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Marine litter pollution on uninhabited islands in Estonia, northeastern Baltic Sea

Tiia Möller-Raid, Maria Põldma, Kristjan Herkül, Kaire Torn, Georg Martin, Kaire Kaljurand, Martin Teeveer, Greta Reisalu, Trude Taevere, Hanna-Eliisa Luts, Karolin Teeveer, Keili Saava, Annely Enke and Lauri London

Estonian Marine Institute, University of Tartu, Mäealuse 14, 12618 Tallinn, Estonia

RESEARCH ARTICLE

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Corresponding author:
Tiia Möller-Raid
tiia.moller@ut.ee

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ABSTRACT

This paper provides results of marine litter surveys carried out on 14 small uninhabited islands located in the coastal waters of Estonia, northeastern Baltic Sea. The islands were visited four times in total during 2019–2020. On each island, a litter survey was conducted on the beach and in terrestrial vegetation with a focus on macrolitter. Calculated over all surveys, the median value of macrolitter items per 100 m long beach section was 10.65, and the median density was 0.006 items m^{-2}. At the sub-basin level, the three islands located in the Gulf of Finland had the highest number of beach litter items per 100 m and the highest density (items m^{-2}), 38.05 and 0.017, respectively. The main litter material, representing 57.3% of all findings, was plastic; however, there were some variances across islands due to local conditions. The environmental variables most strongly correlated with differences in the composition of macrolitter were related to water movement and depth. Microlitter was found in low amounts (up to 60 items kg^{-1}) in the sediment of all studied islands. Litter items used as nest material were noted on all the islands with seabird colonies.

1. Introduction

Human-induced litter is a growing global problem (Borrelle et al. 2020). Marine litter can be found in all marine compartments (beaches, sea surface, water column, seafloor, and within biota) both close to human-populated areas and in remote areas (Galgani et al. 2013). Marine litter consists of items made or used by people that are deliberately discarded or unintentionally lost into the sea or onto beaches, including materials transported into the marine environment from land by rivers, drainage or sewage systems, or winds. Litter, especially plastic, directly affects marine ecosystems and is considered environmentally, economically, and psychologically harmful (e.g., Wyles et al. 2016; Galgani et al. 2019).

The highest densities of litter have been reported adjacent to urban centers, in enclosed seas, and on waterfronts (Barnes et al. 2009). However, distant areas, including remote islands, are also recognized as accumulation areas for marine litter, and considering the lack of human activities in those areas, the litter is transported there by water and wind (e.g., Lavers and Bond 2017; Lavers et al. 2019; Portz et al. 2022). For instance, on Henderson Island (South Pacific Ocean), which is located more than 5000 km from human habitation, the density of visible micro- and macrolitter on the beach has been reported to be as high as 671.6 items m^{-2} (Lavers and Bond 2017). Across Europe, the average presence of litter on the coastline is generally lower: in 2015–2016, the median beach macrolitter quantity was estimated at 150 items per 100 m long beach section, with different regional median values: 40 items per 100 m around the Baltic Sea; 106 items per 100 m around the Black Sea; 233 items per 100 m around the North-East Atlantic and the North Sea; and 274 items per 100 m around the Mediterranean Sea (Hanke et al. 2019). However, there is tremendous variability in litter abundance at the regional scale. For instance, in some regions of the Mediterranean Sea, visible litter can exceed 6600 items per 100 m long beach section (Vlachogianni et al. 2020).

The Baltic Sea region is currently regarded as the cleanest area in Europe in terms of beach litter (HELCOM 2018). Nevertheless, the number of litter items per 100 m of beach section most commonly varies between 50–300. The average number of beach litter items within the Baltic Sea region has been estimated at about 280 items per 100 m of beach section on urban beaches and up to 47 items per 100 m of coastline of natural beaches (HELCOM 2018). However, the threshold for Good Environmental Status (GES) in European seas related to beach litter is set at a maximum of 20 items per 100 m of coastline, which is the target to be achieved (van Loon et al. 2020; European Commission 2022).

Marine litter has various impacts on biota (Kühn et al. 2015) and is also a specific concern for marine protected areas (e.g., Rodríguez-Rodríguez 2012; Polasek et al. 2017; Ibrahim et al. 2020). Beached litter may remain on the shore and degrade into smaller particles (GESAMP 2015). It can also move into the water environment, inland, and/or be ingested by fauna. Among the various impacts on biota, entanglement, smothering, and ingestion are the most frequently described (Kühn et al. 2015). For seabirds, plastic debris as nesting material has already become common (Votier et al. 2011). However, as the use of litter in nests depends on specific species and the availability of litter in the environment, the presence of litter in nests is not ubiquitous – marginal existence of plastic in nests has also been reported, for example in two colonies in the Bay of Biscay, Spain (Delgado et al. 2020). Evidence further shows that plastic bags in dune vegetation affect germination phenology, seedling establishment, and plant interactions via leaching. These processes can lead to changes in dune community structure (de Francesco et al. 2018; Menicagli et al. 2019).

Though the topic of marine litter has gained considerable scientific and public attention in the last decades, there are still fundamental knowledge gaps, primarily in empirical data on the distribution, composition, and amounts of litter in the marine environment. Studies addressing the marine litter problem in the Baltic Sea region have escalated since 2010; earlier work focused mostly on beach litter (e.g., Strand et al. 2015), while in the last decade, more studies have examined microlitter, floating macrolitter, and effects on biota (e.g., Canals et al. 2021; Põldma et al. 2023; Schernewski et al. 2024).

Estonia's location, encompassing several major sub-basins of the Baltic Sea, with a diverse coastline and exposure to winds from several directions, predisposes its coastal areas to the accumulation of marine litter. Thus, the litter status of small uninhabited Estonian islands reflects overall litter pollution in the Baltic Sea and its sub-basins. Numerous small and remote islands are habitats for marine birds and seals, and many endangered plant species also grow in these areas. There are over 2000 islands in Estonian coastal waters; most are located within 5 km of the mainland, and about 90% are under nature conservation (Estonian Nature Conservation Act 2004).

Before this study, no systematic research on marine litter had been conducted on remote, uninhabited islands in the northeastern Baltic Sea. Moreover, most previous studies in the Baltic Sea region have focused on a single litter type without covering related aspects. For example, in beach macrolitter survey areas, no microlitter surveys have been carried out (Press 2020), and vice versa (Urban-Malinga et al. 2020; Ershova et al. 2021; Schröder et al. 2021). This study aimed to fill the knowledge gap on the status and pathways of litter in areas with limited direct human impact in the Baltic Sea. The research provides information on the amounts, composition, and distribution of marine litter on the coasts of small, remote Estonian islands, with a focus on marine macrolitter. To cover various aspects of marine litter and provide supplementary information, we also conducted microlitter surveys and monitored the effects of macrolitter on local biota, where visible. In addition, different survey areas, such as shallow coastal waters, beaches, and terrestrial vegetation near beaches, were covered. Potential relationships between environmental conditions, human pressure, and the amount and composition of marine macrolitter were also addressed.

2. Materials and methods

2.1. Study areas

The study was carried out on small islands located in the coastal waters of Estonia, in the northeastern part of the Baltic Sea (Fig. 1; Table 1). The Baltic Sea is an enclosed, non-tidal sea with a surface area of 420 000 km^2, a catchment area of approximately 1 641 650 km^2, and about 85 million people living around it. There are over one million islands in the Baltic Sea region, the vast majority belonging to Finland and Sweden.

Estonia borders several sub-basins of the Baltic Sea: the Gulf of Finland, the Northern Baltic Proper, the Gulf of Riga, and the Eastern Gotland Basin. The total length of the Estonian coastline is about 3800 km. Of this, 1242 km belong to the mainland, while the remaining ~2550 km belong to the 2222 islands. The Estonian coastline is highly heterogeneous and variable; different coastal types can be distinguished: till (35%), silt (31%), sand (16%), gravel (11%), cliffs (5%), artificial (2%; breakwaters, protecting walls, berms), and scarps (short sections between other shore types) (Tõnisson et al. 2013).

In this study, marine litter surveys were conducted on 14 islands – 13 of which were visited four times, and one only once. The islands were selected based on the following criteria: (1) they are spatially dispersed and represent different water basins; (2) the minimum area is 0.5 km^2; (3) the island has vegetation – at least grass as primary vegetation, but preferably also shrubs and trees; (4) permanent human settlement is absent (according to the Estonian Permanently Inhabited Small Islands Act 2003). The coasts are highly heterogeneous in the northeastern part of the Baltic Sea (Łabuz 2015). Thus, coastal geomorphology (including dominant sediments) of the beaches was not included as a selection criterion. Fieldwork was carried out between June 20, 2019, and October 13, 2020, with visits in different seasons (spring, summer, and autumn). Most of the islands are prohibited from being visited between April and June (bird nesting period), which also affected the timing of fieldwork (Table S1).

2.2. Fieldwork methodology and laboratory analysis

2.2.1. Amounts and composition of macrolitter

The beach litter survey methodology was based on suggestions by the United Nations Environment Programme and

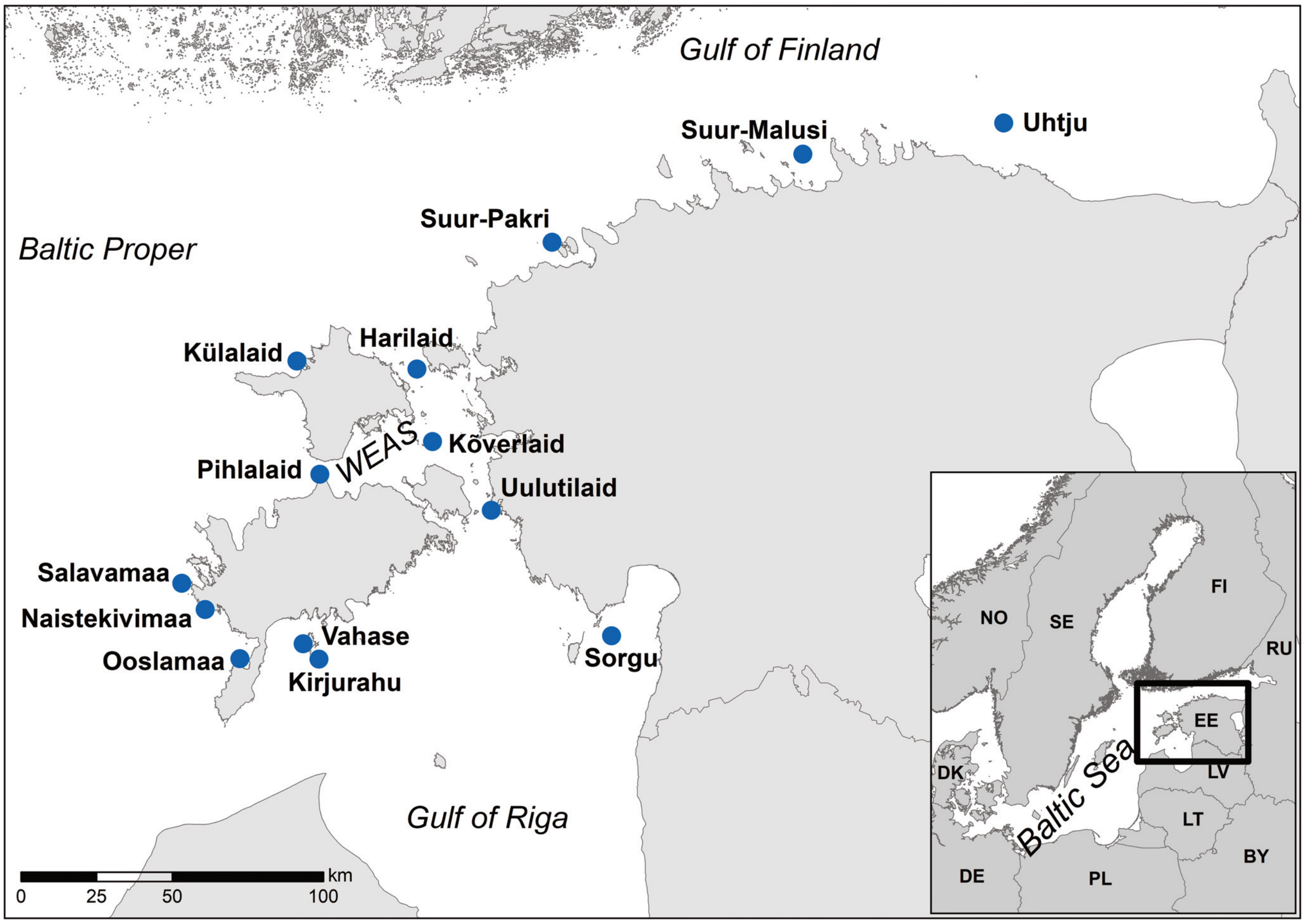

Fig. 1. Location map of the islands surveyed. WEAS – West Estonian Archipelago Sea.

