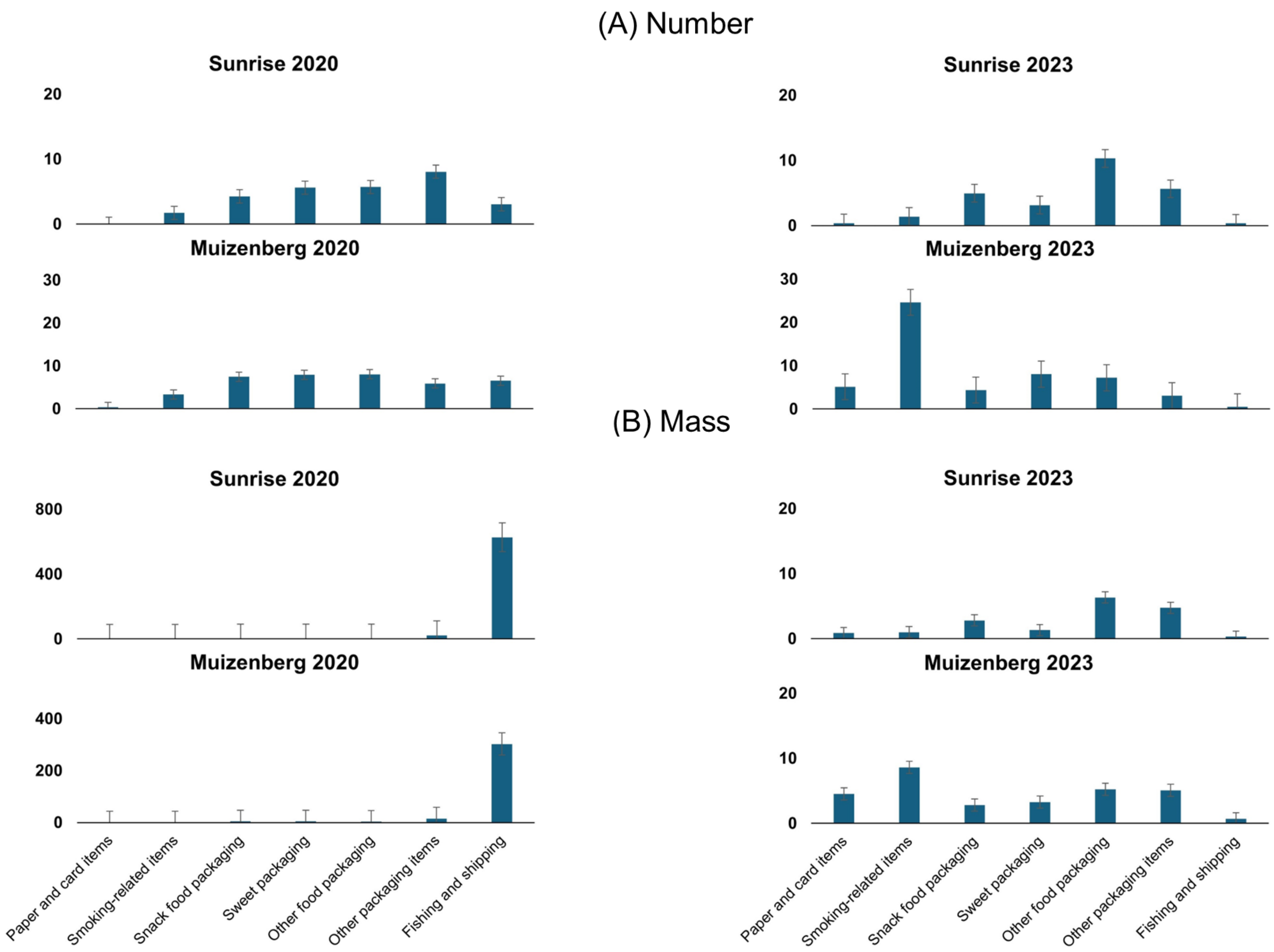


Fig. 2.3. The daily means accumulation rate of items recorded at Muizenberg and Sunrise in 2020 and 2023 by number (A) and mass (B). See Table S 2.17 and S 2.1 for more details

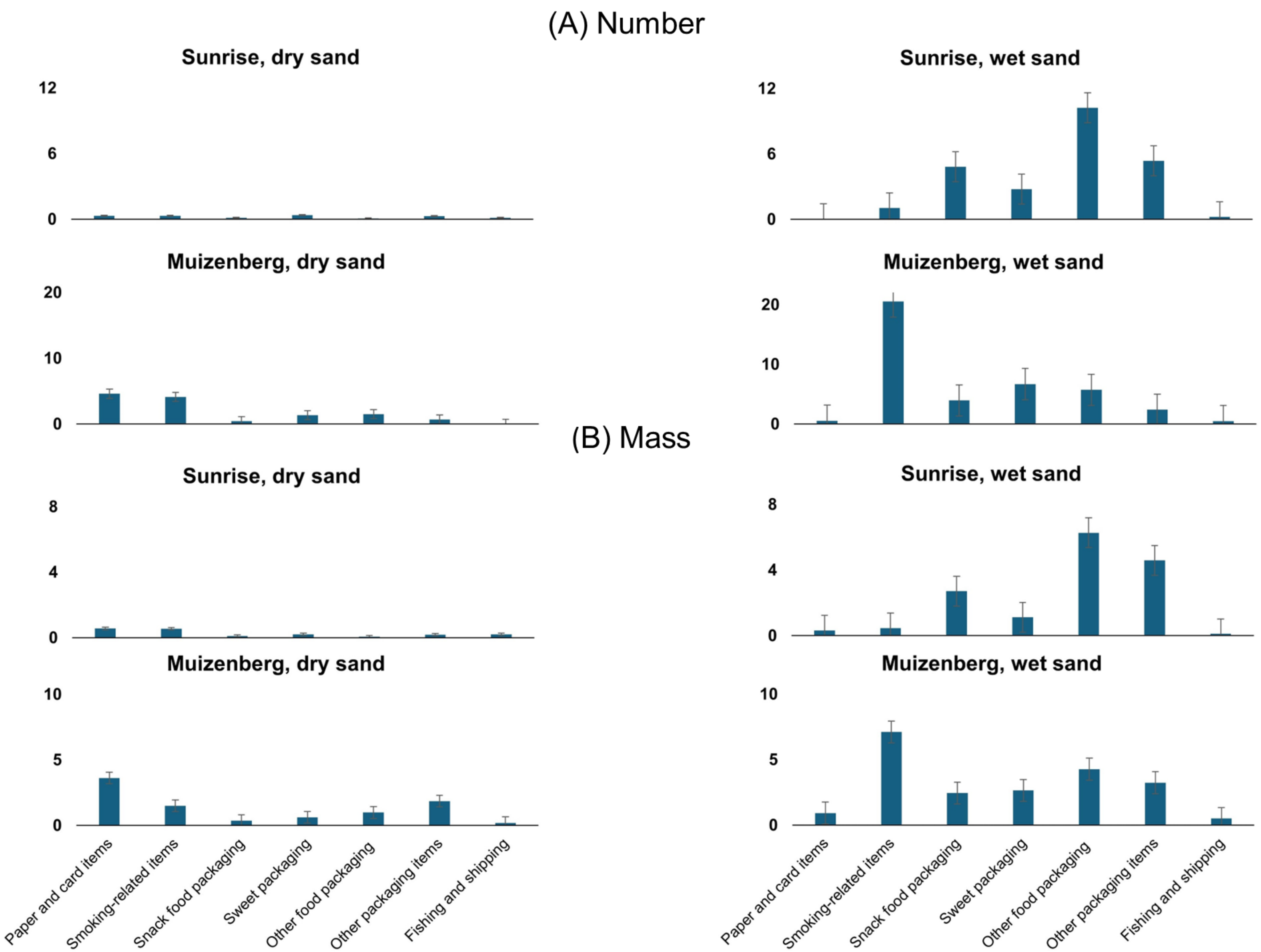


Fig. 2.4. The daily means accumulation rate items recorded on dry and wet sand at Muizenberg and Sunrise in 2023 by number (A) and mass (B). See Table S 2.18 and S 2.20 for more details.

Discussion

Litter-loads

The aim of this study was to understand the impact of beachgoers on beach litter loads. In both sampling years, greater litter loads were recorded at Muizenberg than at Sunrise beach. This was expected, as there are more potential sources of litter around Muizenberg beach than Sunrise beach. These include storm water drainage systems, rivers, and wind-blown litter from inland (Ryan et al., 2009; Chitaka and von Blottniz, 2019). It is important to note that the Zandvlei River, which runs into the ocean at Muizenberg, was closed during both study periods. At Muizenberg, the daily accumulation rate of litter items increased during rainfall events. These flush street litter and litter accumulated in storm drains into the ocean (Chitaka and von Blottniz, 2019; Weideman et al., 2020a). Stormwater drains also have been identified in Australia as major contributors to beach litter loads (Cunningham and Wilson, 2003). At Sunrise beach, the daily accumulation rate of litter loads increased when there were southerly winds (onshore), which facilitates the transport and deposition of litter onto the beach from offshore sources (Eriksson et al., 2013; Thiel et al., 2021).

More litter items were collected in 2020 than in 2023 at both beaches. This was unexpected, as both beaches were closed to visitors in 2020 due to the COVID-19 lockdown (Ryan et al., 2020a). One possible explanation is that rainfall events wash accumulated street litter in the storm drains into the ocean before washing ashore (Chitaka and von Blottnitz, 2019; Weideman, et al., 2020a). Litter loads in 2020 could have been influenced by local, land-based inputs such as accumulated litter in storm drains. This highlights the need for local interventions, such as the installation of storm drain socks and sustained public education campaigns, to prevent urban litter from entering coastal environments. Additionally, as a result of beach closures in 2020, there were no informal clean-up efforts, which would have contributed to the observed increase in litter. Although formal cleaning was suspended in both 2020 and 2023, informal clean-up efforts by beach visitors in 2023 may have helped reduce litter loads. This highlights the value of informal beach cleaning by environmentally conscious beach visitors.

In 2023, a higher number and greater mass of litter was collected on the wet sand than on the dry sand at both beaches. These results are consistent with those of Barnardo et al. (2021), which indicates the reliability of the dry and wet sand method in assessing beach litter loads. On wet sand at Muizenberg in 2023, the GLMs revealed that rainfall and offshore winds brought rain to the area, aiding the movement of street litter from the storm drains into the sea before washing ashore (Chitaka and von Blottniz, 2019; Weideman et al., 2020a). On the dry sand, while rain significantly increased litter on Sunrise Beach, this effect was not observed at Muizenberg. This was surprising given Muizenberg's higher visitor numbers. One possible explanation is that more informal cleaning by beachgoers occurs at Muizenberg, reducing visible litter even after rainfall. Another is the influence of the Zeekoevlei outfall, which carries urban litter into the sea before washing up at Sunrise (Rech et al., 2014; Ryan and Perold, 2021). This highlights the importance of environmentally conscious visitors in the reduction of beach litter at Muizenberg, as well the need for local interventions at Sunrise, such as educational campaigns and the installation of litter traps at Zeekoevlei outfall.

Composition

The composition of beach litter at Muizenberg was substantially different between years. In 2020, there was a larger proportion of plastic fragments, drink bottles and lids, and fishing/shipping items showed signs that they had been at sea for an extended period (with the presence of bites and of epibionts) before washing up on the beaches (Ryan, 2023; Ryan et al., 2024). During 2023, the presence of beach visitors likely caused an increase in the proportion of smoking related items (mainly cigarette butts) and paper items. These are items mostly recorded on urban streets (Ryan et al, 2020a) and beaches (Martinez-Ribes, 2007; Portz et al.; Weideman et al., 2020a; Barnardo et al., 2021; de Melo Nobre et al., 2021; Meakins et al., 2022; Yona et al., 2023). Studies have shown that these are litter items that could be left behind by urban beach visitors, especially during peak seasons (Martinez-Ribes, 2007; Portz et al., 2011; Barnardo et al., 2021). Martinez-Ribes (2007) found that smoking items (mainly cigarette butts) comprised almost 50% of the total litter that came from recreational activities during the holiday season. Another possibility is that rainfall could have facilitated the washing down of these items (mainly cigarette butts) onto beaches from urban streets through storm drains and rivers (Weideman et al., 2020a; Ryan et al., 2020a; Barnardo et al., 2021). On the streets of Cape Town and Durban, tobacco (mainly cigarette butts, which can be easily washed down storm drains and rivers) contributed 33% of the litter items (by number) (Ryan et al., 2020a). In addition, Barnardo et al. (2021) indicated that cigarette butts get stranded on beaches (wet sand) from rivers transporting urban street litter. However, they found that more cigarette butts were collected from the dry sand when beach visitor numbers were high (Barnardo et al., 2021). These results indicate that beachgoers are a major source of pollution at popular beaches.

At Sunrise beach, the litter composition was relatively constant between the sampling periods. Most of the litter items recorded were single use plastics such as food-related and plastic packaging. These are buoyant items which can be transported long distances by the ocean and get stranded along the beach. They are mostly found in storm drainage systems and rivers, which have been identified as significant sources of litter in the coastal environment (Chitaka and von Blottnitz 2019). Chitaka and von Blottnitz (2019), who conducted daily accumulation studies on beach litter along five beaches in Cape Town, found a predominance of single use plastic food packaging items. This has also been reported elsewhere (Munari et al., 2016; Nelms et al., 2017; de Ramos et al., 2021). The findings of Chitaka and Blottnitz (2019) align with this study, demonstrating that single use plastics dominate marine and coastal environments, and the majority of the litter originates from local, land-based sources.

When dry sand litter items were excluded from the PCA (Fig 2.2B), the difference in litter composition between the beaches and years was reduced. This indicates that dry sand litter items accounted for the difference in litter types when the beaches were empty of beachgoers in 2020. At Muizenberg beach, the dry sand litter composition mainly comprised paper and card-related items and smoking items (especially cigarette butts). In 2023, the dry and wet sand comparison was applied at both beaches to infer the contribution of beachgoers when the beaches were open and when they were closed to visitors. At Muizenberg beach (a more frequently visited beach), the dry sand litter (by number) contributed 23%, while 77% of the litter was recorded on the wet sand. At Sunrise beach (a less frequently visited beach), the dry sand litter contributed 6% and 94% of the litter was recorded on the wet sand. These results were consistent with those of Barnardo et al. (2021), who found that, at Bluewater Bay (a popular, tourist beach), the dry sand litter contributed <40% of the litter, whereas >60% was recorded on the wet sand. At Cape Recife (a secluded beach), the dry sand litter contributed <20% and >80% was recorded on the wet sand. This similarity in results suggests the viability of using dry sand to measure the contribution of litter from beachgoers.

Conclusions

This study showed that the dry sand contributed more litter at Muizenberg (frequently used by beachgoers) than at Sunrise (fewer visitors than Muizenberg) and that items typically associated with beachgoer activity, such as cigarette butts and paper or cardboard items, dominated on the dry sand at Muizenberg. This demonstrates the potential of dry sand litter as a proxy for beachgoer litter and supports the validity of the dry and wet sand comparison for understanding the contribution of beachgoers to beach litter. The results of this study support the hypothesis that litter on the dry sand can be used as a measure for litter originating from beachgoers.

Supplementary materials: Chapter 2

Table S2.1. Explored the effects of various factors on the total litter loads by number between the beaches (Muizenberg and Sunrise) over the sampling years using GLM. The factors examined included years (2020 and 2023), wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 50% of the deviance (variation). The intercept in the model includes beach (Muizenberg), sampling year (2020), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	7.133 ± 1.186	6.017	**0.0001**
Beach			
Sunrise	-0.742 ± 0.139	-6.486	**0.0001**
Year			
2023	-0.575 ± 0.221	-2.606	**0.0092**
Wind direction			
Onshore	0.248 ± 0.158	1.570	0.1165
Air temperature	-0.058 ± 0.043	-1.347	0.1779
Wind speed	-0.009 ± 0.055	-0.157	0.8750
Rain	0.028 ± 0.017	1.618	0.1056

Table S2.2. Explored the effects of various factors on the total litter loads by mass between the beaches (Muizenberg and Sunrise) over the sampling years using GLM. The factors examined included years (2020 and 2023), wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 59% of the deviance (variation). The intercept in the model includes beach (Muizenberg), sampling year (2020), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	1.654 ± 4.545	0.364	0.7182
Beach			
Sunrise	-0.860 ± 0.492	-1.747	0.0899
Year			
2023	-1.457 ± 0.844	-1.726	0.0937
Wind direction			
Onshore	0.705 ± 0.603	1.169	0.2506
Air temperature	0.142 ± 0.166	0.853	0.3998
Wind speed	0.572 ± 0.213	2.689	**0.0112**
Rain	-0.061 ± 0.065	-0.930	0.3593

Table S2.3. The number (n·100 m^{-1}·day^{-1}) and mass (g·100 m^{-1}·day^{-1}) of items collected daily in each sampling year at Muizenberg and Sunrise beach, giving the mean ± SD, median and interquartile range (IQR). In 2020, there were no beachgoers while in 2023, there were beachgoers. Accumulation at each beach was surveyed over 10 days in April in each year.

