

Citizen science data indicate a reduction in beach litter in the Lofoten archipelago in the Norwegian Sea

Utført av SALT Lofoten AS og
Lofoten Avfallsselskap

Handelens Miljøfond
c/o House of Business
Henrik Ibsens gate 90
0255 OSLO

www.handelensmiljofond.no

Det må ikke kopieres fra denne rapporten i strid med åndsverksloven. Rapporter lagt ut på Internett, er lagt ut kun for lesing på skjerm og utskrift til eget bruk. Enhver eksemplarframstilling og tilgjengeliggjøring utover dette må avtales med Handelens Miljøfond. Utnyttelse i strid med lov eller avtale, medfører erstatningsansvar.



Citizen science data indicate a reduction in beach litter in the Lofoten archipelago in the Norwegian Sea

Marthe Larsen Haarr^{a,*}, Michael Pantalos^a, Monica Kleffegård Hartviksen^b, Marit Gressetvold^b

^a SALT Lofoten AS, Havnerterminalen, Fiskergata 23, 8301 Svolvær, Norway

^b Lofoten Avfallsselskap (Lofoten Waste Management Company), Lekneskroken 3, 8376 Leknes, Norway

ABSTRACT

Marine litter is a major global challenge, even in the remote reaches of the Arctic. Monitoring temporal trends in litter loadings and composition is key to designing effective preventative and mitigative measures, and to assess their impact. Few data are available, however, by which to do this in the Arctic region. Citizen science data organised by the local waste management company in the Lofoten archipelago in the Norwegian Sea is an exception to this. We analysed volunteer cleanup data (total weight and counts of select litter types, standardised to density per 100 m) from over 200 locations from 2011 to 2018. Results indicate a general decline in beach litter in the region, and particularly in litter types related to private use, such as beverage bottles. These declines are most likely the combined result of extensive cleanup activities and a considerable reduction in local litter inputs.

1. Introduction

Marine litter is one of our time's great environmental concerns. It has been estimated that a staggering 8–13 million tonnes of plastic pollution enters the oceans annually as a result of waste mismanagement on land (Jambeck et al., 2015). In addition, considerable amounts of fishing gears and other fisheries related waste is lost or discarded each year (Macfayden et al., 2009). The magnitude of loss from fisheries and other maritime industries remains uncertain, but a recent study suggests that commercial fishing off Norway alone contributes nearly 400 t of plastic fishing gears to the oceans each year (Deshpande et al., 2020). The very characteristics that make it such a desirable product for a large variety of applications, also makes plastics extremely persistent in the environment (Andrady, 2015). Marine litter poses serious threats to marine life through ingestion, entanglement and smothering (Kühn et al., 2015), and also has negative economic impacts, particularly for industries such as fishing and tourism (Newman et al., 2015). Marine plastic pollution is ubiquitous globally and across all marine environments (Galgani et al., 2015), including in the remote regions of the Arctic (Halsband and Herzke, 2019).

In 2010, the European Union's Marine Strategy Framework Directive recommended the goal of measurable reductions in marine litter in the European region by 2020 (Galgani et al., 2010). The OSPAR Commission has similarly set down objectives for reductions in, and monitoring of, marine litter in the North East Atlantic (OSPAR Commission, 2014). Achieving these goals is challenging not only with respects to implementing effective preventative and mitigative

measures in the region, but also in terms of establishing adequate time series of data by which to assess temporal trends. Robust time series of quantitative and representative beach litter data are generally not available, in large part due to the high cost and logistical challenges associated with collecting such data. Analyses of 25 years of monitoring from the OSPAR Beach Litter Monitoring Program showed few trends in the overall occurrence of litter, but did detect several both positive and negative trends for individual litter types (Schulz et al., 2015). However, considerable local variation among beaches and generally low replication within regions makes grouping of survey locations and assessments of trends over larger areas challenging using the OSPAR method, and results tend to be location specific (Schulz et al., 2019, 2017). Citizen science data from volunteer beach cleanup actions are typically of much lower quality than professionally collected data (e.g., OSPAR), but are also generally available in much greater volumes (Hidalgo-Ruz and Thiel, 2015). Sometimes such data can provide relatively long time series with broad geographical coverage, enabling analyses that would otherwise not have been possible. Such an analysis was conducted across the UK over a decade (2004–2015), yet did not reveal any systemic temporal trends in the total litter amounts (Nelms et al., 2017). However, long-term increases of certain individual litter types was observed (Nelms et al., 2017). The lack of overall change in beach litter pollution levels was suggested to be due to cleanup efforts being sufficient to halt further accumulation of beach litter, but insufficient to actually result in a decrease (Nelms et al., 2017). Currently there is little clear evidence suggesting a successful measurable reduction in marine litter in Europe by 2020, and it seems clear that, among

* Corresponding author.