Intergovernmental Oceanographic Commission (UNEP/IOC) Guidelines on Survey and Monitoring of Marine Litter (2009), MSFD (Marine Strategy Framework Directive) Technical Subgroup on Marine Litter Guidance on Monitoring of Marine Litter in European Seas (Joint Research Centre 2013), and previous beach litter research carried out in Estonia (Press 2020). On each island, litter surveys were conducted in three survey areas: shallow-water survey area, beach survey area, and vegetation survey area (Fig. 2). Shallow-water survey areas were situated in the water near the coastline at a depth of 0.5 m. Beach survey areas were located on land between the coastline and terrestrial vegetation. Beach survey areas were devoid of permanent live terrestrial vegetation. Vegetation survey areas were situated on land next to beach survey areas and were characterized by permanent live terrestrial vegetation (grasses, shrubs, or trees). All survey areas were parallel to the coastline.

According to the beach litter monitoring guidelines, litter should be monitored at least on a 100 m long beach section from the waterline to the back of the beach/start of vegetation (Joint Research Centre 2013) – this was set as a minimum in the current study. The length of the beach survey areas varied between 400–1000 m, and the width varied between 5–35 m (Table 1). Due to the often-present rough terrain and limited accessibility, the vegetation survey areas were generally shorter, and the length of the monitored area varied between 100–750 m. The main aim was to cover all the vegetation layers (primary, secondary, and tertiary) that were present on the island with the purpose of collecting the litter items that had moved inland with the highest water level (including extraordinary storms (Fig. 2). Depending on the local circumstances (i.e., the presence and dominance of either trees/shrubs or grass), the width of the vegetation survey area varied between 5–100 m (Table 1). However, there was great variation in the presence of vegetation layers among islands, e.g., some of the islands lacked shrubs or trees, and some of the islands lacked grass (Table 1). The location, length, and width of the survey areas shown in Table 1 remained constant for all the sampling campaigns.

The length of the shallow-water survey area was set to 100 m and the width to approximately 5 m. Observations in the shallow-water survey area were carried out via snorkeling or using a bathyscaphe. However, the amount of macrolitter in shallow-water areas was minimal and sporadic (only five items in total from three islands); therefore, data on macrolitter in shallow-water areas were not included in further analysis.

The classification system of litter items was based on a modified UNEP/IOC 2009 marine litter list to encompass organic waste (MARLIN 2013), resulting in UNEP/MARLIN codes for litter items found on Baltic beaches (82 categories in total; summarized, e.g., in Haaksi 2020). Accordingly, litter items were classified by material (nine categories): plastic, glass and ceramics (glass), processed wood (wood), textile,

Table 1. Overview of the islands surveyed. Sub-basins: GoF – Gulf of Finland, BP – Baltic Proper, GoR – Gulf of Riga, WEAS – West Estonian Archipelago Sea. Coordinates represent the location of each island, not the exact study area. The beach substrate and terrestrial vegetation taxa describe the dominant features of the islands. Length and width of the surveyed areas are shown separately for beaches and terrestrial vegetation. N – geographical latitude (WGS84), E – geographical longitude (WGS84). Vegetation layers are indicated as follows: ^{1} – primary, ^{2} – secondary, ^{3} – tertiary

Island	Abbreviation	Sub-basin	N	E	Coastline, km	Area, km^2	Beach survey area			Vegetation survey area		
							Substrate	Length, m	Width, m	Vegetation	Length, m	Width, m
Harilaid	Har	WEAS	58.9664	23.0864	3.14	1.50	Sand, stones	500	12	Grass^1	250	20
Kirjurahu	Kir	GoR	58.0993	22.5586	2.03	0.52	Sand, stones	1000	20	Grass^1	160	60
Kõverlaid	Kov	WEAS	58.7520	23.1802	3.16	3.05	Sand, stones	600	5	Grass^1, juniper^2, pine^3	250	5
Külalaid	Kul	BP	58.9841	22.3953	3.34	1.62	Limestone, pebbles, boulders, sand	600	15	Grass^1, juniper^2, pine^3	220	30
Naistekivimaa	Nai	BP	58.2382	21.9123	2.18	1.80	Limestone, pebbles	430	15	Grass^1	370	30
Ooslamaa	Oos	BP	58.0948	22.1160	2.10	0.51	Sand, boulders	1000	12	Grass^1	650	30
Pihlalaid	Pih	WEAS	58.6489	22.5408	1.99	0.66	Stones, pebbles, gravel	1000	12	Grass^1	650	30
Salavamaa	Sal	BP	58.3138	21.7762	3.47	2.66	Limestone, pebbles, boulders, sand	850	15	Grass^1, juniper^2	750	5
Sorgu	Sor	GoR	58.1766	24.2006	2.08	0.58	Sand, stones	550	15	Grass^1, juniper^2	100	100
Suur-Malusi	Sma	GoF	59.6018	25.3288	1.55	0.62	Sand, boulders	400	20	Grass^1	300	40
Suur-Pakri	Spa	GoF	59.3464	23.8620	22.84	12.68	Limestone, pebbles	600	25	Juniper^2	600	25
Uhtju	Uht	GoF	59.6772	26.5122	2.28	0.96	Sand, boulders	1000	30	Grass^1	350	50
Uulutilaid	Uul	GoR	58.5492	23.5195	4.87	3.16	Limestone pebbles, boulders, sand	620	35	Grass^1, juniper^2	470	10
Vahase	Vah	GoR	58.1438	22.4687	6.95	0.72	Gravel, stones	750	15	Grass^1, juniper^2, pine^3	720	10

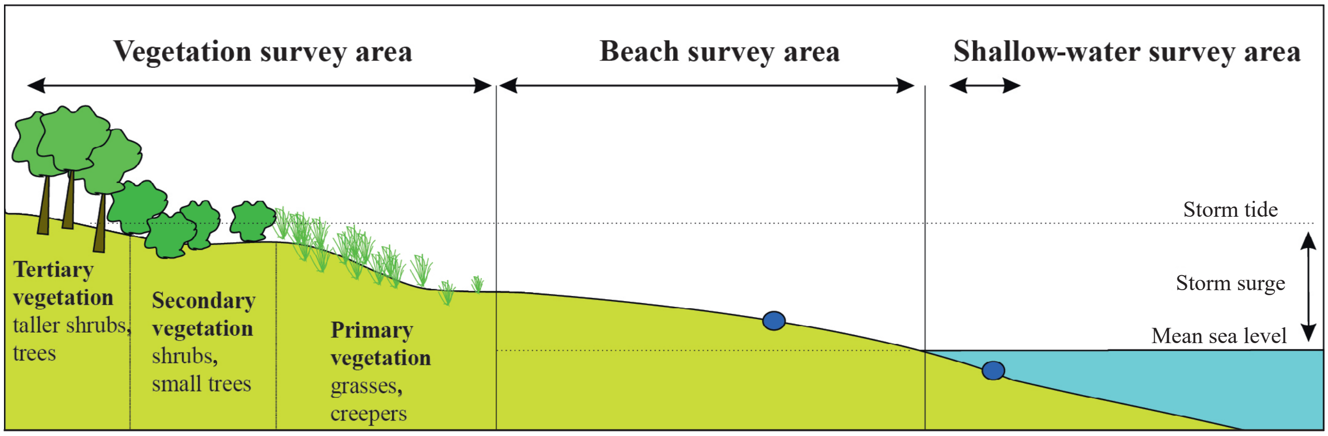

Fig. 2. General sampling scheme illustrating the locations of the survey areas for macrolitter. Blue dots indicate the microlitter sampling areas (shallow-water and beach survey areas).

paper, metal, organic, rubber, and other. The most relevant litter codes (J-codes) of the Europe-oriented marine macrolitter classification system were added for data comparability (Fleet et al. 2021); however, because the classification systems do not fully overlap and an item classified under UNEP/MARLIN may correspond to several MSFD litter codes, the original UNEP/MARLIN classification system was retained as the basis. To estimate possible sources of litter pollution, items were also assigned to source categories: agriculture-related, aquaculture-related, clothing, building and construction-related, fisheries-related, personal hygiene and care-related, medical-related, undefined use, recreation-related, smoking-related, vehicle-related, and hunting-related (based on Fleet et al. 2021).

All visible litter items were recorded in the protocol and, when possible, collected and removed from the survey areas. Most collected items were in the size class >2.5 cm (macrolitter); however, smaller items (<2.5 cm, e.g., cigarette parts, caps/lids, batteries) were included when visible. The total weight of litter from the beach and vegetation survey areas was measured. Only items that could be lifted by hand and removed easily from the environment were included in weight measurements. Large litter items that could not be removed from the location were recorded in the protocol when first observed and were not registered separately on subsequent sampling occasions.

2.2.2. Microlitter in sediment

Microlitter sample collection followed the guidelines of Hidalgo-Ruz et al. (2012). During sample collection and storage, care was taken to avoid additional contamination (Galgani et al. 2013). Several procedures were applied to reduce airborne secondary contamination and cross-contamination, including working plastic-free and including blank measurements at every step. Microlitter samples were collected from beach and shallow coastal sea sediment (top 5 cm) at 0.5 m water depth using a GEMAX sediment tube (diameter 30 mm). Three sediment samples were collected and combined into a single sample for both survey areas (shallow-water and beach survey areas; Fig. 2). Samples were placed in glass jars (previously cleaned with MilliQ water) and stored in a standard refrigerator (4 °C) until laboratory analysis. Sampling coordinates were determined by GPS (accuracy ±3 m), and subsequent island visits used the same coordinates. In total, 106 microlitter samples were collected during the study.

For laboratory analysis, each sample was homogenized by thorough mixing. Then, 100 g of the sample was weighed with a weighing scale (KERN Alt 310-4, accuracy 0.1 mg) into a glass Petri dish and covered with a glass lid. The sample was analyzed in portions on another glass Petri dish. In parallel, a second aliquot of the field sample was investigated for water content to determine the dry weight of the sediment. For this, 100 g of sample was transferred to an evaporating dish and dried at 105 °C. After drying, the subsample was cooled to room temperature in a desiccator, reweighed, and dry weight was calculated.

Microlitter was detected visually under a stereomicroscope (Olympus SZX7, magnification 126x) paired with a camera (Olympus). A semi-qualitative hot needle test was used to distinguish plastic from organic material; the hot needle melts and deforms plastic (Devriese et al. 2015; Avio et al. 2020). The lower size limit for visual inspection has been reported between 5–500 µm (summarized in Pérez-Guevara et al. 2022), with most studies using >100 µm as the lower detection limit (Primpke et al. 2020). Empty blanks were placed in the laboratory for the sample treatment/analysis period and controlled similarly under the microscope afterward to estimate sample pollution during analysis. The controls were given the same full treatment as the samples studied to assess any airborne contamination. If the blank was contaminated, microlitter items with similar characteristics (shape, color, material) were excluded from the results as proposed by Avio et al. (2020). All microlitter items were measured and classified by material, size class, shape, and color (Matiddi et al. 2021). The number of microlitter particles was expressed as items per kg of dry sediment.

2.2.3. Effect of macrolitter on biota

The effect of macrolitter on biota was estimated visually by observing mortal remains, bird nests, and bird pellets in the shallow-water, beach, and vegetation survey areas. Data are reported on an island-based level. In total, ten bird pellets (five each from Uhtju and Sorgu islands) were collected for more detailed laboratory examination.

2.3. Data analysis

Due to topographic differences, the length of macrolitter survey areas varied between the studied islands. To bring litter counts to a standard scale, the counts were recalculated to a 100 m and 1 m^2 scale using the actual dimensions of the survey areas (see Table 1 for the lengths and widths of the survey areas). To calculate the litter counts to a 100 m scale, the counts were divided by the length of the survey areas (measured in meters) and multiplied by 100. The scaling to 1 m^2 was conducted by dividing the litter counts by the size (in square meters) of the survey areas. Two versions of spatial normalization were needed to compare our results with previous findings: normalization on a 100 m scale is predominant in gray literature while normalization on a square meter scale is preferred in scientific literature.

The Kruskal–Wallis test (Kruskal and Wallis 1952) was used to statistically test for differences in univariate variables. When the Kruskal–Wallis test showed significant differences ($p < 0.05$), Wilcoxon pairwise comparison tests (Wilcoxon 1945) were performed to reveal which factor levels differed. The Benjamini–Hochberg method (Benjamini and Hochberg 1995) was used in the Wilcoxon pairwise test for correcting p-values in multiple comparisons. These nonparametric rank-based tests were preferred over analysis of variance (ANOVA) because the assumption of normal distribution was not met. The Shapiro–Wilk test (Shapiro and Wilk 1965) was used to check normality.