	Number of items		**Mass of items (g)**	
	2020	**2023**	**2020**	**2023**
		Muizenberg Beach		
Total	3430	2617	22654	3148
Mean ± SD	85.8 ± 15.9	65.4 ± 19.1	566.4 ± 811.4	78.7 ± 56.8
Median (IQR)	88.1 (79.8-95.1)	61.3 (52.4-74.8)	342.4 (189.0-493.7)	67.3 (44.4-88.9)
		Sunrise Beach		
Total	1731	1302	32221.1	952.8
Mean ± SD	43.3 ± 16.5	32.6 ± 25.8	805.5± 2101.2	23.8 ± 19.3
Median (IQR)	38.6 (31.9-58.1)	21.6 (12.5-48.9)	122.3 (51.8-189)	17.9 (10.1-30.3)

Table S2.4. Explored the effects of various factors on the litter loads by number at Sunrise beach over the sampling years using GLM. The factors examined included years (2020 and 2023), wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 37% of the deviance (variation). The intercept in the model includes sampling year (2020), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	8.605 ± 2.001	4.300	**0.0001**
Year			
2023	-0.961 ± 0.373	-2.573	**0.0101**
Wind direction			
Onshore	0.579 ± 0.269	2.154	**0.0321**
Air temperature	-0.149 ± 0.073	-2.032	**0.0422**
Wind speed	-0.064 ± 0.094	-0.681	0.4957
Rain	0.042 ± 0.029	1.446	0.1482

Table S2.5. Explored the effects of various factors on the litter loads by mass at Sunrise beach over the sampling years using GLM. The factors examined included years (2020 and 2023), wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 73% of the deviance (variation). The intercept in the model includes sampling year (2020), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	3.264 ± 5.237	0.623	0.5431
Year			
2023	-2.125 ± 0.974	-2.182	**0.0466**
Wind direction			
Onshore	1.521 ± 0.695	2.187	**0.0462**
Air temperature	-0.015 ± 0.192	-0.076	0.9407
Wind speed	0.750 ± 0.246	3.056	**0.0086**
Rain	-0.073 ± 0.075	-0.964	0.3513

Table S2.6. Explored the effects of various factors on the litter loads by number at Muizenberg beach over the sampling years using GLM. The factors examined included years (2020 and 2023), wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 57% of the deviance (variation). The intercept in the model includes sampling year (2020), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	4.159 ± 0.714	5.825	**0.0001**
Year			
2023	-0.142 ± 0.133	-1.070	0.2848
Wind direction			
Onshore	0.008 ± 0.094	0.082	0.9349
Air temperature	0.058 ± 0.026	2.227	**0.0259**
Wind speed	0.057 ± 0.033	1.736	0.0826
Rain	0.021 ± 0.010	2.050	**0.0403**

Table S2.7. Explored the effects of various factors on the litter loads by mass at Muizenberg beach over the sampling years using GLM. The factors examined included years (2020 and 2023), wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 54% of the deviance (variation). The intercept in the model includes sampling year (2020), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	0.786 ± 4.424	0.178	0.8600
Year			
2023	-1.207 ± 0.823	-1.467	0.1516
Wind direction			
Onshore	0.515 ± 0.587	0.877	0.3866
Air temperature	0.186 ± 0.162	1.151	0.2579
Wind speed	0.446 ± 0.207	2.149	**0.0388**
Rain	-0.041 ± 0.064	-0.648	0.5213

Table S2.8. A comparison of wet and dry sand litter counts ($n \cdot 100\ m^{-1} \cdot day^{-1}$) and mass ($g \cdot 100\ m^{-1} \cdot day^{-1}$) collected daily on Muizenberg and Sunrise beaches over 10 days in April 2023, showing the means ± standard deviations (SD), and medians and interquartile ranges (IQR).

	Number of items		Mass of items (g)	
	Muizenberg Beach			
	Dry	Wet	Dry	Wet
Total	611	2006	1357	1791
Mean (SD)	15.3 ± 9.6	50.2 ± 21.0	33.9 ± 55.70	44.8 ± 23.2
Median (IQR)	11.5 (8.4-21.6)	44.6 (41.9-50.9)	14.4 (8.2-21.3)	37.8 (27.6-58.9)
	Sunrise Beach			
	Dry	Wet	Dry	Wet
Total	75	1227	114	839
Mean (SD)	1.9 ± 2.4	30.7 ± 26.0	2.9 ± 4.9	21.0 ± 19.8
Median (IQR)	0.8 (0.0-3.1)	20.8 (10.1-48.8)	0.4 (0.0-3.69)	10.4 (7.6-30.3)

Table S2.9. Explored the effects of various factors on the dry sand litter loads by number at Muizenberg beach in 2023 using GLM. The factors examined included wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 32% of the deviance (variation). The intercept in the model includes wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	5.807 ± 4.067	1.428	0.1530
Wind direction			
Onshore	0.225 ± 0.363	0.620	0.5350
Air temperature	-0.055 ± 0.143	-0.385	0.7000
Wind speed	-0.139 ± 0.378	-0.366	0.7140
Rain	-0.020 ± 0.056	-0.357	0.7210

Table S2.10. Explored the effects of various factors on the dry sand litter loads by mass at Muizenberg beach in 2023 using GLM. The factors examined included wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 41% of the deviance (variation). The intercept in the model includes wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	-4.455 ± 10.714	-0.416	0.6950
Wind direction			
Onshore	-0.985 ± 0.957	-1.029	0.3510
Air temperature	0.359 ± 0.376	0.955	0.3830
Wind speed	0.639 ± 1.003	0.637	0.5520
Rain	-0.164 ± 0.149	-1.103	0.3200

Table S2.11. Explored the effects of various factors on the wet sand litter loads by number at Muizenberg beach in 2023 using GLM. The factors examined included wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 80% of the deviance (variation). The intercept in the model includes wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	4.298 ± 1.471	2.921	**0.0035**
Wind direction			
Onshore	-0.378 ± 0.132	-2.863	**0.0042**
Air temperature	0.600 ± 0.051	1.168	0.243
Wind speed	-0.072 ± 0.140	-0.513	0.6083
Rain	0.046 ± 0.021	2.251	**0.0244**

Table S2.12. Explored the effects of various factors on the wet sand litter loads by mass at Muizenberg beach in 2023 using GLM. The factors examined included wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 54% of the deviance (variation). The intercept in the model includes wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	3.431 ± 3.798	0.903	0.4080
Wind direction			
Onshore	0.563 ± 0.339	1.658	0.1580
Air temperature	-0.029 ± 0.133	-0.216	0.8370
Wind speed	0.503 ± 0.356	1.414	0.2160
Rain	-0.050 ± 0.053	-0.942	0.3890

Table S2.13. Explored the effects of various factors on the dry sand litter loads by number at Sunrise beach in 2023 using Hurdle model. The factors examined included wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The intercept in the model includes wind direction (offshore). The GLM was fitted a hurdle model to account for the zero nature of the data.

Count model coefficients (truncated negative binomial with log link):

	Estimate (±SE)	Z-value	P-value
Intercept	-51.309 ± 40.273	-1.274	0.2027
Wind direction			
Onshore	0.303 ± 0.863	0.351	0.7254
Air temperature	1.664 ± 1.310	1.271	0.2039
Wind speed	4.687 ± 3.297	1.422	0.1551
Rain	-0.664 ± 0.249	-2.670	**0.0076**

Zero hurdle model coefficients (binomial with log link):

	Estimate (±SE)	Z-value	P-value
Intercept	$1.174 \times 10^{-2} \pm 6.436 \times 10^{6}$	0	1
Wind direction			
Onshore	$1.192 \times 10^{-1} \pm 3.8326 \times 10^{5}$	0	1
Air temperature	$-3.988 \pm 1.471 \times 10^{5}$	0	1
Wind speed	$-2.256 \pm 9.465 \times 10^{5}$	0	1
Rain	$-9.333 \pm 1.587 \times 10^{5}$	0	1

Table S2.14. Explored the effects of various factors on the dry sand litter loads by mass at Sunrise beach in 2023 using GLM. The factors examined included wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 97% of the deviance (variation). The intercept in the model includes wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	-57.812 ± 10.169	-5.685	0.1108
Wind direction			
Onshore	0.753 ± 0.562	1.340	0.4080
Air temperature	1.998 ± 0.397	5.034	0.1248
Wind speed	4.517 ± 0.606	7.451	0.0849
Rain	-0.470 ± 0.558	-0.843	0.5543

Table S2.15. Explored the effects of various factors on the wet sand litter loads by number at Sunrise beach in 2023 using GLM. The factors examined included wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 52% of the deviance (variation). The intercept in the model includes wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	-15.615 ± 5.089	3.068	**0.0022**
Wind direction			
Onshore	0.747 ± 0.459	1.627	0.1038
Air temperature	-0.463 ± 0.179	-2.591	**0.0096**
Wind speed	-0.500 ± 0.477	-1.048	0.2946
Rain	0.083 ± 0.071	1.174	0.2404

Table S2.16. Explored the effects of various factors on the wet sand litter loads by mass at Sunrise beach in 2023 using GLM. The factors examined included wind strength and direction (onshore and offshore), maximum air temperature, and rainfall. The model explained 72% of the deviance (variation). The intercept in the model includes wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	17.546 ± 5.063	3.466	**0.0179**
Wind direction			
Onshore	1.048 ± 0.452	2.317	0.0683
Air temperature	-0.555 ± 0.178	-3.124	**0.0261**
Wind speed	-0.636 ± 0.474	-1.341	0.2375
Rain	0.082 ± 0.070	1.164	0.2969

Table S2.17. Proportion by number and mass of different categories found in the sampling years (2020 and 2023) at Sunrise beach

Litter Category	Number of items		Mass of items	
	2020	**2023**	**2020**	**2023**
Paper and card items	<1%	1%	<1%	4%
Smoking-related items	4%	4%	<1%	4%
Snack food packaging	10%	15%	<1%	12%
Sweet packaging	13%	10%	<1%	6%
Drink bottles and lids	15%	3%	4%	14%
Fast-food packaging	1%	6%	<1%	2%
Other food packaging	13%	32%	<1%	27%
Other bottles and lids	1%	<1%	10%	<1%
Other packaging items	19%	17%	3%	20%
Disposable items	1%	<1%	<1%	1%
Sewage-related items	2%	1%	<1%	<1%
Fishing and shipping	7%	1%	78%	1%
Other user items	2%	<1%	1%	1%
Plastic fragments	13%	8%	1%	8%
Non-plastic items	1%	<1%	1%	<1%
Total	**1731**	**1302**	**32221.1**	**952.8**

Table S2.18. Proportion by number and mass of the different litter categories found on the dry and wet sand in 2023 at Sunrise beach.

Litter Category	Number of Items		Mass of Items	
	dry	**wet**	**dry**	**wet**
Paper and card items	17%	<1%	20%	2%
Smoking-related items	17%	3%	19%	2%
Snack food packaging	7%	16%	4%	13%
Sweet packaging	20%	9%	7%	5%
Drink bottles and lids	5%	3%	31%	12%
Fast-food packaging	5%	7%	2%	2%
Other food packaging	4%	33%	2%	30%
Other bottles and lids	<1%	<1%	<1%	1%
Other packaging items	15%	18%	6%	22%
Disposable items	<1%	<1%	<1%	1%
Sewage-related items	<1%	1%	<1%	<1%
Fishing and shipping	7%	1%	7%	1%
Other user items	<1%	<1%	<1%	1%
Plastic fragments	3%	8%	1%	8%
Non-plastic items	<1%	<1%	<1%	<1%
Total	**75**	**1227**	**113.9**	**838.9**

Table S2.19. Proportion by number and mass of different categories found in the sampling years (2020 and 2023) at Muizenberg beach.

Litter Category	Number of items		Mass of items	
	2020	**2023**	**2020**	**2023**
Paper and card items	<1%	8%	<1%	6%
Smoking-related items	4%	38%	<1%	11%
Snack food packaging	9%	7%	1%	4%
Sweet packaging	9%	12%	1%	4%
Drink bottles and lids	22%	4%	21%	23%
Fast-food packaging	1%	3%	<1%	2%
Other food packaging	9%	11%	1%	7%
Other bottles and lids	1%	<1%	7%	<1%
Other packaging items	7%	5%	3%	6%
Disposable items	1%	1%	<1%	1%
Sewage-related items	3%	1%	1%	<1%
Fishing and shipping	8%	1%	53%	1%
Other user items	3%	1%	7%	9%
Plastic fragments	23%	6%	2%	4%
Non-plastic items	1%	2%	2%	22%
Total	**3430**	**2617**	**22654.1**	**3147.9**

Table S2.20. Proportion by number and mass of the different litter categories found on the dry and wet sand in 2023 at Muizenberg beach.

Litter Category	Number of Items		Mass of Items	
	dry	**wet**	**dry**	**wet**
Paper and card items	30%	1%	11%	2%
Smoking-related items	27%	41%	4%	16%
Snack food packaging	3%	8%	1%	5%
Sweet packaging	9%	13%	2%	6%
Drink bottles and lids	2%	5%	31%	16%
Fast-food packaging	5%	2%	2%	2%
Other food packaging	10%	11%	3%	10%
Other bottles and lids	<1%	<1%	<1%	<1%
Other packaging items	4%	5%	5%	7%
Disposable items	2%	1%	1%	1%
Sewage-related items	<1%	1%	<1%	<1%
Fishing and shipping	<1%	1%	1%	1%
Other user items	2%	1%	10%	8%
Plastic fragments	2%	7%	1%	6%
Non-plastic items	2%	2%	27%	19%
Total	**611**	**2006**	**1357.1**	**1790.8**

Chapter 3: Seasonal fluctuations in beachgoers litter: A comparison of two South African beaches

Large numbers of beachgoers on Muizenberg beach in summer. Photo: Nwaigwe Chukwudi

Abstract

Reducing litter on beaches requires an understanding of key pollution sources. Litter on beaches could come from various sources, including beachgoers. To quantify the contribution of recreational activities to beach litter loads, I recorded seasonal variation in the daily accumulation on dry sand (mainly originating from beachgoers) and on wet sand (mainly washing ashore) at two adjacent beaches with different numbers of beachgoers in False Bay, South Africa. Accumulation rates were compared to beach visitor numbers to assess seasonal influences on litter loads. Overall (dry and wet sand combined), the daily accumulation rate of litter (by number) at Muizenberg, a popular recreational beach, was two times greater in the winter rainy season compared to other seasons. In contrast, at Sunrise, a less frequently visited recreational beach, it was two times greater in spring compared to other seasons. The daily accumulation rate of litter on dry sand (by number) was two times greater in summer than in other seasons at both beaches. The litter load on dry sand at Muizenberg was approximately 19 and 10 times greater than at Sunrise by number and mass respectively, indicating the significance of beachgoer numbers to beach litter loads, especially during summer. Overall

(dry and wet sand combined), dry sand litter at Muizenberg contributed 35% by number and 46% by mass, whereas at Sunrise it made up 4% by number and 14% by mass. The higher proportion of mass of items at the beaches is due mainly to drink bottles (made from glass). Dry sand litter on both beaches included a higher proportion by number of smoking items (especially cigarette butts) and items made from paper (serviettes, paper packaging, newspaper, and receipts). This study highlights the need for improved education of beachgoers to reduce littering and encourages increased beach cleaning efforts, especially during summer.

Introduction

Beaches and coastal areas offer valuable ecosystem services and resources, such as habitat and food provision, climate regulation and recreational services. The provision of these services is vital to human livelihoods and can be particularly profitable for the tourism industry, a key socioeconomic sector in coastal communities (Mouat et al., 2010; Nachite et al., 2019; Arabi and Nahman, 2020). One of the ways beaches are economically valuable is through beach tourism (Mouat et al., 2010; Arabi and Nahman, 2020). In South Africa, tourism contributes significantly to the economy, providing employment to 9.8% of workers and contributing R125 billion (US$ 8.2 billion) to the Gross Domestic Product (GDP) in 2016 (2.9% of GDP) (Ballance et al., 2000; Arabi and Nahman, 2020). International tourists contributed 3.5% to South Africa's GDP in 2022 (StatsSA, 2024). In Cape Town alone, 12% of foreign tourist activities involve beach visits (Arabi and Nahman., 2020). However, anthropogenic activities produce waste that is left on beaches, which negatively impacts these coastal environments (Arabi and Nahman, 2020; de Ramos et al., 2021).

The prevalence of litter on beaches is increasingly reported globally (Veiga et al., 2016; Mouat et al., 2010). Beach litter can reduce the aesthetic value of beaches, pose health risks to beachgoers, and discourage beach visits, which can negatively affect the tourism sector and reduce socio-economic potential (Ballance et al., 2000; Arabi and Nahman, 2020). According to Ballance et al. (2000), a key consideration for foreign tourists when selecting a beach on the Cape Peninsula is cleanliness. They found that 97% of visitors would avoid beaches with more than 10 litter items per square metre, resulting in the reduction of the recreational value of beaches (Ballance et al., 2000). To mitigate these negative effects on the tourism sector in South Africa, beach cleaning has increased over time (Ballance et al., 2000; Arabi and Nahman, 2020). A report by the City of Cape Town (2021) revealed that the cost of beach clean-ups is estimated at R13 million annually. Given this expense and the reduced socio-economic value of beaches, the identification of beach litter sources is necessary to devise appropriate mitigation strategies to reduce the amount of litter on beaches (Ballance et al., 2000; Veiga et al., 2016; Falk-Anderson, 2021).

Beach litter can originate from a range of sources (Chapter 1). Differentiating among these sources remains a challenge (Veiga et al., 2016; Falk-Anderson, 2021). A major source of litter on beaches is tourism and recreational activity (Santos et al., 2009; Portz et al., 2011; Zhou et al., 2015; Arun et al., 2016; Asensio-Montesinos et al., 2020). Studies have estimated that recreational activities from beachgoers contribute a higher proportion of beach litter loads on urban, popular beaches than they do on village or secluded beaches (Prevenios et al., 2018; Okuku et al., 2020; Barnardo et al., 2021). For instance, a study along the South African coast showed recreational activities contributed 39% at an urban beach and <20% at a secluded, rural beach (Barnardo et al., 2021). Seasonality plays an important role in the accumulation of litter loads on beaches (Martinez-Ribes et al., 2007; Bat et al., 2022; Erüz, et al., 2023). For instance, studies have shown that, with an increase in tourist activities during the summer, higher litter loads are generated on beaches (Martinez-Ribes et al., 2007; Tourinho and Fillmann, 2011; Silva et al., 2016; de Ramos et al., 2021). However, no studies have been published to date that have measured the influence of seasonality on the contribution of beachgoers to beach litter loads using the dry and wet sand method (Chapter 2).

Various approaches have been employed in the attempt to differentiate the contribution of beachgoers from other sources of beach litter and to identify the relative proportion contributed by each source, but all have drawbacks (Veiga et al., 2016; Falk-Anderson, 2021). The dry and wet sand method applied by Barnardo et al. (2021) distinguishes between litter on the dry sand (likely from beachgoers) and litter on the wet sand (likely from offshore sources) to understand how beach visitors influence beach litter loads (Chapters 1 and 2). This chapter used the dry and wet sand method to assess the seasonal impact on beachgoers as a source of beach litter at two beaches with differing visitation rates in False Bay, South Africa.

Methods

Site description

Two 400 m stretches of the long northern beach in False Bay were chosen for sampling: Muizenberg corner and east of Sunrise Beach (Chapter 2, Fig. 2.1). The two beaches differ substantially in the number of visitors, with at least 20 times more visitors at Muizenberg than Sunrise beach.

Data collection

Daily litter accumulation surveys were carried out for 10 days every three months at the two study sites. Sampling on both beaches was carried out on the same day. To account for seasonal variation, the sampling days were chosen to represent each season of the year. The spring collection was from 27 October – 5 November 2022; summer from 27 January – 5 February

2023; autumn from 23 April – 2 May 2023 and winter from 23 July – 1 August 2023. Sampling times were chosen to avoid spring tides to minimize the risk of exhuming old, buried litter (Ryan et al., 2020b). After initial clean ups, all litter items within each 400 m transect were collected for 10 days in each sampling season from the water's edge into the backshore (see Chapter 2 for an explanation of the backshore). Litter items were collected in two areas: the wet and dry sand (see Chapter 2 for more details). All anthropogenic litter items larger than 10 mm were collected and taken to the University of Cape Town where they were processed and classified into 15 broad functional categories (see Chapter 2 for more details on data processing and classification).