E-mail address: marthe@salt.nu (M.L. Haarr).

other things, more data are needed for trend assessment.

The Lofoten archipelago in northern Norway presents an interesting case study for assessing temporal trends in beach litter. On average across Norway, volunteers have cleaned a little under 1% of its coastline annually in recent years (Zimmermann et al., 2018). In the Lofoten archipelago engagement is particularly high, covering approximately 5% of its coastline in 2018 (Hartviksen and Gressetvold, 2018). Cleanup actions in Lofoten have been arranged by the Lofoten Waste Management Company (LAS) since 2011. Volunteers may dispose of collected litter free of charge provided it is accompanied by a data registration sheet showing counts of common litter types. Unlike many citizen science datasets on beach litter, LAS also provides a total weight estimate of litter cleaned at each location as litter is weighed in upon delivery (Falk-Andersson et al., 2019; Hartviksen and Gressetvold, 2018). In addition to high cleanup activity, the archipelago also has a unique geography. Situated in the Norwegian Sea, it extends from like an “arm” to the west of the Norwegian mainland, intersecting both the Norwegian Coastal Current (NCC) and the Norwegian Atlantic Current (ACC, an extension of the Gulf Stream) (Mitchelson-Jacob and Sundby, 2001). The south-eastern (“inner”) shore of the archipelago borders Vestfjorden, a large coastal bay with a complex current pattern of eddies which occur as the NCC is redirected from the upper bay and forced out and around the archipelago (Mitchelson-Jacob and Sundby, 2001). The ACC passes by the north-western (“outer”) shore, bringing waters from the North Sea and across the Atlantic (Mitchelson-Jacob and Sundby, 2001; Skagseth et al., 2008). Consequently, local litter sources are more likely to dominate along the “inner” shore where water comes from along the Norwegian coast with the NCC and may be retained by eddy systems, while the “outer” shore has greater potential to accumulate litter transported from afar (Falk-Andersson et al., 2019).

Our objective was to utilise the LAS dataset as an indicator of local beach litter temporal trends, in terms of both long-term (first-time cleanup locations) and short-term (repeat cleanup locations) accumulation in the Lofoten archipelago, northern Norway. As a secondary objective, we also assessed whether these trends were similar along the inner (fjord) and outer (open ocean) shores of the archipelago given their potential differential exposure to local vs. long-transport sources of marine litter. As the region sees above-average cleanup efforts and has the potential to be significantly impacted by both local and long-distance sources of litter, it is a highly interesting area in which to investigate temporal trends to attempt to assess impacts of beach cleanups and potential trends in continued litter pollution. Data on marine litter in the Arctic is also relatively limited (Halsband and Herzke, 2019), further increasing the value of this extensive citizen science dataset.

2. Methods

2.1. Beach litter data

Litter registrations from beach cleanups from 2011 to 2018 were provided by the Lofoten Waste Management Company (henceforth referred to by its Norwegian acronym LAS). Additionally, data from 2019 for select sites that were part of a multi-year series were provided. The data collected during cleanup actions included total weight, counts of select litter types, location, estimated length of beach cleaned, and the month and year it took place. When coordinates were not provided for the location, LAS staff approximated them based on a mixture of site names, local knowledge, and dialogue with cleanup coordinators.