Nonmetric multidimensional scaling (NMDS; Kruskal 1964) was used to visualize the similarity of litter structure between the islands. Relationships between the multivariate litter structure and environmental variables were studied using the BIOENV method (Clarke and Ainsworth 1993). Nine different environmental and human pressure variables (hereafter “environmental variables”) were included in the analyses to elucidate potential relationships between litter and the surrounding environment (Table 2). All variables were available as georeferenced raster layer datasets. Mean values of all variables were calculated within 50, 500, 5000, and 50 000 m radii around the study sites of each island.

In the analysis of the relationships between litter and environmental variables, the study was designed to investigate spatial patterns exclusively and did not address temporal dynamics. Accordingly, datasets based on time series were represented as multi-year averages capturing the spatial patterns relevant to the analysis. The general geographical patterns of oceanographic conditions (e.g., water currents, wave exposure) have likely remained stable over recent decades, as the primary driving forces – such as coastal and seabed topography and prevailing wind directions – have not undergone significant changes. Similarly, the spatial patterns of shipping intensity are also expected to have remained consistent, given the stable locations of major ports and shipping lanes.

The R programming language, version 4.0.4 (R Core Team 2021), in the development environment RStudio (RStudio Team 2021) was used for data preparation and analysis. Potential multicollinearity among environmental variables was assessed using pairwise Pearson correlation coefficients. The highest observed correlation was 0.83 (between depth

Table 2. Environmental and human pressure variables

Variable	Short name	Source
Water depth (m)	Depth	1
Slope of seabed (°)	Slope	1
Wave exposure at sea surface based on simplified wave model ($m^2\ s^{-1}$): based on long-term (2003–2019) mean wind speeds and directions	Wave	2
Current velocity ($m\ s^{-1}$): long-term (2005–2019) mean current velocity at seabed based on hydrodynamic model	Current	3
Orbital velocity ($m\ s^{-1}$): long-term (1989–2005) mean speed of wind-induced orbital movement of water at seabed based on hydrodynamic model	Orbital	4
Proportion of soft sediment (0…1): proportion of soft seabed sediments derived from spatial models with input from bottom grab sampling, video sampling, and scuba diving	Sediment	5
Duration of ice cover (days): long-term (2000–2016) mean duration of ice cover	Ice	6
Shipping intensity (number of ship crossings): mean shipping intensity per year in 2011–2015 measured as the number of ship crossings in a 1×1 km grid cell based on HELCOM Automatic Identification System data	Shipping	7
Baltic Sea Pressure Index (BSPI): Baltic Sea cumulative human pressure index developed by HELCOM. Higher value indicates stronger human pressure	BSPI	7

Sources:
1 – Bathymetric data by the Estonian Maritime Administration (georeferenced depth raster with 10 m pixel size)
2 – Simplified wave model based on fetch and wind data (Isæus 2004; van der Meijs and Isaeus 2020)
3 – Current speed data by the Marine Systems Institute, Tallinn University of Technology (Maljutenko and Raudsepp 2014)
4 – Orbital velocity data by the Marine Systems Institute, Tallinn University of Technology (Björkqvist et al. 2018)
5 – Databases of the Estonian Marine Institute, University of Tartu
6 – Ice data by the Marine Systems Institute, Tallinn University of Technology (Uiboupin and Pärn 2018)
7 – HELCOM Map and Data Service (https://maps.helcom.fi/website/mapservice/index.html) (HELCOM 2010)

Table 3. Macrolitter amounts in beach and vegetation survey areas, and at the island level (pooled over beach and vegetation survey areas). Sub-basins: GoF – Gulf of Finland, BP – Baltic Proper, GoR – Gulf of Riga, WEAS – West Estonian Archipelago Sea, overall – data pooled over all sub-basins. Abbreviation: SD – standard deviation

Region/ sub-basin	Survey area	No. of surveys	Mean, items 100 m^{-1}	Mean, items m^{-2}	SD, items 100 m^{-1}	SD, items m^{-2}	Median, items 100 m^{-1}	Median, items m^{-2}
Overall	Beach	53	17.39	0.009	17.63	0.0097	10.65	0.006
Overall	Vegetation	53	38.25	0.013	44.32	0.0119	21.36	0.009
Overall	Island	53	22.33	0.011	18.61	0.0088	15.19	0.008
BP	Beach	13	14.07	0.006	14.55	0.0096	8.33	0.006
BP	Vegetation	13	27.82	0.017	30.08	0.0163	19.85	0.010
BP	Island	13	19.18	0.013	14.31	0.0105	14.55	0.008
GoR	Beach	16	8.07	0.003	3.73	0.0028	8.97	0.003
GoR	Vegetation	16	38.23	0.009	50.59	0.0073	18.83	0.007
GoR	Island	16	13.28	0.006	9.64	0.0040	10.27	0.005
GoF	Beach	12	37.67	0.016	18.46	0.0082	38.05	0.017
GoF	Vegetation	12	69.56	0.017	50.87	0.0096	45.83	0.014
GoF	Island	12	45.23	0.015	14.94	0.0052	46.65	0.016
WEAS	Beach	12	13.14	0.011	16.48	0.0133	5.50	0.005
WEAS	Vegetation	12	18.25	0.009	24.18	0.0121	8.54	0.004
WEAS	Island	12	14.90	0.010	17.33	0.0115	7.15	0.005

and slope), and no variables were excluded. All combinations of environmental variables were tested in BIOENV to identify the set of variables that best explained the multivariate structure of litter. Spearman rank correlation was used in BIOENV, and a permutation test (n = 9999) was applied to calculate the statistical significance of relationships.

Environmental data at all radii (50, 500, 5000, and 50 000 m) were tested in BIOENV. Because data at the 5000 m radius resulted in the highest correlation with litter data, only results using this radius are presented in the Results section. Euclidean distance similarity matrices were used in both NMDS and BIOENV. Separate sets of NMDS and BIOENV analyses were run on litter items and litter material data. The litter material dataset was derived by summing litter item counts by material (see Table 4 and Table S2 for litter types and materials).

Separate sets of analyses were also run on data aggregated at the island level and the combined island and survey area level (beach and vegetation survey areas indicated separately). Aggregation at the island level meant that litter count data were summed across survey areas (beach, vegetation). Analysis of similarities (ANOSIM; Clarke 1993) was used to statistically test for differences in litter composition between groups of samples. Euclidean distances were used to produce dissimilarity matrices, and 9999 permutations were applied.

For NMDS and BIOENV, the litter count data in each island were summed over all sampling occasions, representing the cumulative accumulation of litter over time, and scaled to m^2. The computed litter count data were then square root-transformed to downweight the importance of litter types with very high counts. For ANOSIM, data from separate sampling occasions were not summed because intra-group replicates were required.

The R package *vegan* (Oksanen et al. 2020) was used for multivariate analyses (BIOENV, NMDS, ANOSIM). The R package *raster* (Hijmans 2020) was used for handling spatial raster data, *sf* (Pebesma 2018) for handling spatial vector data, *exactextractr* (Baston 2021) for extracting raster statistics in polygons, and *tidyverse* (Wickham et al. 2019) for tabular data manipulation and plotting.

3. Results

3.1. Amount of macrolitter

In total, 12 818 macrolitter items were recorded, and 854 kg of litter was removed from the 14 islands in 2019–2020. Overall, 6011 litter items (362 kg) were removed from the beach survey areas and 6715 items (492 kg) from the vegetation survey areas.

Across all surveys, the median value of macrolitter items was 10.65 per 100 m long beach survey area, and the respective median density for beach macrolitter was 0.006 items m^{-2}. The number of macrolitter items varied between 0–77 items 100 m^{-1} in the beach survey areas and between 0–169 items 100 m^{-1} in the vegetation survey areas. The correlation between mean and median values was strong (linear regression, $r^2 = 0.903$), and both values are presented in Table 3.

The highest median values of marine litter items and density were recorded in the sub-basin of the Gulf of Finland (Table 3). Based on data normalized per 100 m, the Gulf of Finland differed statistically significantly from all other regions (Wilcoxon pairwise test, $p < 0.001$). When normalized per m^2, the Gulf of Finland differed only from the Gulf of Riga (Wilcoxon pairwise test, $p < 0.001$).

The density of litter items per sampling occasion ranged from 0.001 to 0.053 m^{-2} (Fig. 3), with respective weights from 0.0001 to 0.0085 kg m^{-2} (Fig. S2). The density of litter did not differ statistically significantly between sampling occasions (Kruskal–Wallis test, $p > 0.05$). Vegetation survey areas had statistically significantly higher litter density than beach survey areas when data were normalized per 100 m

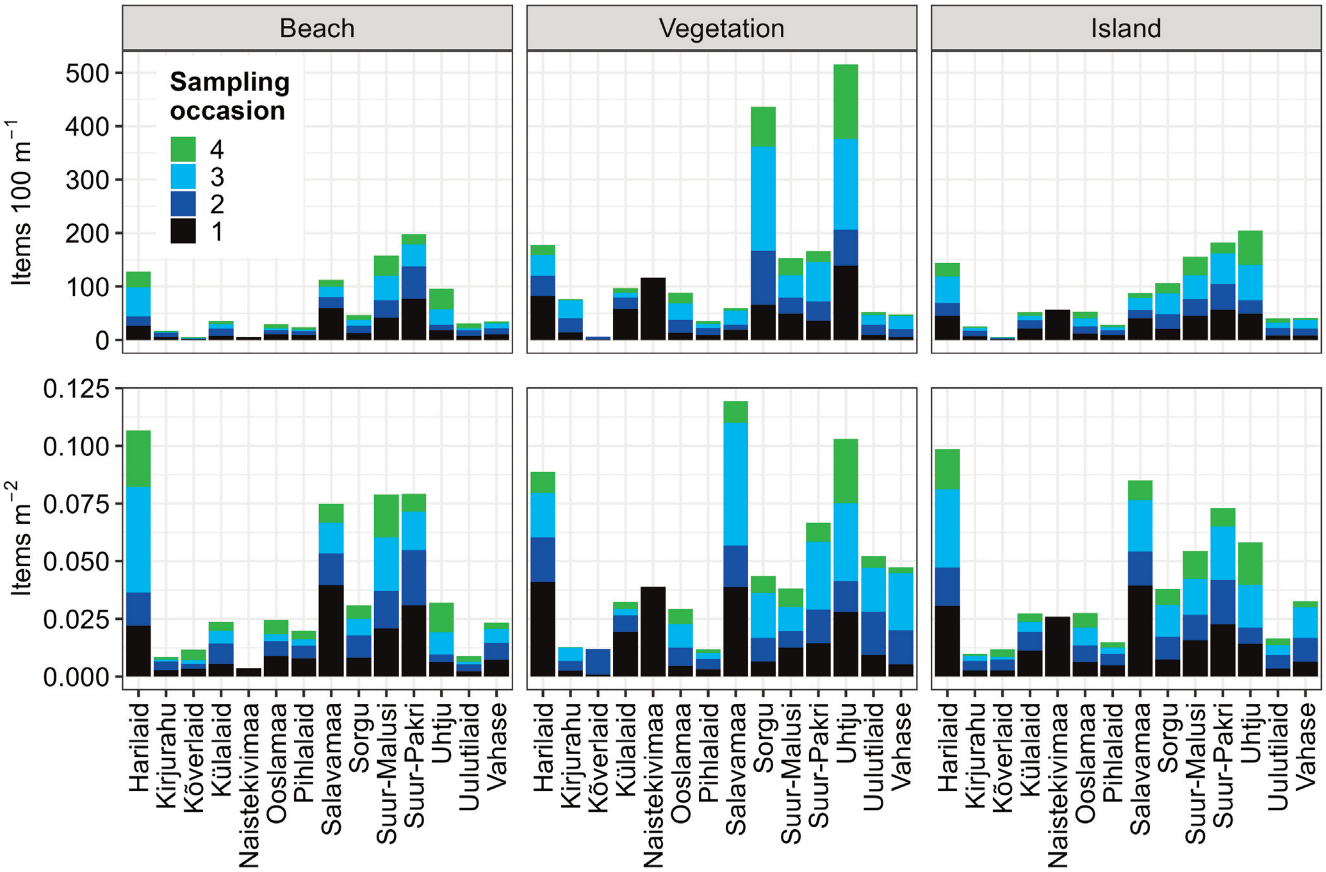

Fig. 3. The number of described litter items per 100 m long survey area and m^2 in the beach survey area, vegetation survey area, and at the island level (beach and vegetation survey areas combined).

(Kruskal–Wallis test, $p = 0.006$), but no difference was found when data were normalized per m^2 (Kruskal–Wallis test, $p = 0.13$).

3.2. Composition of macrolitter

Overall, plastic was the dominant material of litter items with 57.3%, followed by glass and ceramics at 9.2%, processed wood at 8.6%, metal at 12.7%, textile at 6.2%, rubber at 4.5%, and organic, other, and paper <1%. The lowest share of plastic materials was noted for Harilaid (30%) and Pihlalaid (42%), and the highest for Kõverlaid (88%) and Vahase (83%). For most of the islands, the share of plastic ranged between 60–70% (Fig. 4).