Weather data were obtained from the SAWS at Cape Town Airport, 18 km NE of the study site. In summer, there were predominantly southerly winds (nine onshore winds and one offshore wind), with only one minor rainfall event (0.2 mm). Southerly winds also blew during all but one of the autumn sampling days and there were five rainfall events, ranging from 0.2 mm to 24.1 mm. By contrast, in winter, northerly (offshore) winds predominated and there was rainfall on all except one of the sampling days, ranging from 0.1 mm to 13.5 mm. The weather during the sampling days in spring was very similar to those in summer, differing only in that there were no offshore winds, and the single rainfall event was more substantial (2.9 mm). The daily number of beachgoers at Muizenberg was obtained from Shark Spotters, a local shark safety organization that keeps hourly records of beachgoers entering the sea (sharkspotters.org.za), and the daily maximum number of beachgoers was used for the analysis as an index of beach usage. People who did not enter the sea were not counted. To understand how the number of beachgoers varies with seasons, beachgoers data were collected over one-year, ensuring all seasons were represented: summer = December to January, autumn = March to May, winter = June to August, and spring = September to November (Fig 3.2). The trend line indicates a 13-day moving average from the raw data (Fig 3.2).

Data analyses

All statistical analyses were conducted using R version 4.2.3 (R Core Team, 2024). I used Generalized Linear Models (GLMs) to determine the factors that explained the variations in the amount of litter accumulating per day between beaches over the sampling seasons and the sand zones (dry and wet sand). I fitted the GLMs using the *glm* function from the *MASS* and *stats* packages of R (Venables and Ripley, 2002; Core Team 2024). I modelled the number and mass of items per day as a function of beach (site), sampling seasons, and days of the week (weekdays vs. weekends), along with daily rainfall, wind direction, the maximum number of beachgoers, and maximum air temperature. Weekdays were defined as Monday – Friday, while weekends = Saturday and Sunday. I lagged the weather variables, including rainfall, wind strength and its direction, maximum air temperature, and days of the week, by one day as a function of litter items recorded over the previous day. I used a negative binomial distribution to model the number of litter items, accounting for overdispersion, and applied a Gamma distribution for the mass of litter items due to its skewness and semi-continuous nature. At Sunrise, I analysed the mass of dry sand litter using a Gaussian distribution. Since the Gaussian distribution assumes normality, I first performed a Shapiro-Wilk test to assess whether the mass of dry sand litter followed a normal distribution. As the data were not normally distributed, I applied a log transformation and repeated the Shapiro-Wilk test to confirm whether the transformation improved normality. After the transformation, the data were confirmed to be normally distributed. I also used GLMs to determine the factors that explained the variations in the number of beachgoers per day over a one-year period at Muizenberg beach. The number of beachgoers was modelled as a function of season where the summer months were December, January, and February; the autumn months, March, April, and May; the winter months, June, July, and August; and the spring months, September, October, and November. In addition, factors such as days of the week (weekdays vs weekends), air temperature, wind speed, and rainfall were considered. Weekdays were defined as Monday–Friday, while weekends = Saturday, Sunday, and public holidays. I used a negative binomial distribution to model the number of beachgoers, accounting for overdispersion in the data. Lastly, I performed linear correlation analysis to test if there was a relationship between the daily accumulation on the dry and wet sand separately with the maximum number of beachgoers, with the number of beachgoers lagged by one day. I presented data as mean and SD or as median and IQR ranges where data were strongly skewed. For all tests, I applied a significance level of 0.05.

Results

Litter-loads

Across the beaches and sampling seasons, 22 783 items weighing 62.43 kg were recorded. The amount of litter (dry and wet sand combined) accumulating at Muizenberg beach was significantly greater than at Sunrise beach both in terms of the number (two times greater) and mass of litter items (three times greater; Tables S3.1, S3.2, and S3.3). Litter accumulation was also greater in winter, especially following rainfall events (Table S3.2). The greater litter loads at Muizenberg occurred on both dry and wet sand. On the dry sand, the total number of items recorded over the four sampling seasons at Muizenberg was 19 and 10 times greater than at Sunrise beach by number and mass, respectively (Tables 3.1, S3.4, and S3.5). More items tended to accumulate on dry sand in summer and when there was no rain (Tables 3.1, S3.4, and S3.5). On the wet sand, the total number of items at Muizenberg was two times greater than that at Sunrise beach by number and mass (Tables 3.1, S3.6, and S3.7). More items were recorded during winter following rainfall events, especially on weekdays compared to weekends (Table 3.1 and S3.6).

At Muizenberg, the number of litter items recorded on the dry and wet sand combined was approximately two times greater during the winter rainy season than the other seasons (Table S3.8). On the dry and wet sand combined, the mass of litter items was approximately 2 to 6 times greater during winter than other seasons (Table S3.8). The GLMs showed that more litter items (by number and mass) were recorded during the winter rainy season than in other seasons (Tables 3.1, S3.9 and S3.10), with more items collected following rainfall events (Tables 3.1 and S3.9).

At Sunrise beach, the number of litter items on the dry and wet sand combined was two times greater during spring than in other seasons (Table S3.8). By mass, the litter items measured were five to seven times greater during spring than in other seasons (Table S8). The GLMs showed that there was no significant difference among the sampling seasons in the number of items collected and fewer items were collected following weekend days compared to weekdays with an increase during rainfall events (Tables 3.1 and S3.11). By mass, however, greater litter loads were measured during spring and summer with more southerly winds washing more litter items ashore (Table S3.12).

At Muizenberg, dry sand litter comprised 19% to 60% by number and 6% to 80% by mass of daily litter accumulation (Table S3.13). The daily accumulation of dry sand litter items was significantly greater in spring and summer than in other seasons, both in terms of number and mass of litter (Tables 3.1, S3.14, and S3.15). By comparison, the daily accumulation of wet sand items was greatest during winter (Tables 3.1, S3.16, and S3.17), when rainfall events increase the number of items (Tables 3.1 and S3.16).

On the dry sand, there was a significant positive correlation between the number of litter items and the number of beachgoers in summer ($r = 0.93$, $P < 0.001$, Fig. 3.1A), but no correlation was observed in other seasons (r = 0.16, P = 0.40; Fig. 3.1A). The strong correlation between the dry sand litter and number of beachgoers was because of intense usage of the beach during the peak season (summer). By comparison, the amount of wet sand litter was negatively correlated with the number of beachgoers during winter, and this effect was not significant (winter: r = -0.50, P = 0.14: other seasons: r = -0.015, P = 0.94; Fig. 3.1B). The negative correlation between the wet sand litter and number of beachgoers especially during winter was driven by days when there was more litter and there were fewer beachgoers due to rainfall events. The number of beachgoers at Muizenberg is influenced by season, with greater numbers recorded during summer, peaking in the December-January holiday period (Fig. 3.2 and Table S3.18). There are more beachgoers on hot and relatively windless weekend days (Table S3.18). Rainfall had a marginally significant negative impact on numbers of beachgoers (Table S3.18).

At Sunrise beach, dry sand litter items ranged from 1% to 8% by number and 2% to 22% by mass (Table S3.19). Fewer items were collected during winter than in other seasons (Tables 3.1 and S3.20), and litter items by mass was greater during summer compared to other seasons (Table S3.21). On the wet sand, there was no significant difference in the number of items among seasons (Tables 3.1 and S3.22) Fewer items were recorded following weekends and holidays than weekdays and there was an increase following rainfall event (Tables 3.1 and S3.22). However, litter items by mass were greater in summer and spring than in other seasons (Table S3.23).

Table 3.1. GLMs outputs showing significant effects of wind strength and direction (onshore and offshore winds), air temperature, and rainfall on the number of litter items accumulating daily on Muizenberg and Sunrise beaches.

Factors affecting litter loads	Estimate (± SE)	Z-value	P-value
All litter at both beaches among seasons			
Sunrise (< Muizenberg)	-0.902 ± 0.139	-6.486	0.0001
Winter (< in other seasons)	0.606 ± 0.305	1.988	0.0469
Rain (> after rain events)	0.078 ± 0.021	3.717	0.0002
All dry sand litter at both beaches among seasons			
Sunrise (< Muizenberg)	-2.979 ± 0.190	-15.683	0.0001
Rain (< after rain events)	-0.075 ± 0.031	-2.428	0.0152
All wet sand litter at both beaches among seasons			
Sunrise (< Muizenberg)	-0.496 ± 0.150	-3.310	0.0009
Winter (< in other seasons)	0.702 ± 0.328	2.143	0.0321
Weekend (< weekdays)	-0.348 ± 0.158	-2.196	0.0281
Rain (> after rain events)	0.094 ± 0.023	4.160	0.0001
Litter (dry and wet sand combined) at Muizenberg seasonally			
Winter (< in other seasons)	0.723 ± 0.269	2.687	0.0072
Rain (> after rain events)	0.066 ± 0.019	3.581	0.0003
Litter (dry and wet sand combined) at Sunrise seasonally			
Weekend (< weekday)	-0.603 ± 0.304	-2.571	0.0101
Rain (> after rain events)	0.098 ± 0.033	2.919	0.0035
Litter (dry sand) at Muizenberg seasonally			
Summer (< in other seasons)	1.873 ± 0.525	3.565	0.0004
Wind speed (< wind strength)	-0.185 ± 0.081	-2.290	0.0220
Litter (wet sand) at Muizenberg seasonally			
Winter (< in other seasons)	0.837 ± 0.364	2.300	0.0214
Rain (> after rain events)	0.089 ± 0.025	3.564	0.0004
Litter (dry sand) at Sunrise seasonally			
Winter (> in other seasons)	-2.005 ± 0.827	-2.424	0.0153
Rain (< after rain events)	-0.190 ± 0.093	-2.033	0.0420
Litter (wet sand) at Sunrise seasonally			
Weekend (< weekdays)	-0.709 ± 0.242	-2.923	0.0350
Rain (> after rain events)	0.110 ± 0.035	3.184	0.0015

Composition

The dry sand litter composition at both beaches across all four seasons was predominantly smoking related items (especially cigarette butts) and paper items (such as paper serviettes, newspapers, and receipts) by number (Table S3.24, S3.26), but by mass, drink bottles (especially glass bottles) predominated (Table S3.25, S3.27). The wet sand litter composition differed according to beach and season (Table S3. 24, S3.26). Smoking related items (mainly cigarette butts) were common at Muizenberg whereas single use plastics (mainly packaging items) predominated at Sunrise by number (Table S3. 24, S3.26). By mass, however, heavier items were common at Muizenberg (such as processed wood, marine crate, glass drink bottles), while at Sunrise, it was mainly single plastic packaging related items (Table S3.25, S3.27). On the dry sand at Muizenberg, the proportion of paper items ranged from 18% to 30%, while smoking related items (mainly cigarette butts) ranged from 22% to 37% of the total seasonally, with more items collected during summer compared to other seasons (Table S3.24). By mass, the proportion of drink bottles ranged from 26% to 60% of the total seasonally, with more items collected in summer compared to other seasons (Table S3.25). On the wet sand, most of the beach litter comprised smoking related items (mainly cigarette butts) by number (Table S3.24) during winter. The mass of items on the wet sand in winter was significantly increased by a few non-plastic items (eg, a car tyre), which accounted for 87% of the total mass (Table S3.25).

At Sunrise beach, the dry sand litter composition was mostly smoking related items (mainly cigarette butts), which ranged from 17% to 55% of the total seasonally, with more items recorded in summer compared to other seasons (Table S3.26). By mass, the proportion of drink bottles and lids (especially glass bottles) ranged from 31% to 83% of the total seasonally, with more items collected in summer compared to other seasons (Table S3.27) On the wet sand, most of the litter comprised single use plastic related items used for packaging (by number and mass) (Table S3.26).

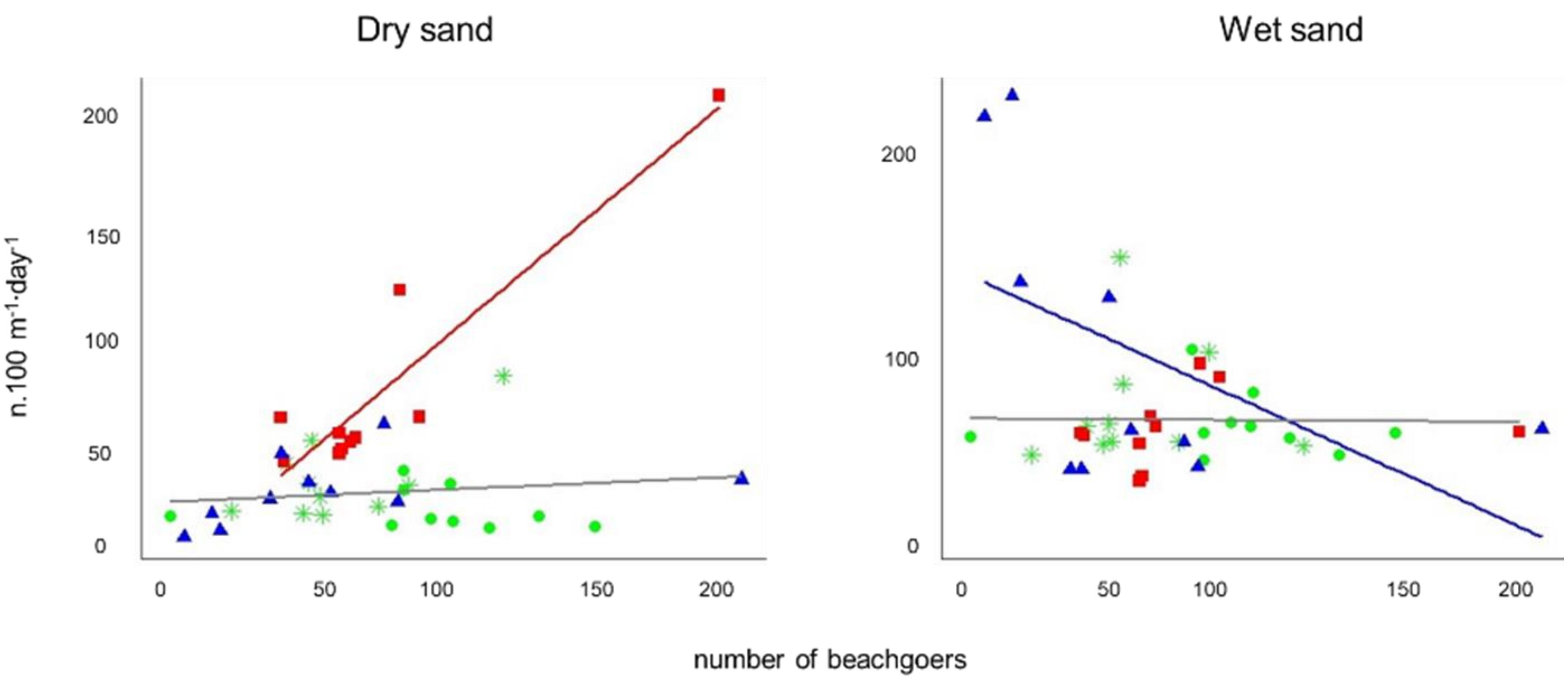


Fig. 3.1. Relationship between the daily accumulation rate (by count) on dry and wet sand and the maximum number of beachgoers from the previous day across sampling seasons. The colours represent different seasons for both dry and wet sand: red for summer, blue for winter, and green for spring and autumn. The shapes correspond to seasons in both dry (left panel) and wet sand (right panel): squares for summer, circles for autumn, asterisks for spring, and triangles for winter.

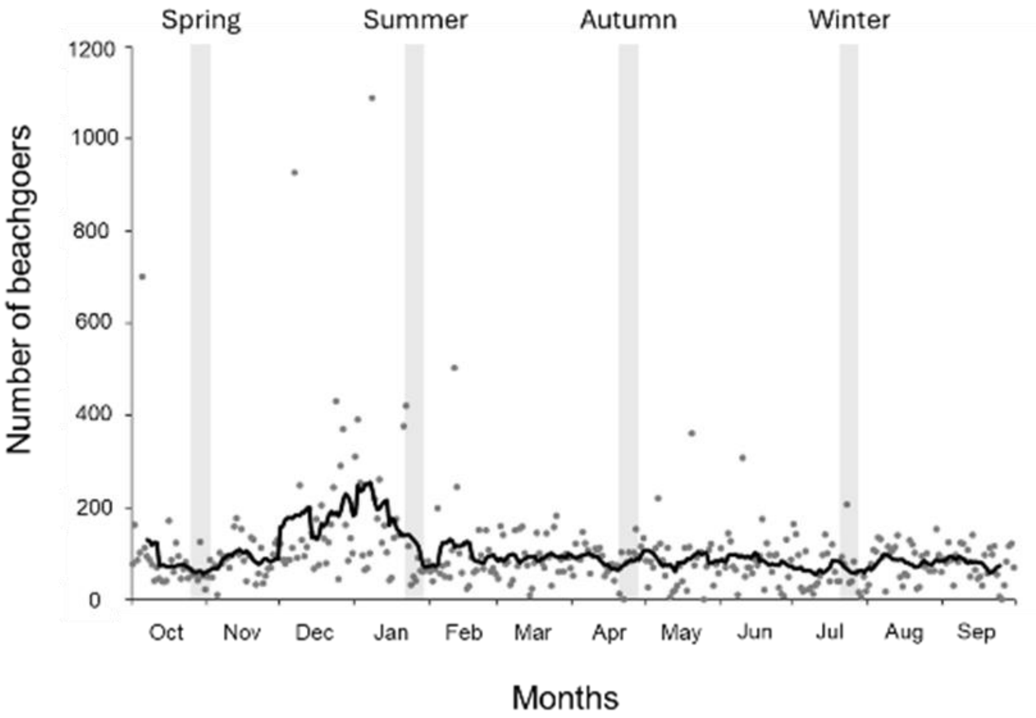


Fig. 3.2. The maximum number of people in the water (including swimmer, paddlers, bathers, and surfers) recorded each day at Muizenberg beach by the Shark Spotters from October 2022 to September 2023. The 10-day litter collection periods are shown by shaded grey bars.

Discussion

In this chapter I assess how litter accumulation rates vary seasonally at two beaches with different numbers of visitors. Recreational activities had a major impact on beach litter composition at the more populated Muizenberg beach, especially in summer. Litter such as paper and smoking related items, particularly cigarette butts, were frequently recorded when most beachgoers were present. In Chapter 2, I tested the efficacy of using the dry sand as an indicator for beachgoer litter and found that the dry sand litter composition at Muizenberg (popular tourist beach) comprised many more paper/card and smoking related items than the litter found washed up on wet sand. This was consistent with the findings of this chapter. The 2023 data (autumn) used in chapter 2 to compare with data collected during COVID-19 (2020) was used in this chapter for the seasonal comparison.