It is important to note that volunteers did not count and identify all litter, only select litter types. This list of litter types registered also changed somewhat through the time series as the protocol was adjusted to meet the perceived local needs (Falk-Andersson et al., 2019). Consequently, we did not consider all the count data available, only counts of litter types recorded consistently throughout the time series. This included 30 litter types classified into four source categories:

“commercial”, “private” (“on the fly”), “household” and “other” (Table 2). Litter types classified as “commercial” included ropes, fishing gear, buoys, fish boxes, bait bags, strapping bands, tarps, jerry cans, dish soap bottles and extruded polystyrene (EPS). The “commercial” source category was dominated by fisheries-related litter types, but also included some litter types that may stem from land-based commercial activities. Litter types classified as “private” included items typically used by individuals “on the fly”, such as beverage bottles and cans, lids and caps, disposable dinnerware and cups, takeaway packaging, plastic bags, clothing, shoes, lighter and tobacco products. Litter types classified as “household” items included food packaging, light bulbs and sanitary pads and tampons. Litter types in both the “private” and “household” source categories may have been used (and lost/discarded) by either persons on shore (e.g., beachgoers) or at sea (e.g., fishermen). Litter types classified as “other” included batteries, car parts, tires, electronics, oil drums and syringes. Attribution of litter types to these source categories is part of LAS’ data collection scheme, and as our objective was to utilise their dataset these categories were retained in analyses. However, we recognise that there are challenges regarding source allocations; considerations concerning this are given in the discussion.

2.2. Statistical analyses

To determine the most common litter types observed, the percentage of recorded litter comprising different litter types and source categories was assessed both based on pooling all registrations and on the cleanup action means. For source categories a chi-square test was carried out to assess whether the proportion of each was different from expected given the uneven number of litter types classified in each category. Expanded polystyrene (EPS), considered part of the “commercial” category, was not registered until 2012. Since LAS believes it to be a common item, basic descriptive statistics were repeated excluding 2011 to allow including EPS in the counts. From 2016 to 2018, beverage bottles of Norwegian and foreign origin were distinguished. Thus, for these three years, Kruskal-Wallis rank-sum tests were carried out to test for significant differences in the density (#/100 m) of Norwegian and foreign bottles between the inner and outer coasts of Lofoten. This was done to test the hypothesis that the outer coast is more likely to receive long-transported litter than the inner coast. We did not assess the ratio of Norwegian to foreign beverage bottles as bottles of unidentifiable origin were not accounted for.

Temporal trends in beach litter density were investigated by considering (1) long-term accumulation represented by the very first time a location was cleaned and excluding subsequent cleanups of the same locations, henceforth referred to as “standing stock”, and (2) short-term accumulation represented by repeated (typically annual), cleanup actions at the same locations (first cleanup action excluded), henceforth referred to as “influx”. In total, data from 704 cleanup actions were provided. However, due to variable quality and detail of litter registrations, not all were included in analyses. Litter quantities were standardised to density per 100 m of shoreline, necessitating the exclusion of any registrations lacking values for length of beach cleaned. Influx trends were only assessed at locations with at least four cleanup actions (minimum three measurements of recently beached litter after long-term accumulations, i.e., first cleanup actions, were removed). Furthermore, only cleanup actions with 50 or more litter items recorded were considered to avoid skewing of the data set by very small cleanup actions. For analyses of standing stock, the number of cleanup actions retained differed for count and weight data as there were a number of actions for which total weight had been recorded but counts not adequately performed. The quality and reliability of count data were determined by LAS staff, and cleanup actions only included in analyses if deemed adequate. The resulting sample size (number of cleanup actions) for each analysis is given in Table 1, and maps of cleanup locations are shown in Fig. 1.

Table 1
Number of cleanup actions (*i.e.*, *n*) included in time series analyses.

	Total weight	Item counts
Litter influx	77 (48 inner shore, 29 outer shore) 20 sites (13 inner shore, 7 outer shore)	77 (48 inner shore, 29 outer shore) 20 sites (13 inner shore, 7 outer shore)
Standing stock	232 (153 inner shore, 79 outer shore)	169 (111 inner shore, 58 outer shore)