The distribution of litter material between the beach survey area and the vegetation survey area was mainly similar; the only difference was that organic waste and litter classified as "other" were mostly found in the beach survey area (Fig. 5). No significant change in the composition of litter material of the islands was noted over the course of sampling occasions (ANOSIM, R = –0.005, $p = 0.52$).

Out of 82 litter categories used under the UNEP/MARLIN litter classification system, 76 were present in the studied areas (Table S2). The most prevalent litter items were plastic bags, food containers, plastic fragments, and plastic bottles – these four litter types formed 44% of all litter findings (Table 4). Items categorized as single-use plastic (PL01–

Table 4. Top ten of litter items found on 14 Estonian uninhabited islands during summer 2019 – autumn 2020. The original UNEP/MARLIN macrolitter codes, together with respective J-codes and sources (Fleet et al. 2021), are presented. For the full list, see Table S1. Glass = glass and ceramics, wood = processed wood

UNEP code	J-code	Name of litter item	Material	Source/activity	Total count	%
PL07	J3	Plastic bags (opaque and clear)	Plastic	Undefined use	1831	14.28
PL06	J30	Food containers, candy wrappers	Plastic	Food consumption-related	1735	13.53
PL24	J79	Other plastic	Plastic	Undefined use	1054	8.22
PL02	J8	Bottles < 2 L	Plastic	Food consumption-related	999	7.79
WD04	J162	Processed timber and pallet crates	Wood	Undefined use	642	5.01
GC07	J208	Glass or ceramic fragments	Glass	Undefined use	569	4.44
FP04	J256	Foam (insulation and packaging)	Plastic	Building and construction-related	499	3.89
GC02	J200	Glass bottles and jars	Glass	Food consumption-related	487	3.80
PL01	J21	Bottle caps and lids	Plastic	Food consumption-related	484	3.78
WD06	J171	Other wood	Wood	Undefined use	357	2.78

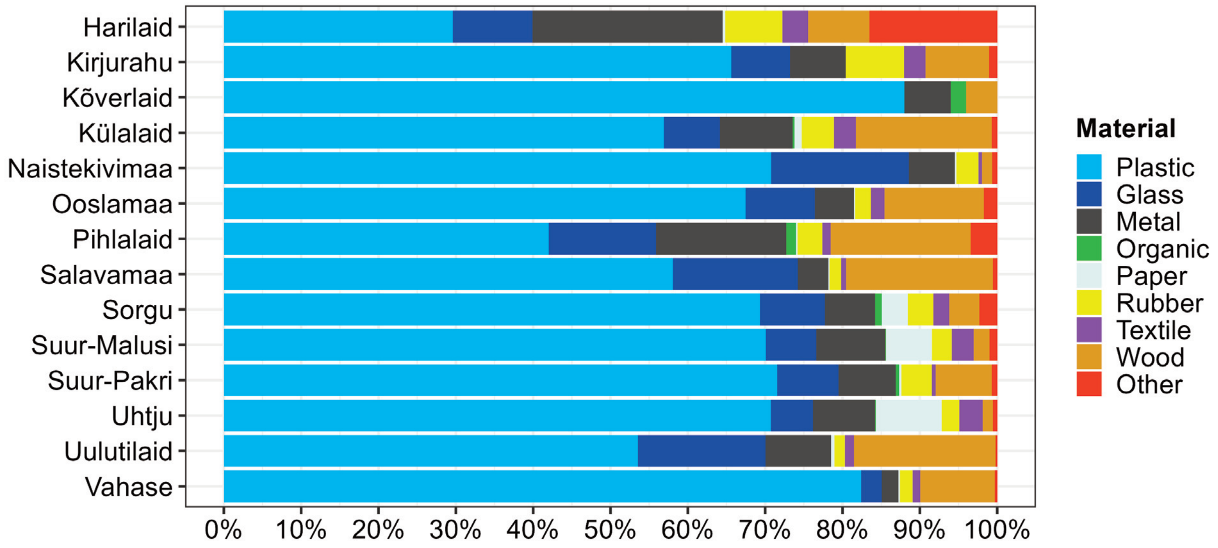

Fig. 4. Share of different macrolitter materials per island, presented over all sampling occasions (beach and vegetation survey areas, items m^{-2}). Glass = glass and ceramics, wood = processed wood.

PL07) were found 5177 times in total, accounting for 40.4% of all findings. Single-use cutlery and cigarette butts, which are both common litter items on public beaches (Addamo et al. 2017), were also found in the islands but in low abundance (34 and 25 items in total, respectively) (Table S2).

For most of the litter items (52.3%), the source could not be defined. Litter related to food consumption amounted to 35.5%, followed by building and construction-related (3.9%), fisheries-related (3%), agriculture-related (1.8%), clothing (1.5%), and recreation-related litter (1.4%). The share of smoking-related, medical-related, personal hygiene and care-related, and vehicle-related sources of litter was less than 1%. The share of different litter pollution sources varied among islands (Fig. S3).

Based on macrolitter composition, there were significant differences between islands (Fig. 6). NMDS ordination (Fig. 7) showed clear differentiation of some islands (e.g., Harilaid); differentiation at the sub-basin level was also detected by ANOSIM (litter item composition: R = 0.27, $p < 0.01$; litter

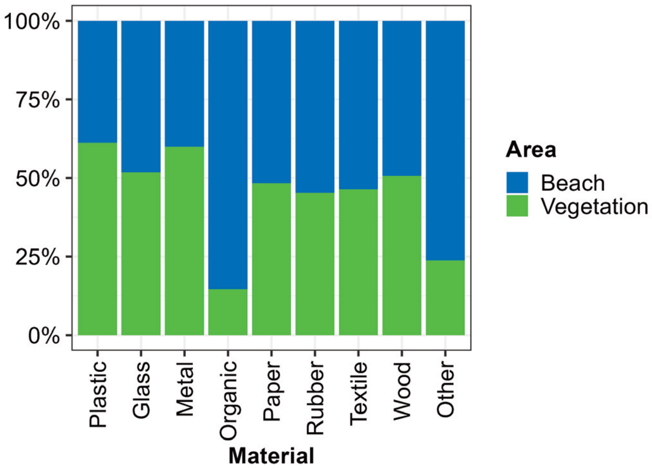

Fig. 5. Proportional distribution of litter materials between survey areas (beach and vegetation, items m^{-2}) based on pooled data from all islands and sampling occasions. Glass = glass and ceramics, wood = processed wood.

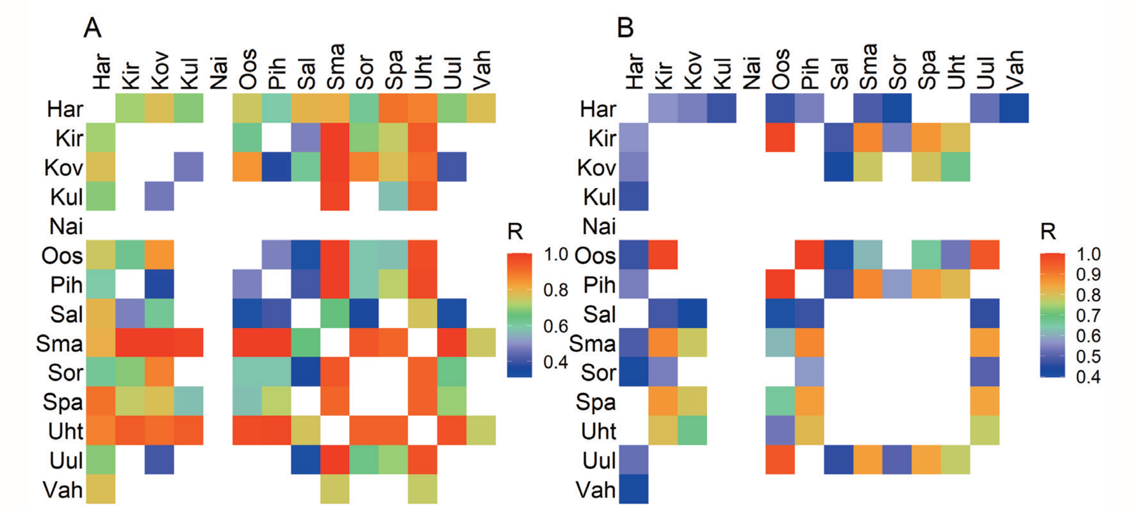

Fig. 6. Results of pairwise ANOSIM of islands' litter item (A) and material composition (B) based on litter data normalized per areal unit (m^2). The litter material dataset was derived by summing litter item counts based on material. Blank cells indicate statistically non-significant differences ($p \geq 0.05$), and all colored cells indicate statistically significant R-values ($p < 0.05$). Higher R-values indicate stronger differentiation. For the abbreviations of island names, see Table 1.

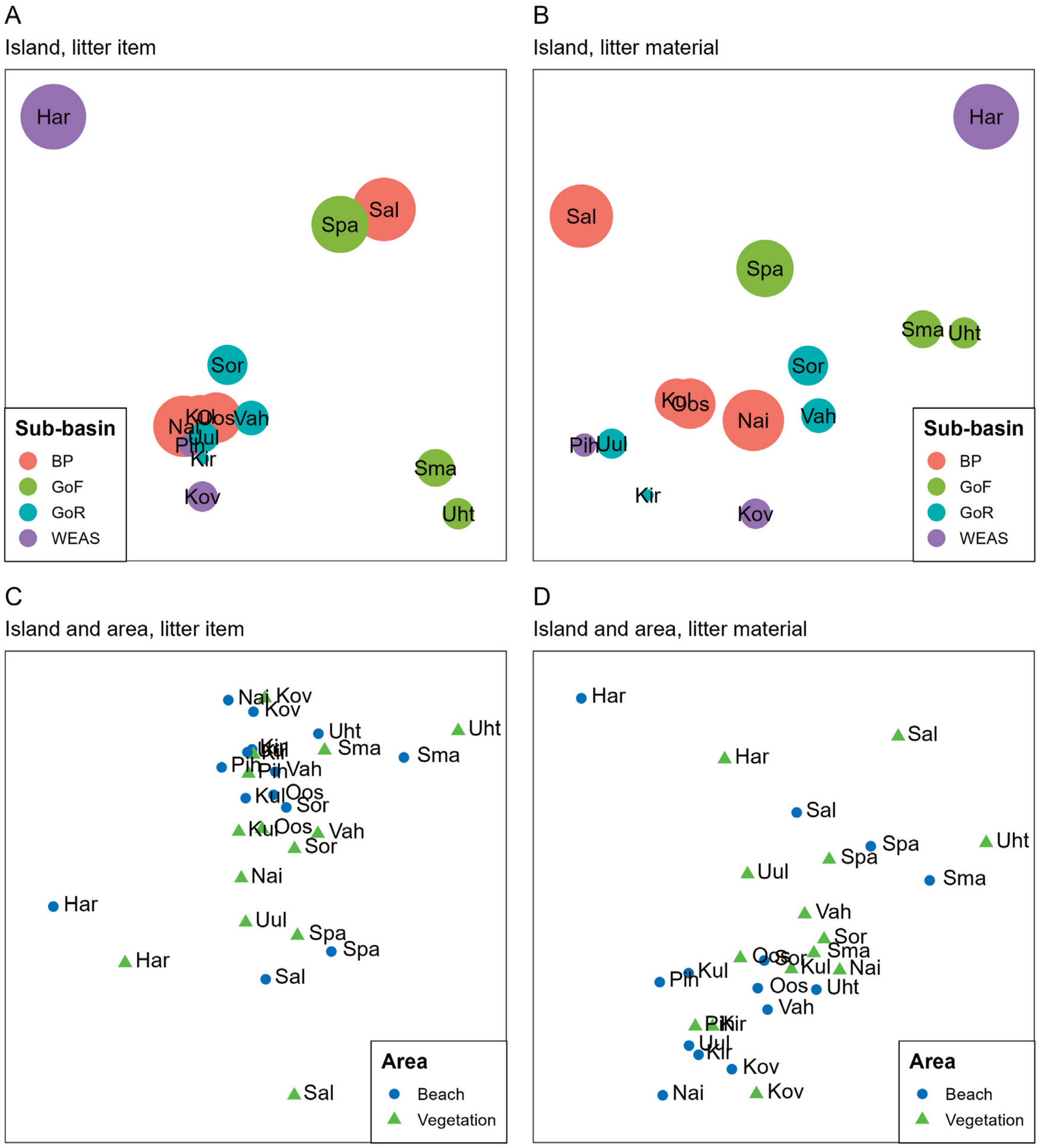

Fig. 7. NMDS ordinations of the similarity structure of litter composition (based on items m^{-2}; the litter material dataset was derived by summing litter item counts based on material). A closer distance between points reflects a higher similarity of litter composition. Plots in the upper row (A, B) represent ordinations on the island level (litter count data summed across survey areas: beach and vegetation). Plots in the lower row (C, D) represent ordinations on the island and survey areas separately (beach, vegetation). Circle sizes in the upper plots (A, B) indicate the total weight of litter. See Fig. 5 for island-level pair-wise comparisons of island differentiation and Table 1 for the abbreviations of island names.

material composition: R = 0.28, $p < 0.01$). There was no indication of a relationship between total weight and litter composition. No differentiation between the beach and vegetation survey areas was noted for litter item composition (ANOSIM, R = 0.02, $p = 0.01$) or litter material composition (ANOSIM, R = 0.02, $p = 0.05$). However, strong differentiation in litter composition between the beach and vegetation survey areas was notable for some islands (e.g., Uhtju, Naistekivimaa, Salavamaa; Fig. 7).