Litter-loads

There was a significant increase in the amount of daily dry sand litter accumulation during summer, the peak season, compared to other seasons. An increase in the number of beachgoers during summer, especially during weekends when the weather conditions are favourable (warm temperatures, low wind speeds, and no rainfall) were the likely causes of this increase. To further confirm the factors influencing the number of beachgoers, the analysis of the beachgoer's number over a one-year period revealed that summer months, weekend days (including holidays), low wind speeds, and no rainfall events influence the number of beachgoers at Muizenberg. This outcome mirrors the findings of other studies that greater litter loads are generated during summer when there is an increase in the number of beachgoers (Martinez-Ribes et al., 2007; Portz et al., 2011; Silva et al., 2016; Araujo et al., 2018; Aytan et al., 2019; Okuku et al., 2020; Barnardo et al., 2021). Barnardo et al. (2021) found that at a Bluewater Bay, a popular tourist beach, greater litter loads were collected on the dry sand during summer than winter.

Greater numbers of beachgoers in other seasons did not result in greater litter loads, indicating a difference in type of beachgoer: those who visit during summer seem more likely to litter, while those who visit in other seasons are less likely to litter. This supports the conclusion that, with an increase in the number of beach visitors, especially summer, greater litter loads are recorded, indicating that beachgoers are a major source of litter on Muizenberg beach.

In my study, the dry sand litter (from beachgoers) contributed 35% (by number) at Muizenberg (popular tourist beach) and 4% (by number) at Sunrise (less popular beach). This result corresponds with the dry and wet sand method used in Port Elizabeth by Barnardo et al. (2021), who estimated that dry sand accounted for 39% at Bluewater Bay (popular tourist beach) and 18% at Cape Recife (less popular beach). In addition, they estimated that during summer, dry sand litter contributed 40% at Bluewater Bay. In my study, the dry sand litter in summer contributed 60%. This little difference in results could be because Barnardo et al. (2021) sampled over only two months in summer: October and February, which are months that fall outside of the peak season for beachgoers.

A discrepancy in findings can also be attributed to the various methodologies used to determine the contribution of beachgoers to beach litter. Of the 16 studies that used the attribution by type, indicator items, or matrix scoring methods and sampled only urban beaches, only six reported (Table 2) a less than 50% contribution by beachgoers to beach litter (8% - 37%). The majority of these studies (Table 2) reported results of over 50% (52% - 94%).

A different picture emerged for the litter loads on the wet sand at Muizenberg. There was a significant increase during the winter rainy season compared to other seasons. The likely contributors to this increase were rainfall events during winter, which would have facilitated the flushing of litter from the Zandvlei River and storm drains into False Bay, near the Muizenberg sample site (Martinez-Ribes et al., 2007; Rech et al., 2014; Silva et al., 2016; Weideman et al., 2020a; Ryan and Perold., 2021). A study that assessed the influence of beach usage, rainfall, and location on the abundance of litter at four Brazilian beaches concluded that greater litter loads (by number) were collected during the rainy season (Silva et al., 2016). The authors suggest that a major contributing factor to this increase in the number of items during the rainy season was the flushing of litter from rivers and storm drainage systems. This supports the finding that a river such as Zandvlei is a prominent source of litter on Muizenberg beach.

The daily accumulation rate of litter on the dry sand at Sunrise showed a similar pattern to Muizenberg in summer, although the number of litter items on the dry sand is much less than Muizenberg. This is to be expected, because Sunrise attracts far fewer visitors than Muizenberg. Barnardo et al. (2021) found that fewer items were collected on the dry sand at a secluded beach (Recife Cape) than at a popular tourist beach (Bluewater Bay). In contrast to the litter on the dry sand at Sunrise beach, there was a constant influx of litter items washing up on the wet sand during all sampling seasons, with more litter items recorded, especially during spring. This was due to onshore winds, which facilitated the transport and deposition of litter from offshore sources. This indicates the need for daily sampling to allow for the capture of episodic events that can account for substantial and sudden fluctuations in accumulation rates. Studies have shown that onshore winds increase litter loads on beaches (Eriksson et al., 2013; Duhec et al., 2015; Chitaka and von Blottniz, 2019; Thiel et al., 2021). In addition, the wet sand at Sunrise showed a decrease in the number of litter items over the weekends. The reduction in beach litter over weekends may be attributed to increased informal cleaning by beachgoers, some of whom pick up litter or clean up after themselves. This highlights the valuable role of informal beach cleaning in maintaining cleaner shorelines.

Composition

The composition of the dry sand litter at both beaches across all sampling seasons was dominated by smoking related items (especially cigarette butts) and paper items (such as serviettes, newspapers and receipts), all of which suggest a strong linkage with beachgoers activities. Studies have shown that items such as these are typically associated with recreational activities on beaches (Martinez-Ribes et al., 2007; Santos et al., 2009; Portz et al., 2011; Araújo et al., 2018; Mghili et al., 2020; Barnardo et al., 2021; de Melo Nobre et al., 2021; Meakins et al., 2022). Paper items were the second most abundant litter type in the dry sand zone, following plastic, on beaches at uMhlanga and Amanzimtoti in KwaZulu-Natal, highlighting the association of paper and card with beachgoer activity (Meakins et al., 2022). At Muizenberg, the proportion of these items peaked during summer, the season in which there is an increase in the number of beachgoers. These results are consistent with those of other studies, such as that of Martinez-Ribes et al (2007), who found that cigarette butts were the most common litter items on beaches on the Balearic Islands during summer, the high tourist season, and Barnardo et al. (2021), who also found more cigarette butts during summer at a popular tourist beach. These findings suggest that recreational activities are a major factor influencing the composition of dry sand litter.

Smoking-related items also predominated the wet sand litter at Muizenberg during the winter rainy season, when they accounted for almost half of all litter items. In contrast, the wet sand composition at Sunrise beach was mostly single use plastic items in all seasons, such as polystyrene trays and barrier and carrier bags. This difference in the wet sand composition at the two beaches across the sampling seasons is expected. At Muizenberg, cigarette butts were mostly collected on wet sand and mainly in winter. Studies have shown that these are items that can be washed into storm drains and rivers and get stranded on beaches (Martinez-Ribes et al., 2007; Rech et al., 2014; Silva et al., 2016; Ryan et al., 2020a; Weideman et al., 2020a; Barnardo et al., 2021). A study by Ryan et al. (2020a) showed that 33% of the street litter in Cape Town (Muizenberg) and Durban (Kloof) came from tobacco products (mainly cigarette butts). This indicates that the composition of beach litter at Muizenberg is significantly impacted by urban factors. Varying litter transport processes contributed to the differences observed between the sites. At Sunrise, mainly single use plastic packaging related items were common (Chitaka and von Blottnitz, 2019). These are lightweight and buoyant items which can be easily carried away by ocean currents and wind over a long distance before washing ashore on beaches. Plastic packaging items (mainly food and other packaging items) has long been a serious environmental issue in South Africa and remains one of the most prevalent plastic litter items on South African beaches (Chitaka and von Blottnitz, 2019; Ryan et al., 2020a; Weideman et al., 2020b). For example, a daily accumulation study on five beaches in Cape Town found that most litter items were single use plastics relating to food and packaging (Chitaka and von Blottnitz, 2019). This aligns with the findings of my study, that single-use plastics are the most common component of marine debris, and that the majority of this debris originates from local land-based sources. Mitigation measures should be geared toward reducing plastic pollution in urban coastal areas.

Conclusions

This study showed that beachgoers were the primary source of litter seasonally (mostly during summer) on the dry sand, whereas the river and the storm water drainage system were the sources of wet sand litter mainly in the winter rainy season. My findings highlight the necessity of better waste management, such as the installation of more waste bins, and of beach cleaning services during the summer. This could be coupled with educational campaigns targeting beachgoers and aimed at reducing the input at source. During winter, efforts should be focussed on removing litter around the river mouth and in storm water drainage systems. This would assist in combatting and reducing the leakage of plastics from land-based sources into wetlands and the sea.

Supplementary materials: Chapter 3

Table S3.1. The total litter-loads of the dry and wet sand litter combined, dry sand litter and wet sand litter between both beaches in all sampling seasons by number (n·100 m^{-1}·day^{-1}) and mass (g·100 m^{-1}·day^{-1}), showing the means ± standard deviations (SD), and medians and interquartile ranges (IQR).

	Dry and wet sand combined		Dry sand		Wet sand	
	Muizenberg	Sunrise	Muizenberg	Sunrise	Muizenberg	Sunrise
	number		number		number	
Total	15933	6850	5622	300	10311	6550
Mean (SD)	99.58 ± 60.58	42.81 ± 41.57	35.14 ± 36.68	1.88 ± 2.59	64.44 ± 55.64	40.94 ± 41.57
Median (IQR)	80.00 (60.4-109.3)	27.75 (13.4-51.2)	27.12 (13.1-44.8)	0.88 (0.3-3.0)	45.12 (37.6-72.2)	25.25 (12.1-51.1)
	mass		mass		mass	
Total	47498.13	14933.02	22098.02	2189.66	25400.11	12743.36
Mean (SD)	296.86 ± 516.55	93.33 ± 103.74	138.11 ± 219.87	13.69 ± 37.47	158.75 ±486.72	79.65 ± 86.52
Median (IQR)	146.58 (75.3-286.0)	47.59 (18.5-134.1)	35.83 (16.4-175.2)	1.69 (0.1-5.3)	65.09 (38.6-110.8)	45.11 (15.7-118.9)

Table S3.2. The explored effects of various factors on the total litter loads by number on dry and wet sand combined, between the beaches (Muizenberg and Sunrise), over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 42% of the deviance (variation). The intercept in the model includes beach (Muizenberg), sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	4.363 ± 1.034	4.218	**0.0001**
Beach			
Sunrise	-0.902 ± 0.139	-6.486	**0.0001**
Season			
Spring	0.506 ± 0.363	1.392	0.1639
Summer	0.246 ± 0.464	0.530	0.5960
Winter	0.606 ± 0.305	1.988	**0.0469**
Day of the week			
Weekend	-0.197 ± 0.147	-1.340	0.1804
Wind direction			
Onshore	0.090 ± 0.191	0.473	0.6361
Air temperature	0.054 ± 0.040	1.337	0.1813
Wind speed	-0.010 ± 0.071	-0.147	0.8829
Rain	0.078 ± 0.021	3.717	**0.0002**

Table S3.3. The explored effects of various factors on the total litter loads by mass on the dry and wet sand combined, between the beaches (Muizenberg and Sunrise), over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 49% of the deviance (variation). The intercept in the model includes beach (Muizenberg), sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	2.857 ± 2.122	1.346	0.1830
Beach			
Sunrise	-1.194 ± 0.285	-4.183	**0.0001**
Season			
Spring	1.204 ± 0.744	1.618	0.1100
Summer	0.863 ± 0.952	0.907	0.3680
Winter	1.343 ± 0.625	2.150	**0.0350**
Day of the week			
Weekend	0.364 ± 0.302	1.206	0.2320
Wind direction			
Onshore	-0.183 ± 0.391	-0.467	0.6420
Air temperature	0.107 ± 0.083	1.297	0.1990
Wind speed	0.126 ± 0.146	0.865	0.3900
Rain	0.035 ± 0.043	0.812	0.4200

Table S3.4. The explored effects of various factors on the total litter loads by number on the dry sand between the beaches (Muizenberg and Sunrise) over the sampling seasons using GLMs. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 73% of the deviance (variation). The intercept in the model includes beach (Muizenberg), sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	5.415 ± 1.397	3.876	**0.0001**
Beach			
Sunrise	-2.979 ± 0.190	-15.683	**0.0001**
Season			
Spring	0.447 ± 0.486	0.920	0.3577
Summer	1.048 ± 0.623	1.683	0.0924
Winter	-0.598 ± 0.417	-1.434	0.1517
Day of the week			
Weekend	0.257 ± 0.197	1.304	0.1922
Wind direction			
Onshore	0.124 ± 0.261	0.477	0.6339
Air temperature	-0.016 ± 0.054	-0.300	0.7641
Wind speed	-0.109 ± 0.096	-1.140	0.2542
Rain	-0.075 ± 0.031	-2.428	**0.0152**

Table S3.5. The explored effects of various factors on the total litter loads by mass on the dry sand between the beaches (Muizenberg and Sunrise) over the sampling seasons using GLMs. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 59% of the deviance (variation). The intercept in the model includes beach (Muizenberg), sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	6.857 ± 2.458	2.790	**0.0070**
Beach			
Sunrise	-2.430 ± 0.330	-7.369	**0.0001**
Season			
Spring	1.916 ± 0.818	2.342	**0.0224**
Summer	2.509 ± 1.060	2.367	**0.0210**
Winter	-1.288 ± 0.739	-1.745	0.0858
Day of the week			
Weekend	0.214 ± 0.338	0.634	0.5285
Wind direction			
Onshore	-0.501 ± 0.437	-1.146	0.2562
Air temperature	-0.052 ± 0.096	-0.545	0.5879
Wind speed	-0.069 ± 0.161	-0.428	0.6704
Rain	-0.107 ± 0.054	-1.976	0.0545

Table S3.6. The explored effects of various factors on the total litter loads by number on the wet sand between the beaches (Muizenberg and Sunrise) over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 34% of the deviance (variation). The intercept in the model includes beach (Muizenberg), sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	3.668 ± 1.113	3.296	**0.0010**
Beach			
Sunrise	-0.496 ± 0.150	-3.310	**0.0009**
Season			
Spring	0.356 ± 0.391	0.910	0.3627
Summer	-0.209 ± 0.500	-0.419	0.6750
Winter	0.702 ± 0.328	2.143	**0.0321**
Day of the week			
Weekend	-0.348 ± 0.158	-2.196	**0.0281**
Wind direction			
Onshore	0.160 ± 0.205	0.778	0.4366
Air temperature	0.058 ± 0.043	1.340	0.1803
Wind speed	0.037 ± 0.077	0.480	0.6315
Rain	0.094 ± 0.023	4.160	**0.0001**

Table S3.7. The explored effects of various factors on the total litter loads by mass on the wet sand between the beaches (Muizenberg and Sunrise) over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 39% of the deviance (variation). The intercept in the model includes beach (Muizenberg), sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	0.862 ± 2.526	0.341	0.7339
Beach			
Sunrise	-0.535 ± 0.340	-1.574	0.1199
Season			
Spring	0.872 ± 0.886	0.984	0.3286
Summer	0.113 ± 1.133	0.100	0.9209
Winter	1.859 ± 0.744	2.500	**0.0148**
Day of the week			
Weekend	0.335 ± 0.359	0.932	0.355
Wind direction			
Onshore	0.244 ± 0.465	0.524	0.6021
Air temperature	0.136 ± 0.098	1.385	0.1706
Wind speed	0.196 ± 0.174	1.129	0.2629
Rain	0.100 ± 0.051	1.926	0.0582

Table S3.8. The number (n·100 m^{-1}·day^{-1}) and mass (g·100 m^{-1}·day^{-1}) of items (dry and wet sand combined) collected daily in each sampling season at both beaches, giving the mean ± SD, median and interquartile range (IQR). Accumulation was surveyed over 10 days in each sampling season.

	Number				**Mass**			
	summer	**autumn**	**winter**	**spring**	**summer**	**autumn**	**winter**	**spring**
					Muizenberg			
Total	4780	2617	4892	3644	17884.91	3147.85	15295.95	11169.42
Mean (SD)	119.5 ± 64.8	65.4 ± 19.1	122.3 ± 85.4	91.1 ± 40.6	447.1 ± 323.8	78.7 ± 56.8	382.4 ± 968.3	279.2 ± 155.2
Median (IQR)	100.4 (79.8-130.6)	61.3 (52.4-74.8)	85.4 (63.6-157.5)	86.6 (61.3-108.1)	288.2 (252.9-579.1)	67.3 (44.4-88.9)	77.8 (43.0-124.3)	232.4 (184.3-439.1)
					Sunrise			
Total	1412	1302	1451	2685	5686.9	952.83	1406.34	6886.95
Mean (SD)	35.3 ± 34.1	32.6 ± 25.8	36.3 ± 40.3	67.1 ± 56.2	142.2 ± 132.1	23.82 ± 19.4	35.2 ± 40.3	172.2 ± 92.2
Median (IQR)	27.8 (16.8-35.9)	21.6 (11.9-48.9)	17.6 (12.6-47.9)	59.3 (22.8-93.8)	104.9 (41.0-195.1)	17.8 (10.0-30.3)	19.8 (10.4-44.6)	181.3 (93.5-244.0)

Table S3.9. The explored effects of various factors on the total litter loads by number on the dry and wet sand combined at Muizenberg beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 45% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	4.927 ± 0.912	5.400	**0.0001**
Season			
Spring	0.581 ± 0.321	1.808	0.0706
Summer	0.791 ± 0.411	1.927	0.0540
Winter	0.723 ± 0.269	2.687	**0.0072**
Day of the week			
Weekend	0.087 ± 0.130	0.671	0.5022
Wind direction			
Onshore	-0.056 ± 0.169	-0.332	0.7397
Air temperature	0.033 ± 0.036	0.939	0.3479
Wind speed	-0.077 ± 0.063	-1.217	0.2238
Rain	0.066 ± 0.019	3.581	**0.0003**

Table S3.10. The explored effects of various factors on the total litter loads by mass on the dry and wet sand combined at Muizenberg beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 43% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	1.964 ± 2.663	0.737	0.4664
Season			
Spring	0.743 ± 0.936	0.794	0.4332
Summer	0.533 ± 1.198	0.445	0.6595
Winter	1.819 ± 0.786	2.316	**0.0274**
Day of the week			
Weekend	0.474 ± 0.379	1.250	0.2205
Wind direction			
Onshore	-0691 ± 0.492	-1.406	0.1697
Air temperature	0.152 ± 0.104	1.466	0.1527
Wind speed	0.178 ± 0.184	0.969	0.3402
Rain	0.005 ± 0.054	0.095	0.9252

Table S3.11. The explored effects of various factors on the total litter loads by number on the dry and wet sand combined at Sunrise beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 33% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	3.988 ± 1.644	2.425	**0.0153**
Season			
Spring	0.665 ± 0.579	1.149	0.2505
Summer	0.029 ± 0.740	0.039	0.9686
Winter	0.192 ± 0.486	0.395	0.6929
Day of the week			
Weekend	-0.603 ± 0.235	-2.571	**0.0101**
Wind direction			
Onshore	0.261 ± 0.304	0.856	0.3917
Air temperature	0.028 ± 0.064	0.430	0.6670
Wind speed	0.022 ± 0.114	0.194	0.8459
Rain	**0.098 ± 0.033**	**2.919**	**0.0035**

Table S3.12. The explored effects of various factors on the total litter loads by mass of the dry and wet sand combined at Muizenberg beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 54% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	4.937 ± 1.909	2.586	**0.0146**
Season			
Spring	2.199 ± 0.671	3.276	**0.0026**
Summer	2.213 ± 0.859	2.577	**0.0150**
Winter	0.090 ± 0.563	0.161	0.8735
Day of the week			
Weekend	0.184 ± 0.272	0.677	0.5033
Wind direction			
Onshore	0.619 ± 0.352	1.755	0.0892
Air temperature	-0.035 ± 0.074	-0.472	0.6399
Wind speed	-0.069 ± 0.132	-0.524	0.6042
Rain	0.058 ± 0.039	1.484	0.1480

Table S3.13. The number (n·100 m^{-1}·day^{-1}) and mass (g·100 m^{-1}·day^{-1}) of items collected on the dry and wet sand daily in each sampling season at Muizenberg beach, giving the mean ± SD, median and interquartile range (IQR). Accumulation was surveyed over 10 days in each sampling season.