The temporal trend analyses of both litter influx and standing stock were conducted using both least-squares linear regression (Falk-Andersson et al., 2019) and Mann-Kendall time series analyses combined with Sen-Theil slope estimations (Schulz et al., 2019; Wilcox, 2010). For least-squares regressions, density data (kg and item counts per 100 m coastline) were natural log transformed. This was done to normalise the highly skewed log-normal distributions of the raw data (Falk-Andersson et al., 2019; Nelms et al., 2017). For standing stock these analyses were carried out as simple ANCOVAs with month (expressed as unique values starting with January 2011 = 1) and shore (inner/fjord vs. outer/open ocean side of the archipelago) as factors. Similar analyses were carried out for litter influx, but here location was added as a random factor to account for potential differences among sites (Nelms et al., 2017). All least-squares regressions were carried out using JMP14. Mann-Kendall time series analyses were carried out on untransformed density data (kg and item counts per 100 m coastline) for the inner (fjord) and outer (open ocean) coasts separately, and 95% confidence intervals calculated through bootstrapping (10,000 iterations). For trends in litter influx, a common slope was calculated based on data points paired within locations. Mann-Kendall time series analyses were carried out in Excel. The above analyses were all carried out using total weight cleaned, counts for each source category, and counts of the most common litter types. Relatively uncommon litter types were excluded as frequent zero observations hinders trend detection (Schulz et al., 2013).

3. Results

3.1. Annual variations in cleanup actions

Overall there was a significant increase in annual cleanup actions through the time series ($F_{1,6} = 30.04$, $p = 0.0015$, $R^2 = 0.83$) with an average increase of 10 cleanups per year. However, this trend was less evident when considering only the actions with sufficient data quality to be retained for analyses. For the 232 cleanup actions retained for standing stock analyses (by total weight), there was no significant trend in the number of actions annually ($F_{1,6} = 0.50$, $p = 0.51$). The majority of cleanup actions took place in May, but this did change through the time series. For the same 232 cleanup actions 61% were carried out in May, and there was a significant decline in the ratio of cleanup actions carried out in May relative to the rest of the year from 2011 to 2018 ($F_{1,6} = 15.7$, $p = 0.007$). This was due to a shift in the waste management company's regulations. Initially LAS allowed free-of-charge deliveries of beach litter only during the spring, but following federal funding cuts for their cleanup program in 2015 they began admitting deliveries any time, leading to a greater seasonal spread in cleanup actions in subsequent years.

3.2. Common litter types and composition

Litter registrations were carried out in adequate detail to assess litter composition during a total of 445 cleanup actions from 2011 to 2018 (Table 3). The most common source category was “commercial” (54%, all registrations pooled), followed by “private” (“on the fly”) (37%), “household” (8%) and “other” (1%). The percentage of “commercial” was considerably higher, and that of “household” and “other” considerably lower, than expected based on the number of litter types

classified as belonging to each ($\chi^2_3 = 60,861$, $p < 0.0001$). The difference between the percentage of “commercial” and “private” evens out when considering the average per cleanup action rather than all litter pooled (46% and 43%, respectively). If the first year (2011) is excluded from the analysis so that Styrofoam can be included (classified as “commercial”), then the percentage of “commercial” litter increases (60% of all registrations pooled, 52% cleanup action mean).

Of the 30 litter types registered throughout the time series, an average of 18 of these were recorded per cleanup action. However, four litter types accounted for half of all observations, and eight for three quarters. The rank of these top eight was somewhat dependent on the method used to calculate them (on all registrations pooled vs. cleanup action means). Rope < 50 cm was consistently the most common (17% mean, 21% pooled), followed by plastic beverage bottles (14% mean and pooled) and lids and caps (10% mean and pooled). The fourth most common item, and adding to 50% cumulatively, however, was food packaging based on cleanup actions means (9%), but buoys and other floats based on pooled data (8%). With rope > 50 cm, strapping bands, and plastic bags these eight litter types constituted 75% of items based on cleanup actions means and 80% of all registrations pooled. The remaining 22 litter types each accounted for < 3% of litter registrations.

When 2011 was removed from the time series and Styrofoam included in the analyses, Styrofoam made the top four types accounting for 50% of registered litter. Rope < 50 cm remained the most common item (16% mean, 19% pooled), followed by plastic beverage bottles (13% mean and pooled) or Styrofoam (11% mean, 14% pooled), depending on whether cleanup action means or all registrations pooled were considered (Fig. 2). The fourth most common item was lids and caps in both cases (9% mean, 8% pooled). The next four most common litter types (the eight together making up 75%–80% of registrations) varied somewhat with method of estimation. Based on cleanup action means these litter types were food packaging (7%), rope > 50 cm (6%), strapping bands (6%) and plastic bags (5%). Based on all registrations pooled these were rope > 50 cm (7%), buoys and other floats (7%), strapping bands (6%) and food packaging (6%) (Fig. 2). Each of the remaining 22 litter types constituted < 3.5% each.