Based on BIOENV analysis, the set of variables that best explained the litter composition structure included current, depth, and orbital speed, with a rank correlation coefficient of 0.766 (Table 5). The BSPI was retrieved among the set of variables best explaining the litter composition only at the item level (rank correlation 0.690). Correlations were higher in the case of litter items compared to litter materials (0.766 vs. 0.627).

3.3. Microlitter in sediment

Microlitter (size >100 µm) was found in the sediment of all studied islands. However, microlitter was not present in every sampling occasion. When data from all islands and sampling episodes were pooled, a potential positive correlation was observed between macrolitter abundance (normalized beach total per m^2) and microlitter abundance in beach sediment (Pearson's $r = 0.27$), although statistical significance was slightly above the conventional threshold ($p = 0.055$). In contrast, no such relationship was found between macrolitter and microlitter abundances in the shallow coastal sea (Pearson's $r = 0.094$, $p = 0.5$).

Table 5. Results of BIOENV analyses. The top five highest correlations are shown for litter item and material (based on items m^{-2}; the litter material dataset was derived by summing litter item counts based on material)

Litter	Variables	No. of variables	Spearman rank correlation R	p
Item	Current, depth, orbital speed	3	0.766	<0.001
Item	Current, depth, slope, orbital speed	4	0.739	<0.001
Item	Current, orbital speed	2	0.737	<0.001
Item	Current, depth, slope, orbital speed, sediment	5	0.716	<0.001
Item	BSPI, current, depth, slope, orbital speed, sediment	6	0.690	<0.001
Material	Current, orbital speed	2	0.627	<0.001
Material	Current, depth, orbital speed	3	0.610	0.001
Material	Current, depth, orbital speed, sediment	4	0.580	0.001
Material	Current	1	0.550	0.001
Material	Current, depth, slope, orbital speed, sediment	5	0.545	0.003

Table 6. Microlitter amounts (number of particles kg^{-1}) in beach and shallow-water survey areas, and at the island level (pooled over beach and shallow-water survey areas). Sub-basins: GoF – Gulf of Finland, BP – Baltic Proper, GoR – Gulf of Riga, WEAS – West Estonian Archipelago Sea, overall – data pooled over all sub-basins. Abbreviation: SD – standard deviation

Region/sub-basin	Survey area	No. of surveys	Mean	SD	Median
Overall	Beach	53	8.11	10.55	0
Overall	Shallow-water	53	5.66	11.98	0
Overall	Island	53	6.89	11.09	0
BP	Beach	13	12.31	15.34	10
BP	Shallow-water	13	2.31	5.95	0
BP	Island	13	7.31	12.67	0
GoR	Beach	16	5.01	7.88	0
GoR	Shallow-water	16	4.38	7.88	0
GoR	Island	16	5.31	7.88	0
GoF	Beach	12	7.10	11.64	0
GoF	Shallow-water	12	5.83	8.26	0
GoF	Island	12	6.67	10.27	0
WEAS	Beach	12	9.17	11.87	5
WEAS	Shallow-water	12	10.83	16.05	10
WEAS	Island	12	10.00	14.14	0

Microlitter was found in 41.5% of sediment samples taken from the beach survey areas and in 34% of sediment samples taken from the shallow-water survey areas. The amount of microlitter in the sediment varied between 0–40 particles kg^{-1} for the beach and 0–60 particles kg^{-1} in the shallow coastal sea (Fig. S4) with an overall mean of 8.11 for the beach section and 5.66 for the sea section (particles kg^{-1}) (Table 6). Most of the observed microlitter particles were <2 mm (67.5% of findings on the beach and 70% in seabed sediment). Across the islands, there were some variations in microlitter composition; however, in beach sediment, plastic fibers and glass fragments were dominant. In shallow-water sediment, plastic fibers, glass, and metal fragments were found in equal amounts (Fig. 8).

3.4. Effect of macrolitter on biota

In total, 254 mortal remains were observed on the 14 islands in 2019–2020. Of these remains, 233 belonged to birds (*Phalacrocorax carbo* on Sorgu island; otherwise *Larus* spp.; Table 7), 19 to seals (16 found on Kirjurahu, one on Sorgu, and one on Suur-Pakri), and two to terrestrial mammals (boar and deer found on Kõverlaid).

Plastic and/or ropes and strings were noted around ten bird corpses. These findings originated from common breeding areas for seabirds in the Gulf of Finland and the Gulf of Riga. However, based solely on visual observations, litter as a probable direct cause of death was noted for three birds (entanglement in a fishing net and a plastic bag entangled around the neck).

No bird nests were found on six islands (Naistekivimaa, Kõverlaid, Salavamaa, Uulutilaid, Vahase, and Külalaid). Only a few nests (<5) were found on two islands, and those did not contain litter (Table 7). On the remaining islands, 30–60 nests were observed. Litter items were used as nest material in 83% of observed nests on Sorgu, 67% on Suur-Malusi, 20% on Uhtju, and 10% on Kirjurahu and Ooslamaa (Table 7). The litter items used as nest material were most commonly plastic bags, plastic food packaging, and ropes and strings (both plastic and textile). On a few occasions, nests had been built within plastic box remains and plastic barrels (observed on Ooslamaa and Kirjurahu). Bird pellets commonly contained fragments of plastic bags, aluminum foil, and glass. Among other items, sharp glass fragments (up to 5 cm in length) and metal clips used in food packaging were noted within bird pellets.

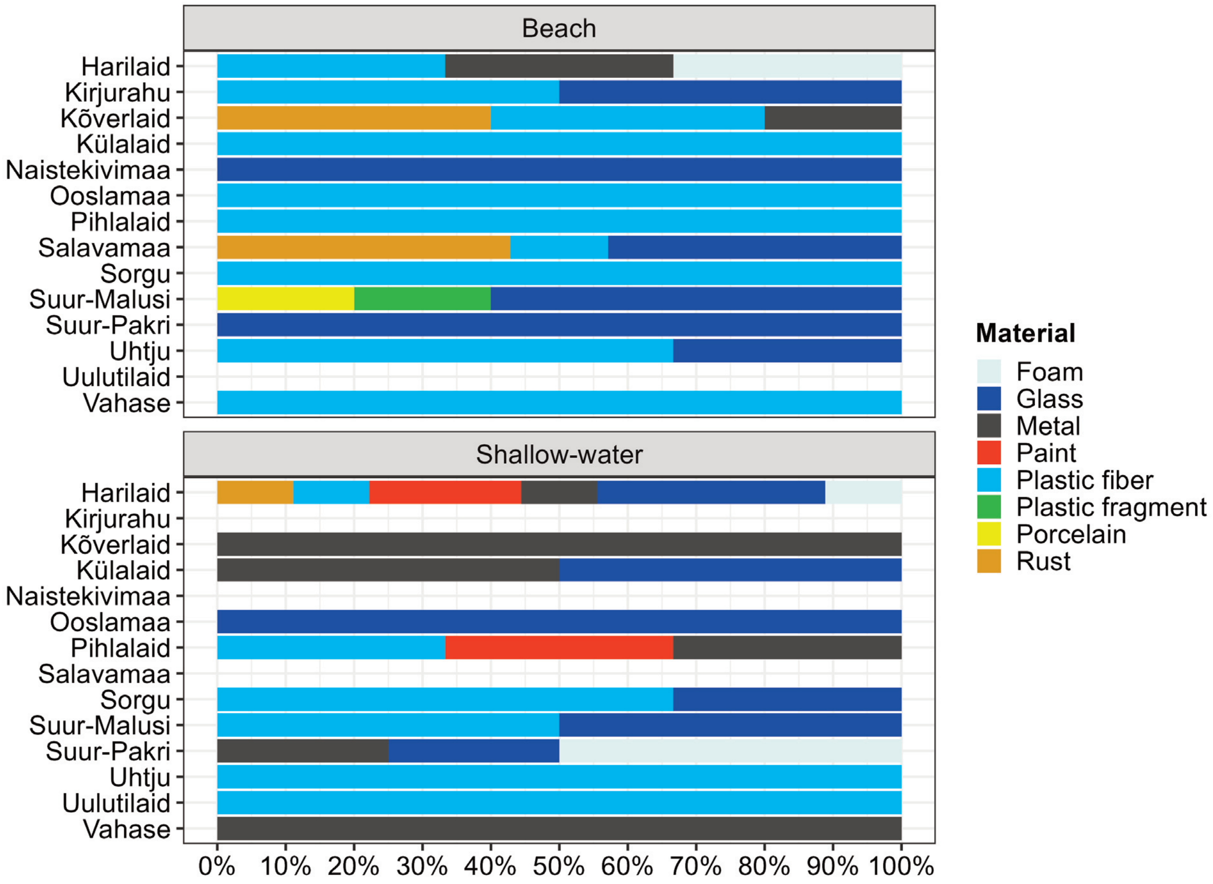

Fig. 8. Share of different microlitter materials per island presented over all sampling occasions.

Table 7. Number of observed bird corpses and nests in relation to the presence of macrolitter

Island	Corpses/deaths related to litter	Nests/nests with litter
Kirjurahu	20/0	30/3
Ooslamaa	44/0	30/3
Pihlalaid	2/0	3/0
Salavamaa	2/0	–
Sorgu	138/2	60/50
Suur-Malusi	9/0	30/20
Suur-Pakri	8/0	3/0
Uhtju	5/1	50/10
Uulutilaid	3/0	–
Vahase	2/0	–

4. Discussion

The study provides valuable insight into the quantity, composition, and distribution of marine litter in natural, uninhabited coastal regions of small islands in the northeastern Baltic Sea. However, the term “uninhabited” does not fully exclude visits from, e.g., summertime tourists, some of whom were observed picking up marine litter. Thus, considering these sporadic cleanups by visitors, the amounts of litter presented here may underestimate the actual pollution load.

4.1. Amount of macrolitter

The value of 20 litter items per 100 m of coastline was set as the threshold, reflecting the agreed value of GES in European seas for beach litter (van Loon et al. 2020; European Commission 2022). This threshold was derived from the 15th percentile of the EU litter count baseline dataset for 2015–2016 (van Loon et al. 2020). For comparison, a minimum of 40 surveys is recommended (van Loon et al. 2020). Based on our study, the median amount of litter was 10.65 items per 100 m in the beach survey areas, indicating that the natural, remote beaches in the northeastern Baltic Sea region can be considered in GES.

The number of macrolitter items in the beach survey areas remained mainly below the Baltic Sea average of 47 items per 100 m of coastline reported previously for natural beaches (HELCOM 2018). At the Baltic Sea level, the status evaluation of marine beach litter for 2016–2021 shows that 11 out of 16 sub-basins exceed the HELCOM threshold of 20 litter items per 100 m of coastline; at the sub-basin level, median values for beach litter ranged between 5–313 items per 100 m of coastline (HELCOM 2023). Previously, the MARLIN project reported an average of 75.7 litter items per 100 m on rural beaches, and a 50% share of plastic (based on six rural beaches in Sweden, Finland, Estonia, and Latvia in 2011–2013; MARLIN 2013).

According to the HELCOM SPICE report, the mean number of beach litter items in the Baltic Sea countries varied between 33.7–354.4 items per 100 m: Finland 354.4, Germany 61.7, Denmark 99.4, Sweden 88.1, Estonia 118.4, Lithuania 222.3, Latvia 180.2, and Poland 33.7. The share of plastic varied between 53% (Latvia) and 89% (Finland). Baseline calculations for rural beaches in the Baltic Sea during 2012–2016 suggest mean and median values of 79.8 and 72.3 beach litter items per 100 m of coastline (Zalewska and Krzyminski 2017). The values presented here, calculated at the Baltic Sea sub-basin level, are below these baseline values.