	Muizenberg beach							
	summer	autumn	winter	spring	summer	autumn	winter	spring
	number				mass			
	dry sand							
Total	2878	611	947	1186	14227.07	1357.1	900.8	5613.77
Mean (SD)	71.95 ± 54.2	15.28 ± 9.6	23.68 ±16.1	29.65 ± 20.5	355.7 ± 327.06	33.93 ± 55.70	22.5 ± 16.97	140.34 ±140.05
Median (IQR)	50.12 (44.8-58.9)	11.50 (8.4-21.6)	21.62 (14.6-29.1)	24.42 (15.1-34.7)	197 (117.2-500.2)	14.41 (8.2-21.3)	18.82 (13.5-24.7)	74.88 (31.5-226.8)
proportion	60.20%	23.30%	19.40%	32.50%	79.50%	43.10%	5.90%	50.30%
	wet sand							
Total	1902	2006	3945	2458	3657.84	1790.75	14395.87	5555.65
Mean (SD)	47.55 ± 24.04	50.15 ± 21.03	98.62 ± 94.52	61.45 ± 40.12	91.45 ± 48.40	44.77 ± 23.22	359.90 ± 973.69	138.89 ± 103.51
Median (IQR)	45.00 (39.0-53.8)	44.62 (41.9-50.9)	46.50 (26.6-140.3)	44.25 (37.6-70.1)	74.36 (56.6-122.8)	37.76 (27.6-58.9)	40.80 (20.0-106.7)	107.68 (74.9-146.3)
proportion	39.80%	76.70%	80.60%	67.50%	20.50%	56.90%	94.10%	49.70%

Table S3.14. The **e**xplored effects of various factors on the litter loads by number on the dry sand at Muizenberg beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 65% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	5.417 ± 1.169	4.635	**0.0001**
Season			
Spring	0.904 ± 0.411	2.199	**0.0279**
Summer	1.873 ± 0.525	3.565	**0.0004**
Winter	0.074 ± 0.347	0.214	0.8304
Day of the week			
Weekend	0.264 ± 0.166	1.584	0.1131
Wind direction			
Onshore	-0.297 ± 0.217	-1.371	0.1705
Air temperature	-0.014 ± 0.046	-0.299	0.7647
Wind speed	-0.185 ± 0.081	-2.290	**0.0220**
Rain	-0.046 ± 0.025	-1.851	0.6416

Table S3.15. The explored effects of various factors on the litter loads by mass on the dry sand at Muizenberg beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 66% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	7.165 ± 2.119	3.381	**0.0020**
Season			
Spring	2.172 ± 0.745	2.916	**0.0065**
Summer	3.203 ± 0.953	3.361	**0.0021**
Winter	-0.772 ± 0.625	-1.235	0.2260
Day of the week			
Weekend	-0.052 ± 0.302	-0.174	0.8631
Wind direction			
Onshore	0.586 ± 0.391	-1.498	0.1444
Air temperature	-0.061 ± 0.083	-0.736	0.4670
Wind speed	-0.149 ± 0.146	-1.019	0.3162
Rain	-0.072 ± 0.043	-1.667	0.1057

Table S3.16. The explored effects of various factors on the litter loads by number on the wet sand at Muizenberg beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 41% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	3.998 ± 1.233	3.243	**0.0012**
Season			
Spring	0.276 ± 0.433	0.636	0.5249
Summer	-0.032 ± 0.554	-0.058	0.9537
Winter	0.837 ± 0.364	2.300	**0.0214**
Day of the week			
Weekend	-0.090 ± 0.176	-0.513	0.6081
Wind direction			
Onshore	0.087 ± 0.228	0.382	0.7025
Air temperature	0.045 ± 0.048	0.941	0.3469
Wind speed	-0.001 ± 0.085	-0.007	0.9940
Rain	0.089 ± 0.025	3.564	**0.0004**

Table S3.17. The explored effects of various factors on the litter loads by mass on the wet sand at Muizenberg beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 49% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	-0.531 ± 2.917	-0.182	0.8567
Season			
Spring	0.191 ± 1.025	0.186	0.8536
Summer	-0.772 ± 1.312	-0.589	0.5603
Winter	2.437 ± 0.861	2.832	**0.0081**
Day of the week			
Weekend	0.301 ± 0.416	0.724	0.4743
Wind direction			
Onshore	0.061 ± 0.539	0.112	0.9113
Air temperature	0.203 ± 0.114	1.781	0.0848
Wind speed	0.234 ± 0.201	1.161	0.2546
Rain	0.120 ± 0.060	2.018	0.0524

Table S3.18. The explored effects of various factors on the maximum number on people per day over a year period (October 2022 to September 2023) at Muizenberg beach using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength, maximum air temperature and rainfall. The model explained 26% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	4.820 ± 0.278	17.339	**0.0001**
Season			
Spring	0.108 ± 0.095	1.134	0.2570
Summer	0.601 ± 0.110	5.446	**0.0001**
Winter	0.004 ± 0.100	0.044	0.9650
Day of the week			
Weekend	0.387 ± 0.072	5.384	**0.0001**
Air temperature	0.012 ± 0.010	1.258	0.2080
Wind speed	-0.062 ± 0.011	-5.739	**0.0001**
Rain	-0.015 ± 0.008	-1.960	**0.0500**

Table S3.19. The number (n·100 m^{-1}·day^{-1}) and mass (g·100 m^{-1}·day^{-1}) of items collected on the dry and wet sand daily in each sampling season at Sunrise beach, giving the mean ± SD, median and interquartile range (IQR). Accumulation was surveyed over 10 days in each sampling season.

	Sunrise beach							
	number				**mass**			
	summer	**autumn**	**winter**	**spring**	**summer**	**autumn**	**winter**	**spring**
	dry sand							
Total	117	75	11	97	1241.1	113.9	28.4	806.26
Mean (SD)	2.93 ± 3.78	1.88 ± 2.53	0.28 ± 0.18	2.43 ± 1.93	31.03 ± 62.95	2.85 ± 4.86	0.71 ± 1.26	20.16 ± 37.40
Median (IQR)	1.63 (1.0-3.6)	0.63 (0.1-3.1)	0.25 (0.3-0.3)	2.50 (0.8-3.5)	4.09 (2.2-7.2)	0.36 (0.0-3.7)	0.15 (0.1-0.3)	4.90 (0.5-13.9)
Proportion	8.30%	5.80%	0.80%	3.6%	21.80%	11.90%	2%	11.70%
	wet sand							
Total	1295	1227	1440	2588	4445.8	838.9	1377.94	6080.7
Mean (SD)	32.38 ± 33.53	30.68 ± 25.95	36.0 ± 40.25	64.70 ± 56.76	111.14 ± 105.82	20.97 ± 19.76	34.45 ± 40.44	152.02 ± 78.74
Median (IQR)	25.25 (13.9-32.0)	20.75 (10.1-48.8)	17.38 (12.6-47.3)	54.38 (19.9-90.4)	80.09 (34.7-159.0)	10.43 (7.6-30.3)	19.53 (8.7-43.6)	144.52 (85.8-229.0)
Proportion	91.70%	94.20%	99.20%	96.40%	78.20%	88.10%	98.00%	88.30%

Table S3.20. The explored effects of various factors on the litter loads by number on the dry sand at Sunrise beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 44% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	4.130 ± 2.627	1.572	0.1158
Season			
Spring	0.607 ± 0.866	0.701	0.4835
Summer	0.955 ± 1.127	0.847	0.3970
Winter	-2.005 ± 0.827	-2.424	**0.0153**
Day of the week			
Weekend	0.267 ± 0.356	0.752	0.4523
Wind direction			
Onshore	0.795 ± 0.515	1.544	0.1227
Air temperature	-0.107 ± 0.100	-1.075	0.2825
Wind speed	-0.089 ± 0.175	-0.506	0.6125
Rain	-0.190 ± 0.093	-2.033	**0.0420**

Table S3.21. The explored effects of various factors on the litter loads by mass on the dry sand at Sunrise beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 43% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a Gaussian distribution, as the data were normally distributed, confirmed by Shapiro-Wilk test.

	Estimate (±SE)	T-value	P-value
Intercept	3.672 ± 2.306	1.592	0.1244
Season			
Spring	1.174 ± 0.719	1.632	0.1157
Summer	1.757 ± 0.948	1.853	0.0763
Winter	-1.434 ± 0.740	-1.939	0.0643
Day of the week			
Weekend	0.183 ± 0.309	0.591	0.5601
Wind direction			
Onshore	-0.122 ± 0.410	-0.297	0.7687
Air temperature	-0.105 ± 0.090	-1.166	0.2552
Wind speed	-0.157 ± 0.142	-1.110	0.2780
Rain	-0.028 ± 0.072	-0.388	0.7014

Table S3.22. The explored effects of various factors on the litter loads by number on the wet sand at Sunrise beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 34% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a negative binomial distribution to account for the data being over-dispersed.

	Estimate (±SE)	Z-value	P-value
Intercept	4.170 ± 1.698	2.456	**0.0141**
Season			
Spring	0.848 ± 0.598	1.419	0.1559
Summer	0.155 ± 0.764	0.202	0.8397
Winter	0.221 ± 0.501	0.441	0.6591
Day of the week			
Weekend	-0.709 ± 0.242	-2.923	**0.0350**
Wind Direction			
Onshore	0.188 ± 0.314	0.599	0.5494
Air temperature	0.020 ± 0.066	0.303	0.7616
Wind speed	0.005 ± 0.117	0.044	0.9647
Rain	0.110 ± 0.035	3.184	**0.0015**

Table S3.23. The explored effects of various factors on the litter loads by mass of the wet sand at Sunrise beach over the sampling seasons using GLM. The factors examined included seasons (summer, autumn, winter and spring), day of the week (weekday and weekend), wind strength and direction (onshore and offshore), maximum air temperature and rainfall. The model explained 55% of the deviance (variation). The intercept in the model includes sampling season (autumn), day of the week (weekday), and wind direction (offshore). The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	5.064 ± 1.904	2.660	**0.0123**
Season			
Spring	2.204 ± 0.669	3.293	**0.0025**
Summer	2.092 ± 0.856	2.444	**0.0204**
Winter	0.091 ± 0.562	0.162	0.8726
Day of the week			
Weekend	-0.020 ± 0.271	-0.074	0.9411
Wind direction			
Onshore	0.790 ± 0.351	2.247	**0.0319**
Air temperature	-0.058 ± 0.074	-0.785	0.4385
Wind speed	-0.028 ± 0.131	-0.211	0.8345
Rain	0.069 ± 0.039	1.784	0.0841

Table S3.24. Percentage composition by number of litter items in the different sampling seasons at Muizenberg beach

	Summer		**Autumn**		**Winter**		**Spring**	
Litter Category	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Paper and Card Items	22%	1%	30%	1%	18%	1%	21%	1%
Smoking Items	28%	24%	27%	41%	37%	49%	22%	19%
Snack Food Packaging	6%	11%	3%	8%	2%	2%	6%	5%
Sweet Packaging	10%	11%	9%	13%	10%	8%	11%	12%
Drink Bottles and Lids	8%	8%	2%	5%	2%	5%	6%	9%
Fast-Food Packaging	5%	2%	5%	2%	4%	3%	5%	2%
Other Food Packaging	7%	10%	10%	11%	9%	7%	9%	9%
Other Bottles and Lids	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
Other Packaging	4%	14%	4%	5%	3%	3%	4%	7%
Disposable	3%	1%	2%	1%	9%	<1%	3%	1%
Sewage	1%	3%	<1%	1%	1%	3%	1%	4%
Fishing and Shipping	<1%	4%	<1%	1%	<1%	1%	1%	7%
Other User Items	1%	2%	2%	1%	1%	<1%	2%	2%
Plastic Fragment	2%	7%	2%	7%	2%	12%	3%	19%
Non-Plastic	3%	2%	2%	2%	2%	6%	4%	3%
Total	**2878**	**1902**	**611**	**2006**	**947**	**3945**	**1186**	**2458**

Table S3.25. Percentage composition by mass of litter items in the different sampling seasons at Muizenberg beach

	Summer		Autumn		Winter		Spring	
Litter Category	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Paper and Card Items	13%	1%	11%	2%	18%	<1%	12%	<1%
Smoking Items	3%	5%	4%	16%	12%	4%	2%	3%
Snack Food Packaging	3%	5%	1%	5%	1%	<1%	2%	2%
Sweet Packaging	1%	3%	2%	6%	5%	1%	1%	4%
Drink Bottles and Lids	49%	16%	31%	16%	26%	2%	60%	18%
Fast-Food Packaging	3%	2%	2%	2%	4%	<1%	2%	2%
Other Food Packaging	3%	7%	3%	10%	6%	1%	2%	3%
Other Bottles and Lids	<1%	1%	<1%	<1%	<1%	<1%	<1%	<1%
Other Packaging	4%	19%	5%	7%	3%	1%	3%	8%
Disposable	1%	1%	1%	1%	3%	<1%	1%	1%
Sewage	2%	3%	<1%	<1%	1%	<1%	<1%	1%
Fishing and Shipping	<1%	5%	1%	1%	<1%	<1%	1%	8%
Other User Items	4%	10%	10%	8%	16%	1%	8%	30%
Plastic Fragment	2%	5%	1%	6%	1%	2%	1%	8%
Non-Plastic	11%	18%	27%	19%	3%	87%	5%	12%
Total	**14227.1**	**3657.8**	**1357.1**	**1790.8**	**900.1**	**14395.9**	**5613.8**	**5555.7**

Table S3.26. Percentage composition by number of litter items in the different sampling seasons at Sunrise beach

	Summer		Autumn		Winter		Spring	
Litter Category	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Paper and Card Items	21%	1%	17%	<1%	9%	<1%	7%	<1%
Smoking Items	33%	4%	17%	3%	27%	4%	55%	2%
Snack Food Packaging	5%	11%	7%	16%	<1%	14%	8%	11%
Sweet Packaging	4%	13%	20%	9%	18%	15%	6%	14%
Drink Bottles and Lids	9%	4%	5%	3%	9%	8%	9%	5%
Fast-Food Packaging	1%	1%	5%	7%	9%	2%	1%	1%
Other Food Packaging	3%	16%	4%	33%	18%	18%	<1%	19%
Other Bottles and Lids	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
Other Packaging	9%	38%	15%	18%	9%	12%	8%	21%
Disposable	<1%	<1%	<1%	<1%	<1%	<1%	1%	1%
Sewage	<1%	2%	<1%	1%	<1%	6%	<1%	8%
Fishing and Shipping	6%	4%	7%	1%	<1%	3%	2%	3%
Other User Items	3%	1%	<1%	<1%	<1%	<1%	1%	1%
Plastic Fragment	<1%	5%	3%	8%	<1%	16%	1%	12%
Non-Plastic	5%	<1%	<1%	<1%	<1%	<1%	<1%	1%
Total	**117**	**1295**	**75**	**1227**	**11**	**1440**	**97**	**2588**

Table S3.27. Percentage composition by mass of litter items in the different sampling seasons at Sunrise beach

	Summer		Autumn		Winter		Spring	
Litter Category	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Paper and Card Items	13%	1%	20%	2%	32%	<1%	5%	1%
Smoking Items	2%	1%	19%	2%	3%	2%	6%	1%
Snack Food Packaging	3%	2%	4%	13%	<1%	7%	1%	4%
Sweet Packaging	<1%	2%	7%	5%	4%	8%	<1%	3%
Drink Bottles and Lids	65%	16%	31%	12%	53%	22%	83%	13%
Fast-Food Packaging	<1%	1%	2%	2%	4%	1%	<1%	1%
Other Food Packaging	1%	7%	2%	30%	3%	8%	<1%	10%
Other Bottles and Lids	<1%	<1%	<1%	1%	<1%	1%	<1%	<1%
Other Packaging	2%	25%	6%	22%	2%	9%	1%	28%
Disposable	<1%	<1%	<1%	1%	<1%	<1%	<1%	1%
Sewage	<1%	2%	<1%	<1%	<1%	2%	<1%	3%
Fishing and Shipping	2%	28%	7%	1%	<1%	9%	1%	5%
Other User Items	7%	3%	<1%	1%	<1%	16%	1%	7%
Plastic Fragment	<1%	4%	1%	8%	<1%	15%	<1%	6%
Non-Plastic	5%	6%	<1%	<1%	<1%	<1%	<1%	17%
Total	**1241.1**	**4445.8**	**113.9**	**838.9**	**28.4**	**1380.9**	**806.3**	**6080.7**

Chapter 4: Does beachgoer litter migrate into the surf zone? A case study at an urban beach

Collecting surf zone litter at Muizenberg beach. Photo: Shark Spotters

Abstract

Beachgoers litter can be a major source of beach litter. This litter may enter the marine environment via the surf zone, but little is known about how much beach litter migrates offshore. This study explores how much beach litter migrates offshore by comparing the abundance and composition of litter in the surf zone with that of beach litter. Samples were collected over 50 days in the austral summers, when beach visitation peaks, of 2013/14 and 2022/23, along two 100 m-transects (T1 and T2) in the surf zone using a fine-mesh net (5 mm). The density of items recorded in 2013 was 4 and 2 times greater than in 2022 by number and mass, respectively. Daily net tows averaged 0.29 ± 0.78 items.m^{-3} in 2013/14 and 0.08 ± 0.12 items.m^{-3}in 2022/23. There was greater daily variation in the litter amount in 2013/14 than in 2022/23, driven by a few days with significantly higher densities. A negative correlation between beach users and litter abundance (r = - 0.49 in 2013/14 and r = - 0.28 in 2022/23) was observed and this suggested that weather conditions that promote the surf zone litter and also responsible for preventing people from attending the beach. In terms of size comparison, most of

the litter items collected from the surf zone (43%) were small (< 0.1g), whereas on the sandy beach (dry and wet sand), items < 0.1 g only contributed 1 to 2% The difference in size was due to the different sampling techniques. Hand picking on beaches targeted items > 10 mm, while the mesh net collected smaller items that were < 5 mm in the surf zone. In terms of composition, small and degraded single use plastic from food and other packaging-related items dominated litter in the surf zone by number and mass. On the nearby sandy beach, paper and smoking-related items (mainly cigarette butts) were the most common by number, whereas glass drink bottles and non-plastic items dominated by mass. At least one-third (35%) of the items in the surf zone in 2022/23 and 18% in 2013/14 showed signs of weathering or were covered with epibionts, indicating that they had been in the sea for some time. These findings suggest that only a small proportion of sandy beach litter generated by beachgoers migrates into the nearby sea.