On average across the three years 2016–2018, the density of bottles was approximately twice as high along the outer, open ocean coast (11 bottles $100 \text{ m}^{-1} \pm \text{SE } 3.4$) than the inner, fjord coast (25 bottles $100 \text{ m}^{-1} \pm \text{SE } 5.3$) of Lofoten (Kruskal-Wallis rank-sum test: $p = 0.003$). This difference was due to a greater presence of foreign bottles along the outer coast. The mean density of Norwegian beverage bottles was similar between both coasts in each of the three years (Table 4). The density of foreign beverage bottles, however, was consistently higher along the outer coast than the inner (Table 4). Pooling data from all three years, the density of foreign bottles was significantly lower than that of Norwegian bottles along the inner coast (Kruskal-Wallis rank-sum test: $p < .0001$). However, there was no significant difference in the density of Norwegian and foreign beverage bottles along the outer coast of Lofoten (Kruskal-Wallis rank-sum test: $p = .18$).

3.3. Temporal trends in standing stock

Least-squares models could only be used for temporal trends in total weight cleaned and the abundance of “commercial” and “private” litter types, as these were the only categories sufficiently common for their

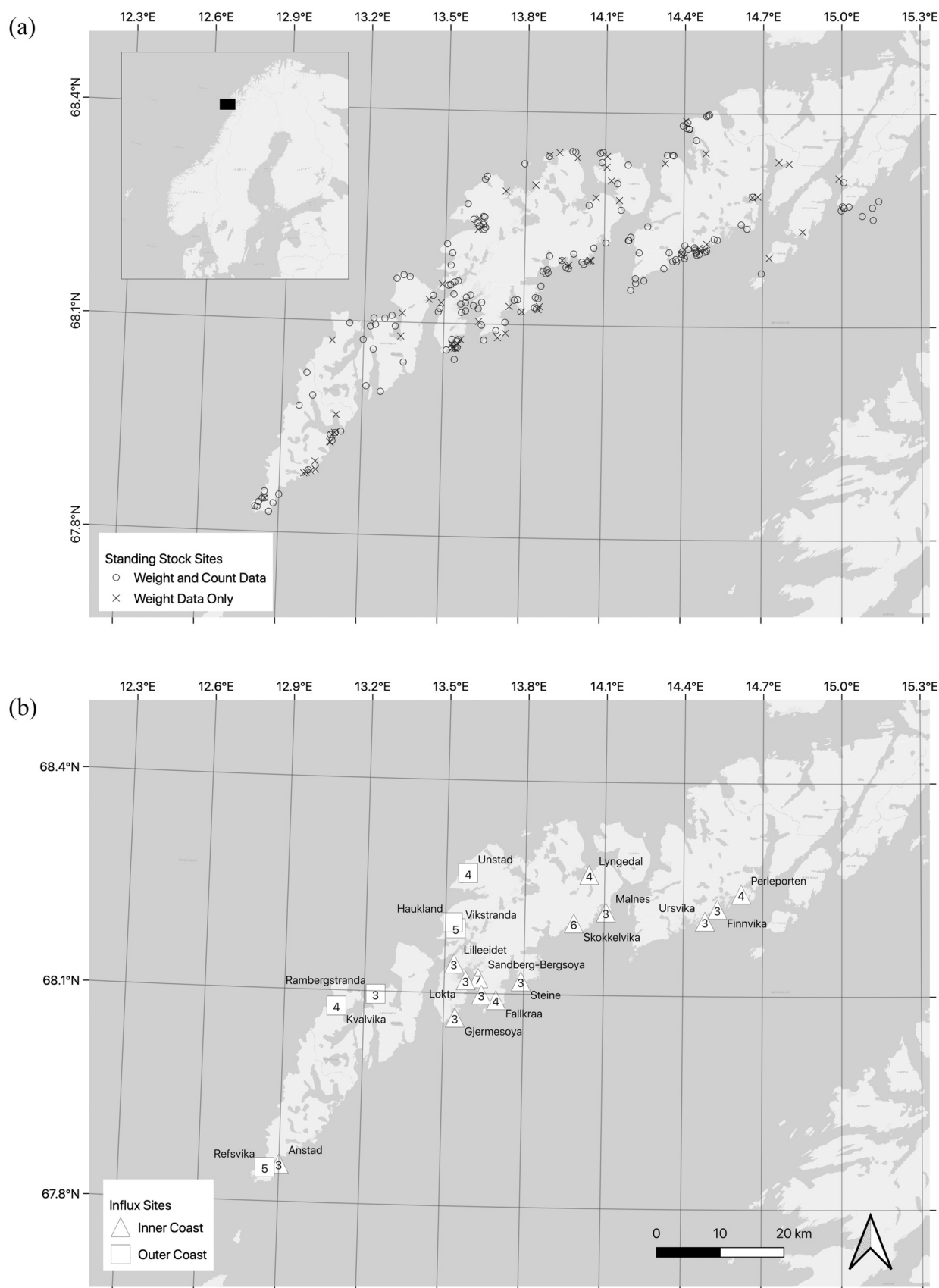


Fig. 1. Maps showing cleanup actions included in time series analyses of (a) standing stock or long-term accumulated litter, and (b) influx or short-term accumulation of litter on beaches. The numbers inside the symbols in b show the number of repeat cleanup actions at each site (excluding the first cleanup at each location). Inner and outer coast distinguishes the coast along the West Fjord facing the Norwegian mainland (the inner coast) from the coast facing the open ocean (outer coast).

Table 2
Litter types counted within each source category.

Commercial	Private ("on the fly")	Household	Other
Rope < 50 cm	Plastic beverage bottles	Food packaging	Batteries
Rope > 50 cm	Beverage cans	Light bulbs	Car parts
Nets/pieces of nets	Glass bottles	Sanitary pads/tampons	Tires
Fish boxes	Lids and caps		Electronics
Bait holders/bags	Disposable dinnerware/cups		Oil drums
Buoys and other floats	Take-away packaging		Syringes
Strapping bands	Plastic bags		
Tarps	Clothing		
Jerry cans	Shoes		
Dish soap bottles	Lighters		
Expanded polystyrene (EPS) ^a	Tobacco products and packaging		

^a From 2012 only, thus not included in standing stock analyses.