The Clean Coastal Index (CCI) has been suggested as a tool for evaluating coastal cleanliness. CCI was originally based on the density of plastic items per m^2 (Alkalay et al. 2007) but has later been used as a general measure of litter density for all types of litter material (Asensio-Montesinos et al. 2021a). In our study, litter density was low – on any sampling occasion, the density of litter on an island did not exceed 0.06 items m^{-2}, and the regional (Gulf of Finland, Baltic Proper, Gulf of Riga, West Estonian Archipelago Sea) median values for density were < 0.02 items m^{-2}. Accordingly, based on CCI, all studied islands can be classified as “very clean” because the litter density was lower than one item per 10 m^2. For comparison, an average of 0.09–0.55 beach litter items m^{-2} for countries in the Baltic Sea region has been reported, reflecting generally low pollution levels when compared to other regions on a global scale (Haseler et al. 2020 and references therein). Urban beaches of the Baltic Sea region can also be regarded as clean – during the summer of 2022, CCI was estimated at 0.05–0.38 items m^{-2} on touristic urban beaches in Poland (Bigus and Jarosiewicz 2023).

The increase of litter load along the sea–inland gradient has been highlighted by, e.g., Šilc et al. (2018) and in this study. Litter pollution in vegetation survey areas was notably higher than in beach survey areas, with a median of 21.36 litter items per 100 m. Similarly, when vegetation survey areas were included, the amount of litter per sampling occasion was considerably higher on some islands, with over 200 litter items per 100 m of survey area.

The total weight of removed litter mostly remained < 5 kg per 100 m in beach survey areas and < 10 kg per 100 m in vegetation survey areas, with a maximum of 27 kg. Usually, weight is not recorded in a regular monitoring process (Hanke et al. 2019), and the presence/absence of large, heavy megalitter can distort monitoring results by weight (Smith and Turrell 2021). Nevertheless, the numbers presented here serve as an indication for a better general understanding of marine litter pollution in the Baltic Sea region and, e.g., related manpower needs for organizing cleanups (Hidalgo-Ruz and Thiel 2015).

No clear trend in litter amount, density, or weight was observed during the two-year study period. Based on previous annual beach litter monitoring in Estonia carried out in 2012–2016, the average number of litter items per 100 m of beach section decreased from 140 to 24 (Press 2020). However, no significant change was noted in 2017–2022, when the average number of litter items per 100 m of beach section varied between 20–43 (Press 2023). In addition to the short study period, the variance in the number of litter findings could also be explained by a combination of seasonal differences (finding litter under high or low vegetation), bird activities, and coastal processes (e.g., Andriolo and Gonçalves 2022).

4.2. Composition of macrolitter

The set of environmental variables that best explained litter composition across islands included water current speed, water depth, and orbital speed at seabed. The effect of wind and storms on beach litter abundance has been shown in earlier studies (e.g., Turrell 2018; Asensio-Montesinos et al. 2021a). The BSPI, which measures the quantity and spatial distribution of potential cumulative pressures on the Baltic Sea, was also retrieved among the variables best explaining litter composition at the item level. In addition to the aforementioned environmental variables, sediment partly explained litter composition based on material. Our study included beaches with different sediments – sand, gravel, cobbles, pebbles, boulders, and rock. Given the heterogeneity and variability of sediments even on a small scale (< 1 km) in the northeastern Baltic Sea region (Łabuz 2015), it was not advisable to focus solely on sandy beaches, as beaches with hard or mixed sediment can also accumulate litter (Asensio-Montesinos et al. 2021b). The beaches of Suur-Pakri, Salavamaa, Naistekivimaa, and Külalaid were dominated by limestone and limestone pebbles; at the same time, the amounts of litter in these areas were notably high. These islands are all exposed to the Baltic Proper and intensive shipping corridors. Investigations of litter on beaches other than sandy ones are limited. However, litter burial and exhumation processes are known to occur on cobble beaches (Asensio-Montesinos et al. 2021b).

Litter composition varied between islands, and differentiation at the sub-basin level was also detected. The share of plastic ranged between 60–70% for most islands, which corresponds to general plastic pollution reported for beaches in the Baltic Sea region (Kideys et al. 2021). At the island level, the percentage of plastic litter items was highest on Kõverlaid (88%) and Vahase (83%), and lowest on Harilaid (30%) and Pihlalaid (42%). Both Kõverlaid and Vahase had overall small amounts of litter. On Vahase, the low amount of litter items and dominance of plastic items most probably reflects sporadic cleanups by summertime tourists. In the case of Kõverlaid, similar results can be explained both by its location and by the specific characteristics of the coastline. Kõverlaid, Pihlalaid, and Uulutilaid, all of which had small amounts of litter, are located within or close to the West Estonian Archipelago Sea, a relatively closed waterbody where marine traffic is mainly local (ferry lines between the largest islands, local fishermen and sailors). As (international) shipping intensity is lower here, litter pollution loads are generally lower (e.g., Čulin and Bielić 2016; this study).

Secondly, Kõverlaid has a very narrow beach section (up to 5 m wide under normal water level), and right next to the beach is a dense, wide belt (up to 50 m) of common reed (*Phragmites australis*). This reed belt acts as a substantial barrier, preventing macrolitter from moving inland. Similar effects have been shown for giant reed (*Arundo donax*) (Battisti et al. 2020) and for mangrove forests (Li et al. 2021). However, at the same time, these reed barriers may also act as litter traps, especially for meso- and microlitter (Battisti et al. 2020).

Among the islands, litter composition was most distinguishable on Harilaid, where the share of plastic was lowest. At the same time, metal, rubber, and items classified as "other" materials were more common. (The "other" category was represented mainly by fragments of asbestos cement, a common roof material in the 20th century.) These materials originate from abandoned and deteriorating facilities – berths and shipwrecks at sea, as well as houses and a lighthouse inland. Until 1992, the island and these facilities were used by the USSR Border Guard. The berth was destroyed during a powerful storm (Gudrun/Erwin) in January 2005, while the houses are facing natural deterioration (Tähiste and Mõniste 2016). Similar abandoned facilities exist on Pihlalaid, where the breakdown of wreckage and local-source pollution is reflected in the litter composition.

Overall, the most prevalent litter items were plastic bags, food containers, plastic fragments, and plastic bottles – these four litter types formed 44% of all findings. Processed wood and glass and ceramic fragments and bottles were also numerous. This pattern is similar to results reported for rural beaches in the Baltic Sea region. However, the small number of cigarette butts (25 in total during the study period) is noteworthy (Addamo et al. 2017; HELCOM 2018). The study period overlapped with the COVID-19 pandemic, which caused an increase in personal protective equipment litter (Roberts et al. 2022). This litter also made its way to the marine environment (Dybas 2021; Peng et al. 2021). During our fieldwork, however, we did not notice an increase in finding masks or rubber gloves (in total, 5 and 17 items, respectively). The masks were mainly related to construction works (dust protection, etc.). However, in the summer of 2020, a new type of litter emerged on Uhtju and Suur-Malusi islands in the Gulf of Finland – hygienic wet wipes. Although not numerous, these items had not been recorded before the pandemic at any studied location. The wet wipes could have been transported to the islands by water and birds.

For most litter items, the possible pollution source could not be defined. However, over one third of the litter items were related to food consumption, which is the dominant source of litter across the Baltic Sea (HELCOM 2018). The shares of building and construction-related, fisheries-related, agriculture-related, clothing, and recreation-related litter were small (< 5%) on most islands. Building and construction-related litter was highest on Harilaid (15%), which is associated with the deteriorating facilities mentioned above. Smoking-related, medical-related, personal hygiene and care-related, and vehicle-related sources were of minimal importance (< 1%).

4.3. Microlitter in sediment

The authors are aware of the currently suggested methodological changes related to research on microlitter in sediment. The results presented here serve as an insight into the microlitter occurrence in the study area. The amount of microlitter in the sediment was relatively low. However, it must be stressed that microlitter items were found on every island studied, and a small positive correlation between macrolitter abundance (normalized beach total per m^2) and microlitter abundance in beach sediment was noted. Our findings indicate that in regions without direct human impact, the amount of microlitter in the sediment was up to 60 items per kg. Surprisingly, these results are comparable with findings in Kiel Fjord, Western Baltic Sea, where an intensively visited beach, a beach near a sewage plant, and a beach polluted with large-size plastic debris were studied, and 1.8–4.5 microlitter particles per kg of dry sediment were counted for the first two beaches and up to 30.2 particles per kg of dry sediment were counted at the site with high litter loads (Schröder et al. 2021). The latter suggests that fragmentation of large plastic litter at the site could be a relevant source of microplastics in the sediments of the Baltic Sea region (Schröder et al. 2021). Similarly, Urban-Malinga et al. (2020) reported the findings from the Polish coast, Southern Baltic Sea, where the highest microplastic concentrations – up to 295 microlitter particles per kg of dry sediment – were reported for urban beaches. Yet, no substantial difference was noted in microplastic pollution between urban beaches and national parks without direct human impact (Urban-Malinga et al. 2020).

4.4. Effect of macrolitter on biota

With human population growth, waste production and litter pollution in the environment (including the marine environment) increase (Jambeck et al. 2015). Human-produced litter in bird nests is also an increasing trend (Votier et al. 2011; Grant et al. 2018) – when suitable litter is available, birds will use it in their nests (Grant et al. 2018). Based on our observations, litter was commonly used as nest material on the bird-breeding islands that are closer to human activities and littering related to them. Previously, human impact on the environment estimated within 100 km of a bird colony has also been significantly related to the prevalence of unnatural debris in nests (O'Hanlon et al. 2021).

On Uhtju and Suur-Malusi islands, the litter composition was most specific, comprising relatively small litter objects – mostly degrading small plastic bags and plastic, metal, and aluminum fragments related to food packaging – which were collected both from nests and vegetation. This litter composition could best be explained by the activity of birds. In the eastern Baltic Sea, birds in the Uhtju region have probably used the Kunda, Rakvere, and other nearby landfills as feeding grounds (though, e.g., the Kunda landfill was closed in

2004 and the Rakvere landfill in 2009), and based on the dominant litter items on the island, it is probable that, in addition to marine-transported litter, birds themselves transport a great deal of the litter from the mainland to the island. At the same time, misuse of food-related plastic items and their origin from ships cannot be excluded. The dominant bird species on Uhtju is seagull (*Larus* spp.), in contrast to Sorgu, where *Phalacrocorax carbo*, breeding both on the ground and in trees, prevails. Previously, it has been shown that litter is a common nest material for birds in the Baltic Sea region – over 55% of cormorant nests located on remote islands in the southern Baltic Sea region contained litter (Schernewski et al. 2018). Results presented here suggest a need for a more comprehensive study on seabirds' litter use, as comparable data are currently lacking for the northeastern Baltic Sea region (Veljo Volke, Estonian Ornithological Society, pers. comm. October 2023).

5. Conclusions

The current study was carried out as a pilot study and aimed to cover different aspects of marine litter pollution on small uninhabited islands in Estonia, in the northeastern Baltic Sea. Calculated over all conducted surveys, the median value of macrolitter items per 100 m of beach section was 10.65, and the respective median density was 0.006 items m^{-2}. Thus, regarding beach litter amounts, the studied islands can be stated to be in Good Environmental Status. However, when the litter pollution of the terrestrial vegetation survey area next to the beach was studied, the medians rose to 21.36 litter items per 100 m and 0.009 items m^{-2}. At the sub-basin level, the islands located in the Gulf of Finland had the highest number of litter items per 100 m and the highest density (items m^{-2}), 38.05 and 0.017, respectively. Litter composition varied between islands; however, the share of plastic was between 60–70% for most islands, and over one-third of the litter items were related to food consumption, which corresponds to general plastic pollution reported for beaches in the Baltic Sea region. The set of environmental variables that best explained litter composition on different islands included current, depth, and orbital speed. Microlitter was found in roughly one-third of the samples, and the amount of microlitter in the sediment was up to 60 items kg^{-1}. Macrolitter was commonly used as nest material on bird-breeding islands that are closer to human activities and littering related to them.

What is also alarming is that 11 of the visited islands are nature conservation areas, and though human access is limited, these areas are clearly affected by marine litter. A more holistic approach to marine litter research is recommended based on the fieldwork effort and the research results. Conducting both macro- and microlitter surveys and considering the possible effect on biota gives a more solid and broader view of the problems and possible solutions related to marine litter. The study also indicates the need for specifically targeted actions in nature conservation areas (irrespective of the dominant coastal sediment) that are prone to accumulate marine litter.

Data availability statement

The data are contained within the article, and the original materials are housed in the Estonian Marine Institute, Faculty of Science and Technology, University of Tartu. Data supporting this study are available upon request from the Estonian environmental monitoring database (keskkonnaportaal.ee, kese@envir.ee), project reference "ST00002774 Eesti väikesaarte mereprügi," or by direct request to the corresponding author of the article.

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Supplementary online data

Supplementary online data to this article can be found at https://doi.org/10.3176/earth.2026.S01 and include Figures S1–S4 and Tables S1 and S2 detailing the different aspects of marine litter distribution in the Estonian coastal sea region.