Introduction

Surveys of sandy beaches have been helpful in identifying potential sources of anthropogenic litter and have revealed that plastic waste often makes up the largest proportion of stranded litter (Munari et al., 2017; Chitaka and von Blottniz, 2019; Weideman et al., 2020b; Chapters 2 and 3). The few studies that have applied the dry and wet sand method (Chapters 2 and 3) have shown that litter items on dry sand likely originate from beachgoers, whereas on the wet sand, litter comes from offshore sources, including rivers and storm drains. For example, the most common litter items collected on dry sand were smoking related items (mainly cigarette butts) and items made from paper and card, whereas on the wet sand, smoking related items (mainly cigarette butts) dominated by number (Barnardo et al., 2021; Chapters 2 and 3). Seasonality plays a role in litter accumulation, as more litter items tend to accumulate on dry sand at popular beaches during the peak season (summer) due to recreational activities, whereas in winter, litter on wet sand comes from rivers, storm drains, and offshore sources (Barnardo et al., 2021; Chapter 2 and 3). Studies assume that beachgoers are a major source of beach litter, when they leave litter behind after recreational activities (Derriak et al., 2002; Martine-Ribes et al., 2007; UNEP, 2009; Okuku et al., 2020; Barnardo et al., 2021; Chapters 2 and 3). However, the extent to which litter generated by beachgoers might travel offshore, and enter the sea through the surf zone, is not well understood.

The surf zone is the interface between the land and ocean (Ramos et al., 2019). Few studies have quantified the abundance and composition of litter items in the surf zone (Thiel et al., 2013; Ramos et al., 2019). Of the few studies that have focused on the surf zone, only one study indicated that the litter profile of the surf zone differs from that of the sandy beach (Thiel et al., 2013), while Ramos et al. (2019), who focussed on the amount and composition of surf zone litter, did not compare this with the sandy beach. Thiel et al. (2013) compared litter items in the nearshore coastal waters to rocky and sandy beaches and found that plastic items (such as shopping bags, food wrappers, ropes, etc.) and manufactured wood items dominated on both the rocky and sandy shores, whereas for plastics, styrofoam (EPS) was the most common items in the nearshore (surf zone). This study indicates that the litter profile of the nearshore (surf zone) slightly differs from that of the sandy beach (Thiel et al., 2013). The slight difference was due to local inputs from beachgoers (sandy and rocky shore) and fishing activities (nearshore).

No studies to date have established a link between litter items generated by recreational activities on sandy beaches and the litter in the surf zone. To test the assumption that beach litter from beachgoers becomes a source of marine litter, litter items were collected from the surf zone for 50 days at Muizenberg beach during summer, when the number of beachgoers is high, during two years: 2013/14 and 2022/23. These were compared to litter on the adjacent sandy beach, where litter on the dry sand was assumed to have originated from beachgoers, and litter on the wet sand assumed to originate from offshore sources (Chapters 2 and 3). The aim of this study was to determine whether the sandy beach litter is a source of litter in the surf zone, and if there is a transfer of beachgoers litter into the surf zone, identify the factors responsible for it.

Methods

Site description

Muizenberg Beach was chosen for this study because it is frequented by large numbers of tourists and locals, especially in summer. Muizenberg is located on the northwest coast of False Bay, in the heart of a densely populated metropolitan area, 27 km from Cape Town's city centre (see Chapters 2 and 3). Several rivers draining the heavily populated Cape Flats enter the northern shore of False Bay, introducing significant litter loads into the bay (Pfaff et al., 2019; Ryan and Perold, 2021). The Zandvlei River mouth was closed during this study.

Two 100 m-long areas in the surf zone at Muizenberg were designated as transects 1 (T1) and 2 (T2) (Fig. 4.1). T1 is located near the southwestern end of the beach where it borders a rocky shoreline. T2 is 50 m northeast of T1 (Fig 4.1). The two transects were positioned between fixed points on the shore, 50 m apart. Every effort was made to standardise sampling in terms of water depth and net depth in the water.

Fig. 4.1. Location of the two-surf zone transects, T1 and T2, in relation to the sandy beach sampling area (yellow line). Note the Zandvlei River was closed during this study.

Field sampling

Daily surf zone sampling at the two transects was carried out for 50 consecutive days during summer, which is when recreational activities by beach users peak (Chapter 3). Net sampling dates were between 29 November and 19 January in 2013/14 and 29 November and 17 January in 2022/23. No data were collected on 6 and 7 Dec 2013, but sampling was conducted on 18 and 19 January 2014 to make up the shortfall. Samples of floating marine litter were collected from the surf zone using a 100 cm wide, 30 cm deep net with 5 mm-mesh and a removable jar to retain the sample. The net was pulled by wading through water 1–1.5 m deep to sample litter in the upper 25–30 cm of the water column. Litter items were removed from the jar and each item stored in zip-lock bags unique to each transect.

On most days, towing was performed 12 times, but there were exceptions to the sampling protocol in both years (see Table S4.1 and S4.2). Sampling started at 7h00 and took approximately 2 hours to complete. In all, 532 tows were carried out in 2013/14 and 584 in 2022/23. To compare the composition of surf zone litter to that on the adjacent sandy beach, litter was collected along a 400 m transect on the beach adjacent to the surf zone (Fig. 4.1). The sandy beach litter was collected for 10 days before and after the 50-day surf-zone sampling. Litter items > or = 10 mm were collected by hand. The sandy beach was separated into two zones: 1) the wet sand zone, including the latest high-tide strandline, and 2) the dry sand zone above the most recent high-tide line (Barnardo et al., 2021). For more details, see Chapters 2 and 3.

Processing of samples

Samples were transported to the University of Cape Town where the litter items were counted, dried, and weighed using an electronic balance (Mettler AE 100, precision: 0.1 mg) and measured using Vernier callipers (accuracy 0.1 mm) to determine their length, width, and thickness. The diameter, height, and thickness were recorded for bottle lids. Litter items were classified based on a modified version of Falk-Andersson's (2021) list for beach litter functional categories (Chapter 2).

Litter items were examined for signs of weathering and deterioration (Fig. 4.2). Each item was categorized using a scoring system: new items showing no signs of weathering or degradation were assigned a score of 0 as fresh items, and old, degraded items were scored as 2, whereas intermediate items (between new and old litter items) were scored as 1. This assessment allowed for differentiation between litter items which appeared fresh and therefore were recently released into the sea, and older litter items showing signs of degradation, such as damage (bites) from marine organisms and the presence of epibionts, indicating that the item had been at sea for an extended period. For information about the sandy beach data processing, see Chapters 2 and 3. Due to the subjective scoring by different observers in the sampling years (2013/14 and 2022/23), there is uncertainty in comparing the age/deterioration scores between years. As a result, I did not report the exact proportions of litter items. However, the rough proportions of new, intermediate, and old items were similar in the different years (Table S4.3).

Fig. 4.2. Image **A** shows an item that is fresh (denoted as 0). Images **B** and **C** show items that are newly and slightly damaged by natural processes (denoted as 1). Image **D** shows an item that has been significantly damaged by natural processes due to prolonged exposure in the water (denoted as 2).

Weather data from Cape Town Airport, 18 km NE of the study site, were obtained from SAWS. Hourly rainfall, wind speed and wind direction, and air temperature were obtained for each sampling day. Hourly maximum wind speed and maximum air temperature was used per day, and the rainfall per day was summated.

There were 7 rainfall events in the 2013/14 collection period (total 25.6 mm, ranging from 0.2 to 7.4 mm per day) and 9 in 2022/23 (46.1 mm, 0.1 to 17.6 mm per day). South-easterly (onshore) winds predominated in both years, occurring on 86% of surf zone sampling days in 2013/14 and 72% in 2022/23. Tidal heights obtained from the South African Navy Hydrographic Office (hydrosan@iafrica.com) for Simonstown, 12 km south of Muizenberg, were used to estimate tidal height at 8h00 each day and to determine whether the tide was rising or falling. Hourly counts of the maximum number of beachgoers per day entering the sea recorded by Shark Spotters (sharkspotters.org.za) were used as an index of beach usage.

Data analyses

All statistical analyses were done in R version 4.2.3 (R Core Team, 2024). Results were considered significant when $P < 0.05$. I applied Generalized Linear Models (GLMs) using the *glm* function from the *mass* and *stats* packages of R (Venables and Ripley, 2002; Core Team 2024) to determine the factors that explained the variations in the densities of litter items by number (items·100 m^{-3}) and mass (g·100 m^{-3}) between sampling periods. I modelled the litter densities by number and mass as a function of transects, sampling periods, tides (either rising or falling) and the tide height during sampling, maximum beachgoers, rainfall, maximum air temperature, wind speed, and direction. The following explanatory variables were lagged by one day, since daily sampling was carried out early morning: maximum beachgoers, rainfall, maximum air temperature, wind speed, and wind direction. I applied negative binomial distribution to account for overdispersion in the data (for the number of litter items). For the mass of litter items, I applied the gamma distribution due to the skewness in the data. I used linear correlation to assess the relationship between the number of litter items in the surf zone and the number of beachgoers the previous day. I presented the data as means ± SD or as medians and IQR ranges where data were strongly skewed. I used chi-squared goodness of fit test to compare the proportion of litter items collected during onshore and offshore winds in the different deterioration states and size classes. To compare the composition and size of litter items collected in the surf zone with those sampled on the sandy beach, I used the two 10-day sandy beach litter sampling periods (spring and summer) in 2022/23 (Chapter 3). No sandy beach litter data collection was carried out in 2013/14. The size of items was calculated using mass of items. I grouped sizes into six categories: 1 = > 100 g, 2 = 10 – 100 g, 3 = 1 – 10 g, 4 = 0.1 – 1 g, 5 = 0.01 – 0.1 g and 6 = 0.001 – 0.01 g. Due to the different sampling techniques used in the surf zone (fine-meshed net) and on the sandy beach (hand-picking), items in size category 6 were collected in the surf zone, but this size group was not found on the beach. I therefore included size 6 in the total litter amounts in the surf zone but excluded it from the size comparison analysis.

Results

Litter abundance

Over the one hundred (100) days of net sampling between 2013/14 and 2022/23, 4257 litter items, weighing 350.7 g, were collected in the surf zone at Muizenberg. A total of 3606 items weighing 269.2 g were collected, while in 2022/23, 651 items weighing 81.5 g were collected.

In 2013/14, a spike in litter items over a few days resulted in a density (number of items) of approximately 4 times that of 2022/23, and the mass was 2 times higher (Tables 4.1 and S4.4). Across both years, the density of items recorded in T1 was approximately 4 times higher than at T2 in terms of both the number and mass of items (Tables 4.1, S4.4, and S4.6). The GLM indicated that wind speed significantly increased the number of litter items in the surf zone. The GLM further indicated that there was a statistically significant negative relationship between the number of beachgoers and litter abundance in the surf zone (Tables 4.1 and S4.5). In addition, the linear correlation analysis revealed a negative association between the litter abundance and the number of beachgoers in both 2013/14 ($r = -0.49$, $P < 0.001$) and 2022/23 ($r = -0.28$, $P = 0.047$, Fig. 4.3). Excluding the days with outliers in 2013/14 (Fig S4.1), a total of 1870 items weighing 106g was recorded. The abundance of litter items (by number) recorded in 2013/14 was two times higher than in 2022/23 (Tables S4.7 and S4.8). There was no significant difference between years by mass of litter (Tables S4.7 and S4.9).

Table 4.1 GLM output showing the effects of wind strength and direction (onshore and offshore winds), tidal height and direction (ebb or flow), and rainfall on litter items by number between the transects over the sampling periods. Note: only significant factors are presented here. For more details, see Table S4.2.

Factors affecting abundance of items	Estimate (± SE)	Z-value	P-value
All litter at both transects in both years			
T1 (> than T2)	0.607 ± 0.246	2.464	0.014
2022/23 (< 2013/14)	-1.191 ± 0.288	-4.142	0.0001
Number of beachgoers (negative)	-0.004 ± 0.001	-4.363	0.0001
Wind speed (> on windy days)	0.116 ± 0.049	2.359	0.018

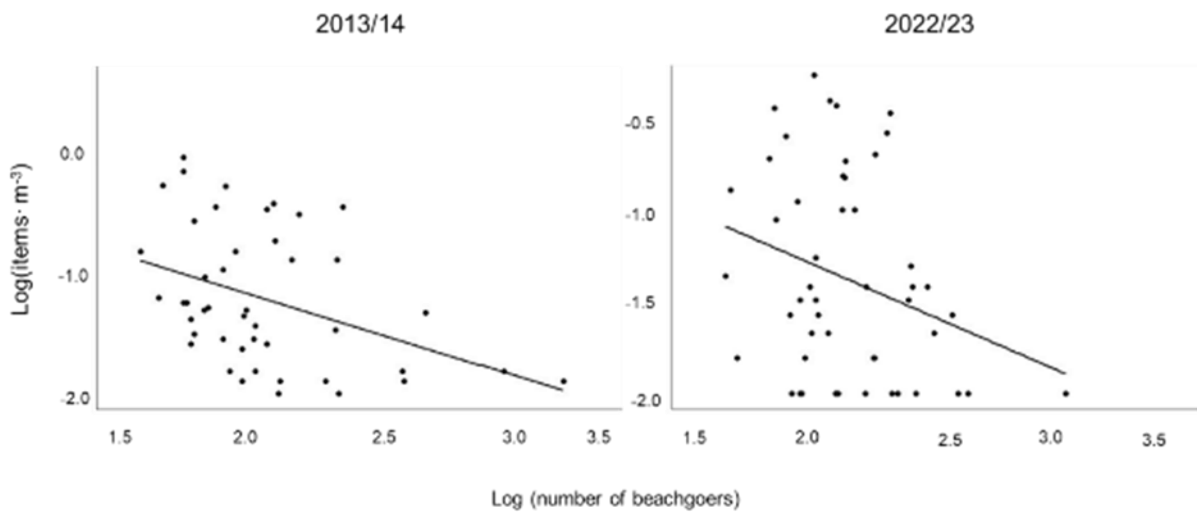


Fig 4.3. The relationship between the maximum number of beachgoers and the density of litter items in the surf zone in the sampling years (data were log transformed).

In 2013/14, the overall mean density of items was 0.29 ± 0.78 items.m^{-3} and 0.02 ± 0.07 g.m^{-3}. On day 17, the daily mean density of 5.28 items.m^{-3} and 0.45 g.m^{-3} was 18 and 23 times higher than the overall mean density by number and mass respectively (Fig. S4.1). In 2022/23, the daily mean density of 0.52 items.m^{-3} on day 1 and 0.07 g.m^{-3} on day 21 was 7 times greater than the overall mean density of 0.08 ± 0.12 items.m^{-3}and 0.01 ± 0.02 g.m^{-3} (Fig. S4.1).

There was no clear difference in degradation state (fresh, intermediate, and old/degraded items) in relation to wind direction (onshore and offshore) (in 2013/14: χ^2 = 0.02, df = 2, P > 0.99 in

2022/23: χ^2 = 0.07, df = 2, P > 0.97). In addition, there was no clear difference in the size classes (small and larger items) in relation to wind direction (onshore and offshore) (in 2013/14: χ^2 = 0.0002, df = 1, P = > 0.99; in 2022/23: χ^2 = 0.01, df = 1, P > 0.91).

Litter characteristics in the surf zone

Following the six size categories, the number of items in each category were given as follows: In 2013/14, litter items in size 6 dominated (55%), whereas in 2022/23, litter items in size 5 dominated with 43% (Table 4.2). Most litter samples collected in the surf zone at Muizenberg were small single use plastic packaging items weighing < 0.1 g (Table 4.2). Of these, items that fell into the "other" category in my version of Falk-Andersson's (2021) list for beach litter functional categories (Chapter 2 and 3) were the most common by number and mass (Table S4.10).

Table 4.2. Size distribution of litter items collected in surf zone in the different sampling years by number and mass. Size 3 = 1 – 10g, size 4 = 0.10 – 1g, size 5 = 0.01 – 0.10g, and size 6 = 0.001 – 0.01g.

Sizes	2013/14		2022/23	
	number	**mass**	**number**	**mass**
Size 3	1%	46%	2%	41%
Size 4	10%	36%	19%	45%
Size 5	34%	16%	43%	12%
Size 6	55%	3%	36%	1%
Total	**3606**	**269.2**	**651**	**81.5**

Surf zone and sandy beach comparison

Due to the differences in sampling techniques between the sandy beach and surf zone, size 6 was excluded from this comparison. No litter items of size 1 and 2 were found in the surf zone. On the sandy beach, they contributed < 2%. Litter items of size 3 were the most common in the surf zone and they contributed 2%. On the sandy beach (dry and wet), they accounted for 25–30% (Table 4.3).

Table 4.3. Size comparison between the surf zone (2022/23) and sandy beach (dry and wet sand) by number. Size 1 = 100 – 1000g, Size 2 = 10 -100g, Size 3 = 1 – 10g, size 4 = 0.10 – 1g, size 5 = 0.01 – 0.10g

Sizes	Surf zone	Wet sand	Dry sand
Size 1	<1%	<1%	1%
Size 2	<1%	7%	4%
Size 3	2%	25%	30%
Size 4	19%	69%	62%
Size 5	43%	2%	1%
Total	**419**	**4360**	**4064**

Litter composition in the surf zone differed from sandy beach litter by number and mass. Most of the items collected from the surf zone were single use plastic packaging items. Other packaging items and other food packaging items dominated by number and mass. In contrast to the dry sand, items made from paper and card and smoking-related items (mainly cigarette butts) predominated by number, while drink bottles (mostly made of glass) accounted for more than half of the total items by mass. On wet sand, smoking-related items (primarily cigarette butts) were prevalent in terms of count, while heavier items dominated by mass, including user items like flip-flops, and non-plastic materials, particularly processed wood (Fig. 4.4 and S4.11).