distributions to be normalised by a log transformation. Total weight cleaned showed a marginally significant effect of time ($F_{1,228} = 3.89$, $p = .05$) (Fig. 3a), with an average annual decline of approximately 8%. There was no interaction between time and coast ($F_{1,228} = 0.07$, $p = .79$). However, there was a significant effect of coast ($F_{1,228} = 5.93$, $p = .02$), with there being, on average, 66% more litter cleaned by weight per 100 m of beach along the inner coast than the outer coast of the archipelago. Despite significant trends, variability was considerable ($R^2 = 0.04$). The model residuals were normally distributed (Shapiro-Wilk W test: $p = .42$). There was no effect of time for the number of "commercial" litter types ($F_{1,165} = 1.23$, $p = .27$), nor an effect of coast ($F_{1,165} = 0.85$, $p = .58$) or interaction between coast and time ($F_{1,165} = 0.03$, $p = .86$) (Fig. 3b). The model residuals were normally distributed (Shapiro-Wilk W test: $p = .86$). For "private" litter, there was a significant negative effect of time ($F_{1,164} = 4.48$, $p = .04$) (Fig. 3c) with an annual reduction in abundance of approximately 10%. There was no effect of coast ($F_{1,164} = 0.29$, $p = .59$) or interaction between it and time ($F_{1,164} = 0.00$, $p = .99$). Despite significant trends, variability was considerable ($R^2 = 0.03$). The model residuals were normally distributed (Shapiro-Wilk W test: $p = .42$).

Results were similar using non-parametric Mann-Kendall time series analyses combined with Sen-Theil slope estimations. There were evidence of declines in "private" and "household" litter types along both coasts, and in "commercial" litter along the inner coast alone (Table 5). On average, there was a reduction in the number of "commercial" litter items cleaned along the inner coasts of 4.2 items per 100 m from 2011 to 2018. Similarly, there was an average reduction in the number of "private" ("on the fly") litter items cleaned along the inner and outer coasts at the start and end of the time series of 6.1 and 5.0 items per 100 m, respectively. The average total reduction in "household" litter was more modest with 1.8 and 1.9 fewer items per 100 m along the inner and outer coasts, respectively. Of the most common litter types,

Table 3
List of cleanup actions, total item counts and per cent of registered litter types classified within each source category (all actions pooled) annually.