References

Addamo, A. M., Laroche, P. and Hanke, G. 2017. *Top Marine Beach Litter Items in Europe: A Review and Synthesis Based on Beach Litter Data*. EUR 29249 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/496717

Alkalay, R., Pasternak, G. and Zask, A. 2007. Clean-coast index – a new approach for beach cleanliness assessment. *Ocean and Coastal Management*, **50**(5–6), 352–362. https://doi.org/10.1016/j.ocecoaman.2006.10.002

Andriolo, U. and Gonçalves, G. 2022. Is coastal erosion a source of marine litter pollution? Evidence of coastal dunes being a reservoir of plastics. *Marine Pollution Bulletin*, 174, 113307. https://doi.org/10.1016/j.marpolbul.2021.113307

Asensio-Montesinos, F., Anfuso, G., Aguilar-Torrelo, M. T. and Oliva Ramírez, M. 2021a. Abundance and temporal distribution of beach litter on the coast of Ceuta (North Africa, Gibraltar Strait). *Water*, **13**(19), 2739. https://doi.org/10.3390/w13192739

Asensio-Montesinos, F., Anfuso, G., Williams, A. T. and Sanz-Lázaro, C. 2021b. Litter behaviour on Mediterranean cobble beaches, SE Spain. *Marine Pollution Bulletin*, **173**, 113106. https://doi.org/10.1016/j.marpolbul.2021.113106

Avio, C. G., Pittura, L., d'Errico, G., Abel, S., Amorello, S., Marino, G. et al. 2020. Distribution and characterization of microplastic particles and textile microfibers in Adriatic food webs: general insights for biomonitoring strategies. *Environmental Pollution*, **258**, 113766. https://doi.org/10.1016/j.envpol.2019.113766

Barnes, D. K. A., Galgani, F., Thompson, R. C. and Barlaz, M. 2009. Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of The Royal Society B*, **364**(1526), 1985–1998. https://doi.org/10.1098/rstb.2008.0205

Baston, D. 2021. *Exactextractr: Fast Extraction from Raster Datasets using Polygons*. R package version 0.7.2. https://CRAN.R-project.org/package=exactextractr (accessed 2023-01-12).

Battisti, C., Fanelli, G., Filpa, A. and Cerfolli, F. 2020. Giant reed (*Arundo donax*) wrack as sink for plastic beach litter: first evidence and implication. *Marine Pollution Bulletin*, **155**, 111179. https://doi.org/10.1016/j.marpolbul.2020.111179

Benjamini, Y. and Hochberg, Y. 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, **57**(1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Bigus, K. and Jarosiewicz, A. 2023. Using the Coastal Clean Index to assess the impact of anthropogenic pressure on sandy beaches in Ustka, Poland. *Studia Quaternaria*, **40**(2), 67–76. https://doi.org/10.24425/sq.2023.148033

Björkqvist, J.-V., Lukas, I., Alari, V., van Vledder, G. P., Hulst, S., Pettersson, H. et al. 2018. Comparing a 41-year model hindcast with decades of wave measurements from the Baltic Sea. *Ocean Engineering*, **152**, 57–71. https://doi.org/10.1016/j.oceaneng.2018.01.048

Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A. et al. 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science*, **369**(6510), 1515–1518. https://doi.org/10.1126/SCIENCE.ABA3656

Canals, M., Pham, C. K., Bergmann, M., Gutow, L., Hanke, G., van Sebille, E. et al. 2021. The quest for seafloor macrolitter: a critical review of background knowledge, current methods and future prospects. *Environmental Research Letters*, **16**(2), 023001. https://doi.org/10.1088/1748-9326/abc6d4

Clarke, K. R. 1993. Non-parametric multivariate analysis of changes in community structure. *Australian Journal of Ecology*, **18**(1), 117–143. https://doi.org/10.1111/j.1442-9993.1993.tb00438.x

Clarke, K. R. and Ainsworth, M. 1993. A method of linking multivariate community structure to environmental variables. *Marine Ecology Progress Series*, **92**, 205–219. https://doi.org/10.3354/meps092205

Čulin, J. and Bielić, T. 2016. Plastic pollution from ships. *Pomorski zbornik*, **51**(1), 57–66. https://doi.org/10.18048/2016.51.04

Delgado, S., Zorrozua, N. and Arizaga, J. 2020. Marginal presence of plastic in nests of yellow-legged gulls (*Larus michahellis*) in the southeastern Bay of Biscay. *Animal Biodiversity and Conservation*, **43**(2), 191–195. https://doi.org/10.32800/abc.2020.43.0191

Devriese, L. I., van der Meulen, M. D., Maes, T., Bekaert, K., Paul-Pont, I., Frére, L. et al. 2015. Microplastic contamination in brown shrimp (*Crangon crangon*, Linnaeus 1758) from coastal waters of the southern North Sea and Channel area. *Marine Pollution Bulletin*, **98**(1–2), 179–187. https://doi.org/10.1016/j.marpolbul.2015.06.051

Dybas, C. L. 2021. Surgical masks on the beach: COVID-19 and marine plastic pollution. *Oceanography*, **34**(1), 12–14. https://doi.org/10.5670/oceanog.2021.105

Ershova, A. A., Eremina, T. R., Chubarenko, I. P. and Esiukova, E. E. 2021. Marine litter in the Russian Gulf of Finland and South-East Baltic: application of different methods of beach sand sampling. In *Plastics in the Aquatic Environment – Part I* (Stock, F., Reifferscheid, G., Brennholt, N. and Kostianaia, E., eds). The Handbook of Environmental Chemistry, Vol. 111. Springer, Cham. https://doi.org/10.1007/698_2021_746

Estonian Nature Conservation Act. 2004. Riigi Teataja I, **38**, 258.

Estonian Permanently Inhabited Small Islands Act. 2003. Riigi Teataja I, **23**, 141.

European Commission. 2022. MSFD CIS Guidance Document No. 19, Article 8 MSFD, May 2022. https://www.aquabiota.se/wp-content/uploads/european-commission-2022.-msfd-cis-guidance-document-no.-19-article-8-msfd-may-2022.pdf?utm_source=chatgpt.com

Fleet, D., Vlachogianni, T. and Hanke, G. 2021. *Joint List of Litter Categories for Marine Macrolitter Monitoring: Manual for the Application of the Classification System*. EUR 30348 EN. Publications Office of the European Union, Luxembourg. https://dx.doi.org/10.2760/127473

de Francesco, M. C., Carranza, M. L. and Stanisci, A. 2018. Beach litter in Mediterranean coastal dunes: an insight on the Adriatic coast (central Italy). *Rendiconti Lincei. Scienze Fisiche e Naturali*, **29**, 825–830. https://doi.org/10.1007/s12210-018-0740-5

Galgani, F., Hanke, G., Werner, S. and De Vrees, L. 2013. Marine litter within the European Marine Strategy Framework Directive. *ICES Journal of Marine Science*, **70**(6), 1055–1064. https://doi.org/10.1093/icesjms/fst122

Galgani, L., Beiras, R., Galgani, F., Panti, C. and Borja, A. 2019. Editorial: Impacts of marine litter. *Frontiers in Marine Science*, **6**, 208. https://doi.org/10.3389/fmars.2019.00208

GESAMP. 2015. *Sources, Fate and Effects of Microplastics in the Marine Environment: A Global Assessment* (Kershaw, P. J., ed.). International Maritime Organization, London.

Grant, M. L., Lavers, J. L., Stuckenbrock, S., Sharp, P. B. and Bond, A. L. 2018. The use of anthropogenic marine debris as a nesting material by brown boobies (*Sula leucogaster*). *Marine Pollution Bulletin*, **137**, 96–103. https://doi.org/10.1016/j.marpolbul.2018.10.016

Haaksi, H. 2020. *Task 2.1.1 Development of Baselines of Marine Litter - Identification of Top Litter Items in the Baltic Sea Region*. HELCOM, Helsinki. https://helcom.fi/wp-content/uploads/2020/04/Theme-2_Deliverable-2.1.1.b.pdf

Hanke, G., Walwoort, D., van Loon, W., Addamo, A. M., Brosich, A., del Mar Chaves Montero, M. et al. 2019. *EU Marine Beach Litter Baselines: Analysis of a Pan-European 2012-2016 Beach Litter Dataset*. EUR 30022 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/16903

Haseler, M., Balciunas, A., Hauk, R., Sabaliauskaite, V., Chubarenko, I., Ershova, A. et al. 2020. Marine litter pollution in Baltic Sea beaches – application of the sand rake method. *Frontiers in Environmental Science*, **8**, 599978. https://doi.org/10.3389/fenvs.2020.599978

HELCOM. 2010. Towards a tool for quantifying anthropogenic pressures and potential impacts on the Baltic Sea marine environment: a background document on the method, data and testing of the Baltic Sea Pressure and Impact Indices. *Baltic Sea Environment Proceedings*, **125**. https://doi.org/10.13140/RG.2.1.2148.6961

HELCOM. 2018. State of the Baltic Sea – second HELCOM holistic assessment 2011–2016. *Baltic Sea Environment Proceedings*, **155**. https://helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials

HELCOM. 2023. *Beach Litter.* HELCOM Core Indicator Report. https://indicators.helcom.fi/wp-content/uploads/2023/04/Beach-litter_Final_April_2023-1.pdf (accessed 2025-01-28).

Hidalgo-Ruz, V. and Thiel, M. 2015. The contribution of citizen scientists to the monitoring of marine litter. In *Marine Anthropogenic Litter* (Bergmann, M., Gutow, L. and Klages, M., eds). Springer, Cham, 429–447. https://doi.org/10.1007/978-3-319-16510-3_16

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C. and Thiel, M. 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. *Environmental Science & Technology*, **46**(6), 3060–3075. https://doi.org/10.1021/es2031505

Hijmans, R. J. 2020. *Raster: Geographic Data Analysis and Modeling*. R package version 3.4-5. https://CRAN.R-project.org/package=raster (accessed 2023-01-12).

Ibrahim, E. A. A., Osman, N. A. R. and Eisa, O. A. M. 2020. Status of the beach litter in the UNESCO World Heritage Site of Dungonab and Mukkawar Island Marine National Park in Sudan, Red Sea. *International Journal of Ecology*, 6904745. https://doi.org/10.1155/2020/6904745

Isæus, M. 2004. *Factors structuring Fucus communities at open and complex coastlines in the Baltic Sea*. PhD dissertation. Stockholm University, Sweden.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A. et al. 2015. Plastic waste inputs from land into the ocean. *Science*, **347**(6223), 768–771. https://doi.org/10.1126/science.1260352

Joint Research Centre: Institute for Environment and Sustainability and MSFD Technical Subgroup on Marine Litter. 2013. *Guidance on Monitoring of Marine Litter in European Seas*. EUR 26113 EN. Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2788/99816

Kideys, A. E., Šubelj, G. and Aydın, M. 2021. *Marine Litter and European Beaches: Learning from Citizen Science*. ETC/ICM Technical Report 1/2021. European Topic Centre on Inland, Coastal and Marine Waters, Copenhagen.

Kruskal, J. B. 1964. Nonmetric multidimensional scaling: a numerical method. *Psychometrika*, **29**, 115–129.

Kruskal, W. H. and Wallis, W. A. 1952. Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, **47**(260), 583–621. https://doi.org/10.2307/2280779

Kühn, S., Bravo Revolledoo, E. L., van Franeker, J. A. 2015. Deleterious effects of litter on marine life. In *Marine Anthropogenic Litter* (Bergmann, M., Gutow, L. and Klages, M., eds). Springer, Berlin, 75–116.

Łabuz, T. A. 2015. Environmental impacts – coastal erosion and coastline changes. In *Second Assessment of Climate Change for the Baltic Sea Basin, Regional Climate Studies* (The BACC II Author Team, eds). Springer, Cham, 381–396. https://doi.org/10.1007/978-3-319-16006-1_20

Lavers, J. L. and Bond, A. L. 2017. Exceptional and rapid accumulation of anthropogenic debris on one of the world's most remote and pristine islands. *PNAS*, **114**(23), 6052–6055. https://doi.org/10.1073/pnas.1619818114

Lavers, J. L., Dicks, L., Dicks, M. R. and Finger, A. 2019. Significant plastic accumulation on the Cocos (Keeling) Islands, Australia. *Scientific Reports*, **9**, 7102. https://doi.org/10.1038/s41598-019-43375-4

Li, D., Zhao, L., Guo, Z., Yang, X., Deng, W., Zhong, H. et al. 2021. Marine debris in the Beilun Estuary mangrove forest: monitoring, assessment and implications. *International Journal of Environmental Research and Public Health*, **18**(20), 10826. https://doi.org/10.3390/ijerph182010826

van Loon, W., Hanke, G., Fleet, D., Werner, S., Barry, J., Strand, J. et al. 2020. *A European Threshold Value and Assessment Method for Macro Litter on Coastlines*. EUR 30347 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/54369

Maljutenko, I. and Raudsepp, U. 2014. Validation of GETM model simulated long-term salinity fields in the pathway of saltwater transport in response to the Major Baltic Inflows in the Baltic Sea. In *2014 IEEE/OES Baltic International Symposium (BALTIC), Tallinn, Estonia, 27–29 May 2014* (Carroll, J., ed.). IEEE, 23–31. https://doi.org/10.1109/BALTIC.2014.6887830

MARLIN. 2013. *Final Report of Baltic Marine Litter Project MARLIN – Litter Monitoring and Raising Awareness 2011-2013*. https://pidasaaristosiistina.fi/wp-content/uploads/2023/06/Marlin_Final_Report_2014.pdf (accessed 2025-10-01).