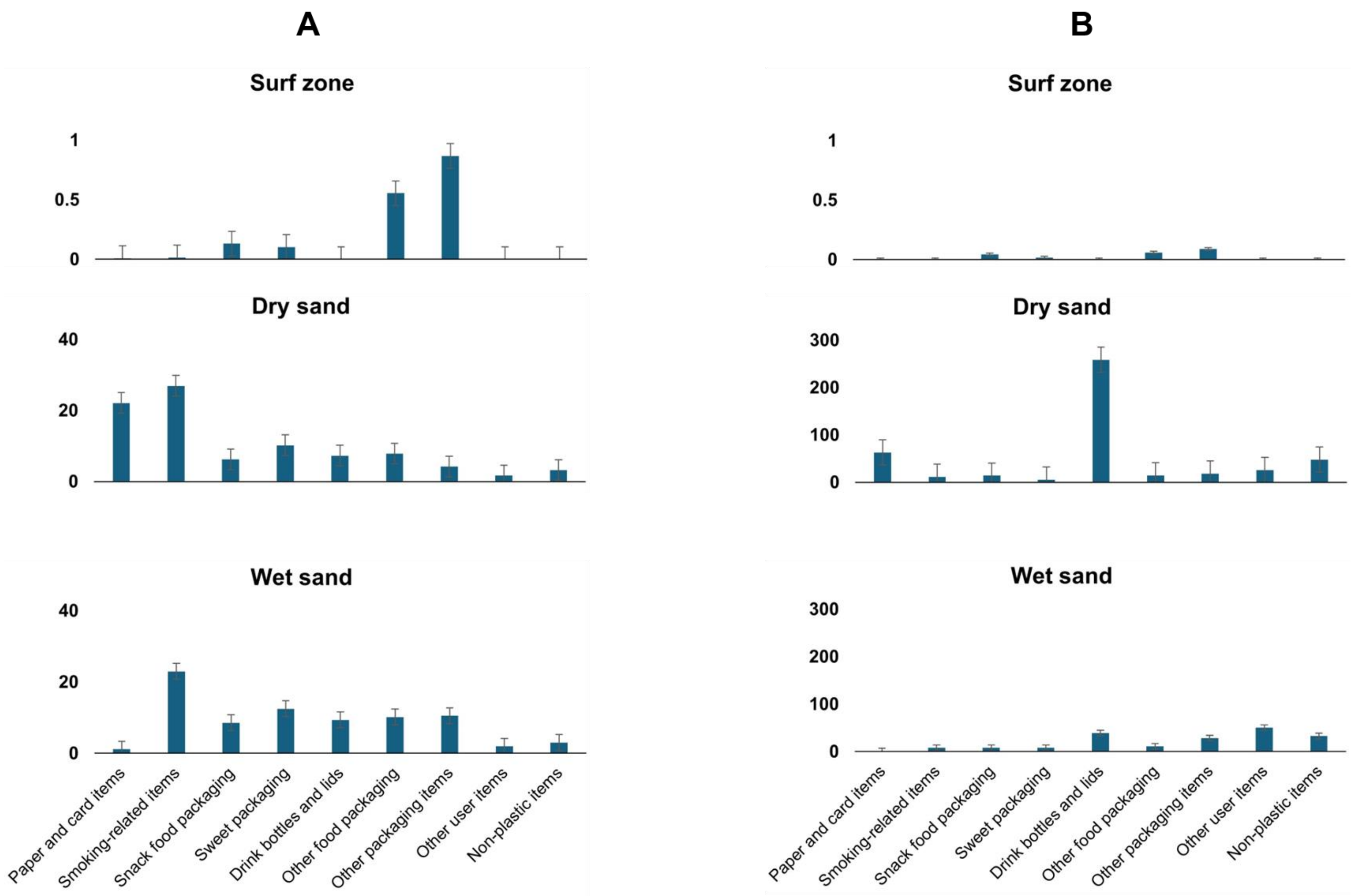


Fig.4.4. Mean density of different types of litter items in the surf zone and on dry and wetsand. A = number of items and B = mass of items. See Table S4.7 for details.

Discussion

Litter from beachgoers engaging in recreational activities is one of the main sources of beach litter and it enters the sea through the surf zone. However, little is known about how beach litter from beachgoers migrates offshore through the surf zone. In this chapter, I explore this question by comparing the composition of litter collected in the surf zone to that expected to come from littering beachgoers on the dry sand. I also assess whether the number of beachgoers influences litter in the surf zone, as well as other environmental factors such as wind direction and rain events.

Variations in litter abundance in the surf zone

There was considerable variation in the density of surf zone litter each day, with very high values recorded on a few days in 2013/14 (Fig. S4.1). On day 17 in particular, the daily mean was 18 times higher than the overall mean density (the number of items sampled summed up to 18% of the total net catches from the 50 days). Widely spaced sampling intervals may overlook these events, which can underestimate litter abundance. On the few occasions when there were large densities of litter items, a local upwelling event might have pushed litter up from the seabed. Weideman et al. (2020b) found that the litter recorded in November 2017 along the rocky shore at Muizenberg likely originated from the False Bay seabed and was carried ashore by a local upwelling event. This suggests that the seabed is a local sink as litter items occasionally washes ashore during upwelling events (Koutsodendris et al., 2008; Woodall et al., 2014; Chubarenko and Stepanova, 2017; Weideman et al., 2020b). Plastic wastes in the sea water could lead to physical and toxicological harm of sea organisms and wildlife (Woodall et al., 2014). Hence, it is important that mitigation measures targeting at reducing the amount of plastics entering the marine environment generated by humankind are implemented.

Factors affecting litter abundance in the surf zone

Studies have shown that recreational activity of beachgoers is an important source of beach litter (Portz et al., 2011; Araujo et al., 2018; Gjyli et al., 2020; Chapters 2 and 3). In this study, the abundance of litter in the surf zone was negatively correlated to the number of beachgoers on the beach on prior day. This relationship could possibly be attributed to weather conditions such as windspeed and rainfall, as beachgoers are likely to avoid the beach during rainy and windy days, which are favourable conditions for higher litter loads in the surf zone. People also tend to avoid the beach if it is full of litter, and as a result litter on beaches can reduce its aesthetic and economic values (Ballance et al., 2000). The increase in litter brought about by storms, wind, and rain can however be mitigated by beach cleaning. High wind speed was another factor influencing the abundance of litter in the surf zone. Strong onshore winds facilitate stranding of litter on beaches (Thiel et al., 2013; Duhec et al., 2015; Pfaff et al., 2019). In my study, the wind direction was mostly onshore (southerly), preventing sandy beach litter from being blown into the sea. However, on a few occasions, offshore winds (northerly) blew the dry sand litter items (from beachgoers) into the adjacent nearby sea. The net tows captured some of the dry sand litter in the daily catch of items from the surf zone and the few dry sand litter items collected were fresh and buoyant. These items were of South African origin, which suggests that mitigation should be geared toward encouraging beachgoers to change their behaviour and educating them about plastic pollution. Tidal movement is another important factor in the transfer of litter items between the seawater and the sandy beach (McDermid and McMullen, 2004; Eriksson et al., 2013). In my study, tidal movement had no significant impact on the abundance of litter items in the surf zone at Muizenberg. This might be due to other factors overwhelming any effect of tidal direction or state on the abundance of litter items. But, on a few peak days, such as Christmas and New Year's Day, when beachgoer numbers were high and more beach litter was generated, the incoming tide might have carried away much of the litter. The mesh net captured only a small portion of the water volume. So, the effect was not clearly reflected in the collected items. Addressing this limitation might require using larger nets.

Variations in the size and composition of beach and surf zone litter

In the surf zone, most of the litter items collected were in size categories 5 and 6 in both sampling years, indicating the prevalence of smaller litter items. No litter items > 10g (size categories 2 and 1) were collected in the surf zone, whereas on the sandy beach, some of the litter items were found in the size categories 2 and 1. The difference in the size of litter items between the surf zone and the wet and dry sand can be explained in part by the sampling methods applied. Hand picking on beaches targeted items of > 10 mm, while the net captured items down to 2-5 mm in the surf zone.

By composition (excluding the small items), single-use plastic packaging-related items were the most abundant type of litter recorded in the surf zone. (by number and mass). These are items that are easily washed down storm drains and rivers into the sea (Rech et al., 2014; Weideman et al., 2020a; Ryan and Perold, 2021). Plastic packaging-related pollution is a major problem in South Africa and these items are commonly found in the marine environment in South Africa (Chikata and von Blottnitz, 2019; Weideman et al., 2020b; Ryan and Perold, 2021). Weidemann et al. (2020b), for example, found that plastic packaging was the most prevalent litter item washing ashore along the sandy and rocky shore at Muizenberg. By contrast, on the sandy beach (dry sand) most litter items (by number) were made from paper and card or were smoking-related items (mainly cigarette butts), while by mass, most were glass drink bottles (Chapters 2 and 3). On the wet sand (litter items washing ashore), smoking-related items (mainly cigarette butts), dominated by number. These are easily washed onto beaches through rivers and storm drains from the urban streets (Ryan et al., 2020a; Weideman et al., 2020a; Barnardo et al., 2021; Chapters 2 and 3). By mass, much heavier items were recorded, such as marine crates, pipes, a bike helmet, processed wood, and car parts, (Chapters 2 and 3) indicating that the composition of litter items collected on the sandy beach (from beachgoers and items washing onto the beach) and those collected in the surf zone differ, and that litter items originating from beachgoers are not a major source of litter items in the nearby sea via the surf zone.

Conclusions

My study showed that the quantity of surf zone litter can vary significantly from day to day. Occasional episodes of high litter abundance were observed, lasting one to two days. Notably, during 2013/14, a few days with elevated litter densities were likely influenced by local upwelling events, which may have displaced litter from the seabed. A negative correlation was observed between litter abundance and the number of beach users, as the weather conditions that increase litter abundance also deter people from visiting the beach. Beach littering when the number of beachgoers is high, mainly on busy days such as Christmas and New Year's Day, were expected to increase the input of litter in the surf zone, but the dominant onshore wind at Muizenberg largely prevented sandy beach litter from reaching the sea. Most of the litter collected from the surf zone was smaller items (< 10 g). On the sandy beach, some items tended to be larger (> 10 g). By composition, litter items collected in the surf zone differed from that on the adjacent sandy beach. Most of the items collected from the surf zone were small, degraded, single-use plastic packaging-related items (by number and mass) which had been at sea for a while (with evidence of bites and epibionts). On the sandy beach, litter comprised smoking-related (mainly cigarette butts) and paper items on the dry sand, but on the wet sand, it was mainly smoking-related items (mainly cigarette butts). Glass drink bottles and processed timbers made up most of the mass. Indicating that litter characteristics in the surf zone differs from those on the sandy beach. The few new items collected from the surf zone might have been washed down from storm drains, rivers or blown from the sandy beach (mainly during offshore winds), suggesting a need for local solutions to littering, such as awareness campaigns. Findings indicated that only a small proportion of sandy beach litter generated by beachgoers migrated offshore via the surf zone. The assumption that there was a relationship between the number of beachgoers and litter abundance in the surf zone was not supported by this dataset.

Supplementary materials: Chapter 4

Table S4. 1. Summary of the exceptions to the sampling protocol in 2013/14 sampling year.

Date	Transects	Transects/day
29/11/2013	Only T1	3
30/11/2013	Only T1	3
01/12/2013	Only T1	3
02/12/2013	Only T1	3
03/12/2013	Only T1	12
04/12/2013	Only T1	3
05/12/2013	Only T1	3
06/12/2013	Not Sampled	Not Sampled
07/12/2013	Not Sampled	Not Sampled
17/12/2013	Only T1	4
19/12/2013	Only T1	6
15/01/2014	Only T1	6

Table S4.2. Summary of the exceptions to the sampling protocol in 2022/23 sampling year.

Date	Transects	Transects/day
29/11/2022	Both transects	6
30/11/2022	Both transects	6
01/12/2022	Both transects	8

Table S4.3. Deterioration state of litter items collected in the surf zone in the different sampling years by number and mass. Fresh items = score 0, Old/degraded items = score 2, and intermediate or final items = score 1.

Sizes	2013/14		2022/23	
	number	**mass**	**number**	**mass**
New	15%	44%	14%	33%
Old	18%	13%	35%	24%
Intermediate	66%	43%	51%	43%
Total	**3606**	**269.2**	**651**	**81.5**

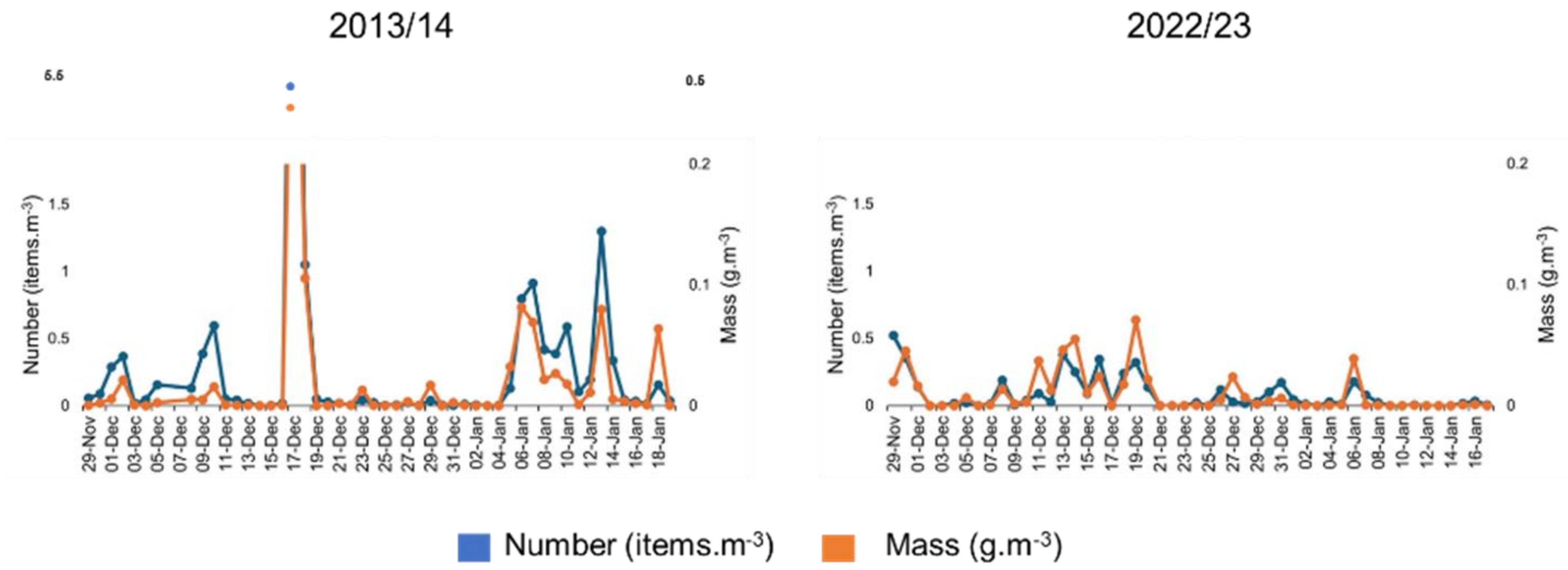


Fig S4.1. Time series (50-days sampling) of litter densities by number and mass in the different sampling years.

Table S4.4. The daily abundance (items·100 m^{-3}) and density (g·100 m^{-3}) of items collected in the different sampling years at T1 and T2 for the 50 days sampling period. Given the mean ± SD, median and interquartile range.

	Number of items		**Mass of items (g)**	
	2013/14	**2022/23**	**2013/14**	**2022/23**
		Transect 1		
Total	2640	388	226.9	58.7
Mean ± SD	23.3 ± 76.1	5.0 ± 8.9	1.9 ± 6.6	0.7 ± 1.0
Median (IQR)	2.5 (0.6-16.0)	1.1 (0-5.0)	0.1 (0-1.0)	0.02 (0-0.6)
		Transect 2		
Total	966	263	42.4	22.8
Mean ± SD	5.4 ± 9.8	3.2 ± 6	0.2 ± 0.6	0.3 ± 0.5
Median (IQR)	0.7 (0-6.0)	0.5 (0-3.0)	0.10 (0-0.1)	0.003 (0-0.1)

Table S4.5. GLM outputs of abundance of items (number per 100 m^3) modelled in relation to transect type, sampling years, wind strength and direction, tidal cycle, tidal height, rainfall, and maximum number of beachgoers between sampling years (100 days net sampling). The model explained 28% of the deviance (variation). The intercept in the model includes sampling transect (T2), sampling year (2013), wind direction (offshore), tidal cycle (incoming or advancing). The GLM was fit with a negative binomial distribution due to overdispersion in the data.

	Estimate (±SE)	Z-value	P-value
Intercept	1.117 ± 0.847	1.318	0.1874
Transect			
T1	0.607 ± 0.246	2.464	**0.0137**
Year			
2022/23	-1.191 ± 0.288	-4.142	**0.0001**
Wind direction			
Onshore	0.073 ± 0.326	0.225	0.8223
Tide			
Falling	0.249 ± 0.283	0.880	0.3789
Tide height	0.459 ± 0.250	1.831	0.0671
Wind speed	0.116 ± 0.049	2.359	**0.0183**
Rain	0.022 ± 0.050	0.445	0.6562
Beachgoers	-0.004 ± 0.001	-4.363	**0.0001**

Table S4.6. GLM outputs of abundance of items (mass per 100 m^3) modelled in relation to transect type, sampling years, wind strength and direction, tidal cycle, tidal height, rainfall, and maximum number of beachgoers between sampling years (100 days net sampling). The model explained 30% of the deviance (variation). The intercept in the model includes sampling transect (T2), sampling year (2013), wind direction (offshore), tidal cycle (incoming or advancing). The GLM was fit with a negative binomial distribution due to overdispersion in the data. The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	-0.900 ± 0.756	-1.191	0.2351
Transect			
T1	0.857 ± 0.223	3.839	**0.0002**
Year			
2022/23	-0.472 ± 0.262	-1.802	0.0731
Wind direction			
Onshore	0.106 ± 0.292	0.364	0.7159
Tide			
Falling	-0.158 ± 0.257	-0.616	0.5385
Tide height	0.253 ± 0.227	1.114	0.2667
Wind speed	0.081 ± 0.045	1.798	0.0737
Rain	0.036 ± 0.046	0.773	0.4407
Beachgoers	-0.001 ± 0.001	-1.707	0.0894

Table S4.7. Excluding days with outliers - daily abundance (items·100 m^{-3}) and density (g·100 m^{-3}) of items collected in the different sampling years at T1 and T2 for the 50 days sampling period. Given the mean ± SD, median and interquartile range.

	Number of items		**Mass of items (g)**	
	2013/14	**2022/23**	**2013/14**	**20223/23**
		Transect 1		
Total	904	388	63.6	58.7
Mean ± SD	7.3 ± 11	5.0 ± 8.9	0.45 ± 0.8	0.7 ± 1.0
Median (IQR)	2.2 (0.6-8.9)	1.1 (0-5.0)	0.04 (0-0.38)	0.02 (0-0.6)
		Transect 2		
Total	966	263	42.4	22.8
Mean ± SD	5.4 ± 9.8	3.2 ± 6	0.2 ± 0.6	0.3 ± 0.5
Median (IQR)	0.7 (0-6.0)	0.5 (0-3.0)	0.10 (0-0.1)	0.003 (0-0.1)

Table S4.8. Excluding days with outliers - GLM outputs of abundance of items (number per 100 m^3) modelled in relation to transect type, sampling years, wind strength and direction, tidal cycle, tidal height, rainfall, and maximum number of beachgoers between sampling years (100 days net sampling). The model explained 21% of the deviance (variation). The intercept in the model includes sampling transect (T2), sampling year (2013), wind direction (offshore), tidal cycle (incoming or advancing). The GLM was fit with a negative binomial distribution due to overdispersion in the data.