Matiddi, M., Pham, C. K., Anastasopoulou, A., Andresmaa, E., Avio, C. G., Bianchi, J. et al. 2021. *Monitoring Micro-Litter Ingestion in Marine Fish: A Harmonized Protocol for MSFD and RSCs Areas*. MSFD TG Marine Litter. Joint Research Centre, European Commission, Luxembourg.

van der Meijs, F., Isaeus, M. 2020. *Wave Exposure Calculations for the Gulf of Finland*. AquaBiota Water Research, AquaBiota Report, 13.

Menicagli, V., Balestri, E. and Lardicci, C. 2019. Exposure of coastal dune vegetation to plastic bag leachates: a neglected impact of plastic litter. *Science of The Total Environment*, **15**, 737–748. https://doi.org/10.1016/j.scitotenv.2019.05.245

O'Hanlon, N. J., Bond, A. L., Masden, E. A., Lavers, J. L. and James, N. A. 2021. Measuring nest incorporation of anthropogenic debris by seabirds: an opportunistic approach increases geographic scope and reduces costs. *Marine Pollution Bulletin*, **171**, 112706. https://doi.org/10.1016/j.marpolbul.2021.112706

Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R. et al. 2020. *Vegan: Community Ecology Package*. R package version 2.5-7. https://CRAN.R-project.org/package=vegan (accessed 2023-01-12).

Pebesma, E. 2018. Simple features for R: standardized support for spatial vector data. *The R Journal*, **10**(1), 439–446. https://doi.org/10.32614/RJ-2018-009

Peng, Y., Wu, P., Schartup, A. T., Zhang, Y. 2021. Pandemic's plastic waste is choking the seas. *Nature*, **599**, 350. https://doi.org/10.1038/d41586-021-03078-1

Pérez-Guevara, F., Roy, P. D., Kutralam-Muniasamy, G. and Shruti, V. C. 2022. Coverage of microplastic data underreporting and progress toward standardization. *Science of The Total Environment*, **829**, 154727. https://doi.org/10.1016/j.scitotenv.2022.154727

Polasek, L., Bering, J., Kim, H., Neitlich, P., Pister, B., Terwilliger, M. et al. 2017. Marine debris in five national parks in Alaska. *Marine Pollution Bulletin*, **117**(1–2), 371–379. https://doi.org/10.1016/j.marpolbul.2017.01.085

Põldma, M., Torn, K. and Saks, L. 2023. Microlitter in fish and benthic invertebrates of the NE Baltic Sea: abundance, composition and bioindicators. *International Journal of Environmental Impacts*, **6**(3), 143–153. https://doi.org/10.18280/ijei.060307

Portz, L., Manzolli, R. P., Villate-Daza, D. A. and Fontán-Bouzas, Á. 2022. Where does marine litter hide? The Provedencia and Santa Catalina Island problem, SEAFLOWER Reserve (Colombia). *Science of The Total Environment*, **813**, 151878. https://doi.org/10.1016/j.scitotenv.2021.151878

Press, M. 2020. *Merelise prügi seire Eesti rannikualadel 2019-2020*. Project report. Hoia Eesti Merd MTÜ. https://hem.ee/wp-content/uploads/2021/05/Projekti-6865_aruanne-2019-2020.pdf (accessed 2024-02-15).

Press, M. 2023. *Merelise prügi seire Eesti rannikualadel 2021-2022*. Project report. Hoia Eesti Merd MTÜ. https://hem.ee/wp-content/uploads/2023/05/Projekti-6865_aruanne_2021-2022_fin_w.pdf (accessed 2024-02-15).

Primpke, S., Christiansen, S. H., Cowger, W., De Frond, H., Deshpande, A., Fischer, M. et al. 2020. Critical assessment of analytical methods for the harmonized and cost-efficient analysis of microplastics. *Applied Spectroscopy*, **74**(9), 1012–1047. https://doi.org/10.1177/0003702820921465

R Core Team. 2021. *R: A language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna. https://www.R-project.org (accessed 2023-01-12).

Roberts, K. P., Phang, S. C., Williams, J. B., Hutchinson, D. J., Kolstoe, S. E., de Bie, J. et al. 2022. Increased personal protective equipment litter as a result of COVID-19 measures. *Nature Sustainability*, **5**, 272–279. https://doi.org/10.1038/s41893-021-00824-1

Rodríguez-Rodríguez, D. 2012. Littering in protected areas: a conservation and management challenge – a case study from the Autonomous Region of Madrid, Spain. *Journal of Sustainable Tourism*, **20**(7), 1011–1024. https://doi.org/10.1080/09669582.2011.651221

RStudio Team. 2021. *RStudio: Integrated Development Environment for R*. RStudio, PBC, Boston. http://www.rstudio.com (accessed 2023-01-12).

Schernewski, G., Balciunas, A., Gräwe, D., Gräwe, U., Klesse, K., Schulz, M. et al. 2018. Beach macro-litter monitoring on southern Baltic beaches: results, experiences and recommendations. *Journal of Coastal Conservation*, **22**, 5–25. https://doi.org/10.1007/s11852-016-0489-x

Schernewski, G., Escobar Sánchez, G., Felsing, S., Gatel Rebours, M., Haseler, M., Hauk, R. et al. 2024. Emission, transport and retention of floating marine macro-litter (plastics): the role of Baltic harbor and sailing festivals. *Sustainability*, **16**(3), 1220. https://doi.org/10.3390/su16031220

Schröder, K., Kossel, E. and Lenz, M. 2021. Microplastic abundance in beach sediments of the Kiel Fjord, Western Baltic Sea. *En-*

vironmental Science and Pollution Research, **28**, 26515–26528. https://doi.org/10.1007/s11356-020-12220-x

Shapiro, S. S. and Wilk, M. B. 1965. An analysis of variance test for normality (complete samples). *Biometrika*, **52**(3–4), 591–611. https://doi.org/10.1093/biomet/52.3-4.591

Šilc, U., Küzmič, F., Caković, D. and Stešević, D. 2018. Beach litter along various sand dune habitats in the southern Adriatic (E Mediterranean). *Marine Pollution Bulletin*, **128**, 353–360. https://doi.org/10.1016/j.marpolbul.2018.01.045

Smith, L. and Turrell, W. R. 2021. Monitoring plastic beach litter by number or by weight: the implications of fragmentation. *Frontiers in Marine Science*, **8**, 702570. https://doi.org/10.3389/fmars.2021.702570

Strand, J., Tairova, Z., Danielsen, J., Hansen, J. W., Magnusson, K., Naustvoll, L.-J. et al. 2015. *Marine Litter in Nordic Waters*. Nordic Council of Ministers, Copenhagen. https://doi.org/10.6027/TN2015-521

Tähiste, A. and Mõniste, M. 2016. *Merepiirivalve tehnilise vaatluse post Harilaiul Vormsi vallas Läänemaal (Technical Observation Post of Maritime Border Guard in Harilaiu, Vormsi County, Läänemaa)*. Projekti „Eesti 20. sajandi (1870–1991) sõjalise ehituspärandi kaardistamine ja analüüs” aruanne (Report of the project “Mapping and analysis of military construction heritage from 1970 to 1991 in Estonia”). https://www.mil.hiiumaa.ee/xx/Laanemaa-Vormsi-Harilaid.pdf

Tõnisson, H., Orviku, K., Lapinskis, J., Gulbinskas, S. and Žaromskis, R. 2013. The Baltic States: Estonia, Latvia and Lithuania. In *Coastal Erosion and Protection in Europe* (Pranzini, E. and Williams, A., eds). Routledge, Oxon, 47–80.

Turrell, W. R. 2018. A simple model of wind-blown tidal strandlines: how marine litter is deposited on a mid-latitude, macro-tidal shelf sea beach. *Marine Pollution Bulletin*, **137**, 315–330. https://doi.org/10.1016/j.marpolbul.2018.10.024

Uiboupin, R. and Pärn, O. 2018. *Mereala planeeringu alusuuring: jääolude analüüs ja kaartide koostamine (Marine Spatial Planning: Analysis of Ice Conditions and Production of Maps)*. TTÜ Meresüsteemide Instituut, Tallinn.

United Nations Environment Programme and Intergovernmental Oceanographic Commission 2009. *UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter*. Regional Seas Reports and Studies No. 186, IOC Technical Series No. 83. https://wedocs.unep.org/20. 500.11822/13604

Urban-Malinga, B., Zalewski, M., Jakubowska, A., Wodzinowski, T., Malinga, M., Palys, B. et al. 2020. Microplastics on sandy beaches of the southern Baltic Sea. *Marine Pollution Bulletin*, **155**, 111170. https://doi.org/10.1016/j.marpolbul.2020.111170

Vlachogianni, T., Skocir, M., Constantin, P., Labbe, C., Orthodoxou, D., Pesmatzoglou, I. et al. 2020. Plastic pollution on the Mediterranean coastline: generating fit-for-purpose data to support decision-making via a participatory-science initiative. *Science of The Total Environment*, **711**, 135058. https://doi.org/10.1016/j.scitotenv.2019.135058

Votier, S. C., Archibald, K., Morgan, G. and Morgan, L. 2011. The use of plastic debris as nesting material by a colonial seabird and associated entanglement mortality. *Marine Pollution Bulletin*, **62**(1), 168–172. https://doi.org/10.1016/j.marpolbul.2010.11.009

Wickham, H., Averick, M., Bryan, J., Chang, W., D’Agostino McGowan, L., François, R. et al. 2019. Welcome to the tidyverse. *Journal of Open Source Software*, **4**(43), 1686. https://doi.org/10.21105/joss.01686

Wilcoxon, F. 1945. Individual comparisons by ranking methods. *Biometrics Bulletin*, **1**(6), 80–83. https://doi.org/10.2307/3001968

Wyles, K. J., Pahl, S., Thomas, K. and Thompson, R. C. 2016. Factors that can undermine the psychological benefits of coastal environments: exploring the effect of tidal state, presence, and type of litter. *Environment and Behavior*, **48**(9), 1095–1126. https://doi.org/10.1177/0013916515592177

Zalewska, T. and Krzymiński, W. 2017. *Task 2.1.1 Development of Baselines of Marine Litter - Report on the Analysis of Compiled Beach Litter Data and Proposals for Setting Preliminary Beach Litter Baselines in the Baltic Sea*. HELCOM, Helsinki. https://helcom.fi/wp-content/uploads/2020/04/Theme-2_Deliverable-2.1.1.a.pdf

Mereprügi levik Eesti rannikumere asustamata väikesaartel

Tiia Möller-Raid, Maria Põldma, Kristjan Herkül, Kaire Torn, Georg Martin, Kaire Kaljurand, Martin Teeveer, Greta Reisalu, Trude Taevere, Hanna-Eliisa Luts, Karolin Teeveer, Keili Saava, Annely Enke ja Lauri London

Mereprügi hulka kuuluvad kõik mitteloodusliku päritolu esemed, mida leidub mere- ja rannikukeskkonnas, ning prügi levik ja kogused peegeldavad otsest inimmõju merekeskkonnale. Artikkel annab ülevaate mereprügi uuringutest, mis teostati aastatel 2019–2020 neljateistkümnel Eesti rannikumere asustamata väikesaarel. Makroprügi (prügiesemed suurusega > 2,5 cm) esinemist hinnati nii rannal kui ka rannaga piirneval taimestikuga alal. Mereprügi arvukuse mediaanväärtus oli rannaalal 10,65 ühikut ja taimestikuga alal 21,65 ühikut 100 m pikkuse lõigu kohta. Keskmisest enam mereprügi esines Soome lahe saartel (mediaanväärtus rannaalal 38,05 ühikut ja taimestikuga alal 45,83 ühikut 100 m kohta). Peamine mereprügi materjal oli plast, mis moodustas 57,3% kõikidest leidudest. Kõigi uuritud saarte rannaala setetest leiti ka mikroprügi (prügiesemed suurusega < 0,5 cm), hinnangulised kogused olid kuni 60 eset ühe kg kuivsette kohta. Samuti täheldati lindude pesitsusaladel mereprügi kasutust pesamaterjalina. Uurimistulemused viitavad vajadusele käsitleda mereprügiga seotud probleeme ja uuringuid senisest terviklikumalt.