	Estimate (±SE)	Z-value	P-value
Intercept	0.821 ± 0.813	1.010	0.3124
Transect			
T1	0.151 ± 0.238	0.635	0.5253
Year			
2022/23	-0.780 ± 0.276	-2.823	**0.0048**
Wind direction			
Onshore	-0.047 ± 0.310	-0.152	0.8790
Tide			
Falling	0.400 ± 0.271	1.476	0.1400
Tide height	0.591 ± 0.241	2.450	**0.0143**
Wind speed	0.107 ± 0.048	2.247	**0.0246**
Rain	0.047 ± 0.048	0.990	0.3222
Beachgoers	-0.003 ± 0.001	-3.776	**0.0002**

Table S4.9. Excluding days with outliers - GLM outputs of abundance of items (mass per 100 m^3) modelled in relation to transect type, sampling years, wind strength and direction, tidal cycle, tidal height, rainfall, and maximum number of beachgoers between sampling years (100 days net sampling). The model explained 14% of the deviance (variation). The intercept in the model includes sampling transect (T2), sampling year (2013), wind direction (offshore), tidal cycle (incoming or advancing). The GLM was fit with a negative binomial distribution due to overdispersion in the data. The GLM was fitted with a Gamma distribution to account for the skewness and semi-continuous nature of the data.

	Estimate (±SE)	T-value	P-value
Intercept	-0.638 ± 0.700	-0.913	0.3626
Transect			
T1	0.434 ± 0.208	2.089	**0.0381**
Year			
2022/23	-0.067 ± 0.243	-0.278	0.7813
Wind direction			
Onshore	0.000 ± 0.268	0.000	1.0000
Tide			
Falling	-0.033 ± 0.238	-0.127	0.8988
Tide height	3.151 ± 0.211	1.497	0.1361
Wind speed	0.037 ± 0.042	0.900	0.3695
Rain	0.053 ± 0.042	1.254	0.2113
Beachgoers	-0.000 ± 0.000	-0.631	0.5291

Table S4.10. Percentage composition by number and mass of items in the surf zone collected during 2013/14 and 2022/23. Note this composition included Size 3 = 1 – 10g, size 4 = 0.10 – 1g, size 5 = 0.01 – 0.10g, and size 6 = 0.001 – 0.01g.

Litter Category	**2013/14**		**2022/23**	
	Number	**Mass**	**Number**	**Mass**
Paper and card items	<1%	<1%	<1%	<1%
Smoking items	<1%	<1%	1%	1%
Snack food packaging	<1%	<1%	7%	18%
Sweet packaging	<1%	<1%	5%	7%
Drink bottles and lids	<1%	<1%	<1%	<1%
Fast-food packaging	<1%	<1%	<1%	<1%
Other food packaging	21%	28%	28%	24%
Other bottles and lids	<1%	<1%	<1%	1%
Other packaging	58%	43%	44%	36%
Disposable	<1%	<1%	<1%	<1%
Sewage	<1%	<1%	2%	3%
Fishing and shipping	2%	<1	7%	6%
Other user items	4%	6%	<1%	<1%
Plastic fragment	15%	22%	4%	4%
Non-plastic	<1%	<1%	<1%	<1%
Total	**3606**	**269.2**	**651**	**81.5**

Table S4.11. Percentage composition by number and mass of items in the surf zone and sandy beach (dry and wet sand) collected during 2022/23. Note size 6 (0.001-0.01g) was excluded from this comparison.

Litter Category	**Surf zone**	**Wet sand**	**Dry sand**	**Surf zone**	**Wet sand**	**Dry sand**
		Number			**Mass (g)**	
Paper and card items	1%	1%	22%	<1%	1%	13%
Smoking items	1%	21%	27%	1%	4%	2%
Snack food packaging	7%	8%	6%	18%	3%	3%
Sweet packaging	7%	11%	10%	7%	4%	1%
Drink bottles and lids	<1%	9%	7%	<1%	17%	52%
Fast-food packaging	<1%	2%	5%	<1%	2%	3%
Other food packaging	26%	9%	8%	24%	5%	3%
Other bottles and lids	<1%	<1%	<1%	1%	<1%	<1%
Other packaging	45%	10%	4%	36%	13%	4%
Disposable	<1%	1%	3%	<1%	1%	1%
Sewage	3%	3%	1%	3%	2%	2%
Fishing and shipping	3%	6%	1%	6%	7%	<1%
Other user items	<1%	2%	2%	<1%	22%	5%
Plastic fragment	6%	14%	2%	4%	7%	1%
Non-plastic	<1%	3%	3%	<1%	14%	10%
Total	**419**	**4360**	**4064**	**80.4**	**19840.8**	**9213.5**

Chapter 5: Synthesis

Large crowds on Muizenberg beach on 1 January 2023. Photo: Peter Ryan

Beaches worldwide provide significant social, ecological, and economic benefits to humanity (Mouat et al., 2010; Arabi and Nahman, 2020; Chapter 1). They play a critical role in the socio-economic development of coastal communities by generating income and creating employment opportunities. In South Africa, tourism plays a vital economic role, employing 9.8% of the workforce and contributing R125 billion (US$8.2 billion), or 2.9% of GDP, to the economy in 2016 (Arabi & Nahman, 2020; Chapter 3). Beach litter diminishes the aesthetic and socio-economic value of coastal environments, with the resultant negative impacts deterring tourists from visiting these areas (Ballance et al., 2000; Arabi and Nahman, 2020; Chapter 1). Consequently, implementing effective mitigation measures to address beach litter is essential, not only for environmental conservation but also for maintaining the socio-economic benefits associated with beaches.

Litter on beaches originates from various sources: 1) local land-based sources that transport litter from urban areas via rivers and storm drains which gets stranded on beaches shortly after entering the sea (Rech et al., 2014; Maclean et al., 2021; Ryan and Perold, 2021); 2) beachgoers who litter beaches during recreational activities; 3) ships that dump litter while at sea; or 4) marine litter that can drift long distances (Ryan et al., 2009; Veiga et al., 2016; Ryan, 2023; Ryan et al., 2024). Quantifying sources of beach litter is essential for effective mitigation actions, and this is what my thesis explores by addressing two main aims: 1) estimating the relative litter input from beachgoers, and 2) exploring how much of beachgoer litter might be exported offshore via the surf zone.

First, I explored the sources of beach litter by applying the dry and wet sand method developed by Barnardo and Ribbink (2020) and Ryan et al. (2020b) (Chapter 2). This method has been applied in a few studies (Okuku et al., 2020; Barnardo et al., 2021) but has not been validated. I tested the efficacy of the method by comparing the daily accumulation rate of litter items at two urban beaches with different visitation rates during two time periods; during the COVID-19 pandemic, when the beaches were closed to visitors, and after the pandemic in 2023. I applied the dry–wet sand method to infer the contribution of beachgoers to beach litter when the beaches were re-opened, to see whether the dry sand component accounted for differences between years with and without visitors. I also compared the amount and composition of litter on dry sand (likely from beachgoers) and wet sand (likely from offshore sources) at both beaches sampled seasonally (Chapter 3). Finally, I evaluated if the litter generated by beachgoers migrates to the adjacent ocean via the surf zone (Chapter 4). The main outcomes of my research are as follows:

Estimating the contribution of beachgoers to beach litter loads

In Chapter 2, I investigated how the daily dry sand litter accumulation could be used to infer litter originating from beachgoers. I compared the amount and composition of daily litter accumulations collected during the COVID-19 pandemic (in the absence of beachgoers) and in 2023 (when beaches were open to visitors) at two urban beaches. I expected greater litter loads in 2023 due to the presence of recreational activities on beaches, but interestingly litter loads were higher in 2020 than in 2023 at both beaches. Higher litter accumulation when the beaches were closed to visitors can be attributed, in part, to more onshore winds in 2020 than in 2023, which facilitated the deposition of marine debris onto the beach (Duhec et al., 2015; Chitaka and von Blottnitz, 2019; Thiel et al., 2021). The presence of less litter while beaches were being frequented can be partly attributed to, and highlights the relevance of, informal beach cleaning (Ballance et al., 2000; Mouat et al., 2010). Litter composition differed between the two periods. In 2020, I found that the predominant litter types, such as fishing and shipping items, drink bottles and lids, had bites and epibionts, which suggest that they have been at sea for prolonged periods (Duhec et al., 2015; Ryan, 2023; Ryan et al., 2024). In 2023, I recorded that the predominant litter types were those most likely left behind after recreational activities mainly on the dry sand such as items made from paper and smoking related items (Martinez-Ribes, 2007; Portz et al.; Weideman et al., 2020a; Barnardo et al., 2021; de Melo Nobre et al., 2021; Yona et al., 2023). By excluding the dry sand litter from the principal component analysis for 2023, I found that the composition of litter was different in 2020, when the beaches were empty of visitors. This outcome supported the use of daily accumulation data on the dry sand as a reasonable proxy for beachgoer litter contributions. I recorded that litter (by number) on the dry sand accounted for 23% of daily beach litter at Muizenberg and 6% at Sunrise , indicating the prevalence of more litter from beachgoers at a popular urban beach (Araújo et al., 2018; Okuku et al., 2020; Barnardo et al., 2021). These results were similar to those of Barnardo et al. (2021), who found that dry sand litter at Bluewater Bay, a popular beach, contributed 39%, and 17% at Cape Recife, a secluded beach. The similarity of our findings, which were arrived at by sampling beaches with similar visitor numbers and by using the same method, indicate that the litter collected on dry sand provides a useful measure of beachgoer litter.

Seasonal fluctuations in beachgoers litter: A comparison of two South African beaches

In Chapter 3, I used dry sand daily accumulation data to infer the extent of littering by beachgoers seasonally at the two beaches. I recorded that the daily accumulation of dry sand litter (from beachgoers) was higher in summer than in spring, autumn or winter, particularly at the more popular urban beach (Muizenberg). This finding aligns with studies on seasonal variations in beach litter, particularly at popular recreational beaches during peak seasons (Martinez-Ribes et al., 2007; Araújo et al., 2018; Barnardo et al., 2021; de Ramos et al., 2021). I also found a strong correlation between the daily accumulation of dry sand litter and the number of beachgoers in summer (Fig. 3.1A), suggesting that people who visit the beach in summer are more likely to litter (Martinez-Ribes et al., 2007; Portz et al., 2011; Silva et al., 2016; Araujo et al., 2018; Barnardo et al., 2021; de Ramos et al., 2021). This can be attributed to the likelihood, during peak season, of extended beach visits, engaging in recreational activities that would produce more litter. My findings highlight the need for more frequent beach clean-ups during peak season, along with additional mitigation measures such as educational litter awareness campaigns and the installation of more waste bins. The overall contribution from beachgoers was estimated at 35% at Muizenberg (popular beach) and 4% at

Sunrise (less popular beach) by number. These results revealed that beachgoers are not the primary source of beach litter. The major source is litter washing ashore (wet sand), either from local land-based sources, entering False Bay via rivers and storm drains, or from offshore sources. These conclusions highlight the need for local intervention actions on land as well as better enforcement of legislation banning the dumping of plastics from vessels at sea (Ryan et al., 2021).

Seasonally, the proportion of dry sand litter (by number) varied between 19% and 60% at Muizenberg, whereas at Sunrise, it ranged from 1% to 8%. My findings suggest that was similar to that of Barnardo et al, who arrived at 39% and 17% (2021). Our findings diverge slightly for the amount of litter contributed in summer (60% at Muizenberg and 40% at Bluewater Bay), but this can be explained by a slight difference in sampling times: mine were in peak season (Dec-Jan), while theirs occurred in October and February, just outside of the peak season. Of the15 studies of urban beaches that used other methodologies (attribution by type, indicator items, or matrix scoring) (Chapter 1, Table 2), only five reported a beachgoer contribution of < 50%, with results ranging from 8-37%. The rest reported contributions ranging from 52-94%. Differences in results may in part be due to variations in numbers of beachgoers and the types of beaches studied as well as methods used in assessing the contribution of beachgoers to beach litter loads. Arun et al (2016), for example, reported a beachgoer contribution to beach litter of 75%, but this finding is not surprising given that the beach in question receives, on average, 30 000 visitors during the week and 50 000 on weekdays and holidays. Another factor could be differences in methodologies across studies, either highlighting a weakness in the methodology, or demonstrating that direct comparisons of studies using differing methodologies should be made cautiously. For example, two studies of urban beaches classified a > 50% proportion of beach litter as of "unknown" or "mixed" origin (Santos et al., 2009; Silva-Iniguez and Fischer, 2003). Using the attribution by litter type method, Santos et al (2009) attributed just 8% of litter to beachgoers, and classified 54% as of unknown origin. Silva-Iniguez and Fischer (2003) used the indicator method and reported a beachgoer contribution of 18%, with 69% of beach litter classified as of unknown origin, or originating from mixed sources.

Does beachgoer litter migrate into the surf zone?

In Chapter 4, I tested if litter from beachgoers is a major source of litter found in the surf zone adjacent to the beach during the peak season. In 2022/23, I repeated a study conducted in

2013/14 that compared the composition of litter items on the sandy beach with that in the nearby surf zone 2022/23). Comparing the litter loads in the two periods, I found a significant decrease in 2022/23, which suggests that environmental education and awareness campaigns have been effective in mitigating beach littering and in improving waste management. In 2013/14, the few occasions with very high litter densities lasting one to two days were likely influenced by local upwelling events (Weideman et al., 2020b). Suggesting that the seabed at Muizenberg is a local sink for plastic pollution (Pfaff et al., 2019; Weideman et al., 2020b). As discussed in Chapter 3, the proportion of dry sand litter from beachgoers peaked in summer. Studies have revealed that beach visitors are an important source of beach litter during the peak season (summer) (Araújo et al., 2018; Martinez-Ribes et al., 2007; Barnardo et al., 2021), and it is assumed that litter from beachgoers enters the marine environment through the surf zone (Thiel et al., 2013). However, I found a negative relationship between the amount of litter recorded in the surf zone and the number of beachgoers on the previous day. Weather conditions, such as strong wind or rain events, which simultaneously deter beachgoers and increase surf zone litter, may account for this relationship. I expected to see more litter from beachgoers (dry sand) being transported offshore, but onshore winds predominated at Muizenberg during the sampling periods, limiting litter migration into the sea. On the few days with offshore winds, some of the sampled litter included food packaging items which come the dry sand and other local, land-based sources (Weideman et al., 2020b; Ryan et al., 2020a; Chitaka and von Blottnitz, 2019), confirming the need for measures to be put in place to curb littering. Most of the litter items in the surf zone were small, single-use plastics (< 10 g) that showed signs of damage or colonisation by marine organisms, indicating their prolonged stay in the sea (Duhec et al., 2015; Ryan, 2023; Ryan et al., 2024). On the sandy beach, some of the larger litter items (>10 g) primarily composed of items from paper and smoking-related items, mainly cigarette butts (Martinez-Ribes et al., 2007; Araújo et al., 2018; de Melo Nobre et al., 2021; Chapter 3). The assumption that litter from beachgoers is the major source of litter in the nearby ocean via the surf zone was not established by this study.

Takeaway key points and possible solutions

The findings from chapter 2 suggest that it is encouraging that more people are becoming aware of the issue of marine pollution and actively working to reduce it. I found that litter on beaches is still a major concern. Informal beach cleaning (no formal cleaning during this study) plays a crucial role in removing significant amounts of anthropogenic waste that contributes to the degradation of beach aesthetics and overall environmental quality (Ballance et al., 2000; Mouat et al., 2010). Additionally, these cleanup efforts promote environmental stewardship by encouraging public participation in conservation activities (Mouat et al., 2010). Chapter 3 highlights the role of beachgoers in contributing to beach litter loads, but only on heavily used beaches, particularly during summer. Mitigation measures should be geared towards sensitizing beach visitors to the need for reducing litter on beaches and more waste bins should be made available during summer. More importantly, beachgoers need to be educated about the consequences of the litter they leave behind. Partnering with NGOs, schools, and the private sector through corporate social responsibility (CSR) initiatives can support awareness campaigns and clean-ups, helping reduce litter and promoting responsible beach use. Encouraging individuals to change deeply ingrained habits can be challenging without adequate education and the enforcement of laws and regulations (Schultz et al., 2013; da Costa, 2020). It is essential for beachgoers to acknowledge their contribution to this issue, adjust their attitudes, and actively participate in mitigating beach litter. On the other hand, litter on wet sand at Muizenberg (originating from rivers, storm drains, and offshore sources) accounted for > 50% of beach litter. Mitigation measures should be targeted not only at removing litter from storm drains and the river mouth, but also at littering in general, as these litter items originate from street litter. Chapter 4 underscores the fact that, while beachgoers can be a significant source of beach litter (Barnardo et al., 2021; Chapter 3), relatively little of this litter migrates offshore, unless there are strong offshore winds. Litter in the surf zone at Muizenberg mainly comes from rivers, storm drains, and offshore sources. The assumption that there was a relationship between the number of beachgoers and litter abundance in the surf zone was not supported by this study.

Limitations

This study faced certain limitations that should be considered in future research. In chapters 2 and 3, one challenge was the potential removal of beach litter due to informal cleaning efforts, which may have affected sampling accuracy. Informing the public about ongoing research and placing strategically located signs on-site could help mitigate this issue (Barnardo and Ribbink, 2020; Barnardo et al., 2021). Additionally, this study did not account for the types of beach users and their behaviours, which may influence litter accumulation. Understanding how different user groups such as picnickers, walkers, or swimmers contribute to littering could provide a more refined analysis of the primary sources of beach litter (from beachgoers). Finally, the mesh net size used affected the size of samples collected in chapter 4. Only a small area could be covered by the net.

Suggestions for Future Research

Future studies should refine beachgoer counts by categorizing individuals based on their activities, allowing for a more detailed understanding of littering behaviours. Also, future research should investigate beachgoer demographics, including whether visitors are local residents or tourists. This information could help identify key litter sources, improve the targeting of awareness campaigns, and support more effective mitigation strategies. To improve sample collection in chapter 4, larger mesh nets should be used, as they would be more effective in capturing the range of litter sizes typically found on beaches. Additionally, in chapters 2 and 3 repeated accumulation studies using the dry and wet sand method could provide valuable long-term data on litter trends and the effectiveness of mitigation efforts. This method has already been validated and has strong potential for monitoring changes in litter from beachgoers (Barnardo and Ribbink, 2020). Expanding its application beyond the Western Cape to other provinces and even internationally could help establish key baseline data for beach litter monitoring and management.

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