Year	Cleanup actions	Total items counted	Commercial (%)	Private ("on the fly") (%)	Household (%)	Other (%)
2011	31	17,477	57.1	27.2	14.9	0.7
2012	42	16,656	53.1	37.6	7.6	1.7
2013	30	12,036	47.7	44.3	6.2	1.9
2014	40	14,604	49.2	43.7	6.2	0.8
2015	52	21,922	54.5	36.9	7.5	1.2
2016	64	35,220	58.1	34.2	7.1	0.6
2017	80	34,173	49.5	42.2	7.3	1.0
2018	106	40,551	57.8	33.8	7.3	1.0
Total	445	192,630	54.3	36.8	7.9	1.0

Table 4
Annual Kruskal-Wallis rank-sum tests for the density (#/100m) of Norwegian and foreign bottles at locations on the inner (fjord) vs. the outer (open ocean) coast of Lofoten. Numbers given are sample means \pm SE with n (number cleanup actions) in parentheses. Significant differences between the inner and outer coasts are indicated in bold.

Year	Norwegian bottles		Foreign bottles	
	Inner coast	Outer coast	Inner coast	Outer coast
2016	10.4 \pm 4.6 (58) $p = 0.31$	16.2 \pm 7.7 (33)	7.1 \pm 4.8 (58) $p < 0.0001$	25.5 \pm 9.6 (33)
2017	4.8 \pm 1.5 (47) $p = 0.24$	9.0 \pm 3.1 (42)	3.5 \pm 1.9 (47) $p = 0.0004$	20.8 \pm 7.3 (42)
2018	5.4 \pm 1.6 (61) $p = 0.92$	2.5 \pm 0.5 (40)	1.9 \pm 0.6 (59) $p = 0.02$	4.4 \pm 1.3 (40)

Table 5
Results of non-parametric Mann-Kendall time series analyses combined with Sen-Theil slope estimations (month⁻¹) for temporal trends in the standing stock (or accumulated litter) on beaches cleaned for the first time 2011–2018. Significant trends are highlighted in bold. All densities are standardised per 100 m coast cleaned. See Table 1 for sample size (# cleanup actions for weight and count data along the inner and outer shores).

Metric	Inner (fjord) coast			Outer (open ocean) coast		
	Slope	Lower 95% CI	Upper 95% CI	Slope	Lower 95% CI	Upper 95% CI
Total weight (kg)	-0.003	-0.006	0.000	-0.017	-0.046	0.004
Commercial (#)	-0.050	-0.067	-0.031	-0.021	-0.055	0.011
Private (#)	-0.072	-0.092	-0.050	-0.059	-0.087	-0.038
Household (#)	-0.020	-0.025	-0.016	-0.023	-0.031	-0.014
Other (#)	0.000	0.000	0.000	-0.001	-0.002	0.000
Rope < 50 cm	-0.014	-0.019	-0.008	-0.010	-0.020	-0.002
Beverage bottles	0.000	-0.001	0.004	0.003	-0.004	0.010
Lids and caps	-0.003	-0.006	-0.001	-0.002	-0.010	0.000
Food packaging	-0.014	-0.019	-0.011	-0.020	-0.028	-0.013
Buoys and floats	0.000	0.000	0.000	0.006	0.004	0.009
Rope > 50 cm	0.000	-0.001	0.000	-0.014	-0.019	-0.007
Strapping bands	0.000	0.000	0.000	-0.006	-0.010	-0.003
Plastic bags	-0.014	-0.018	-0.011	-0.011	-0.014	-0.006

rope fragments shorter than half a meter, food packaging, and plastic bags showed significant declines along both coasts, and longer pieces of rope and strapping bands showed declines along the outer coast only (Table 5). The results also indicated a slight increase in the standing stock of buoys and other floats along the outer coast (Table 5).

3.4. Temporal trends in litter influx

As for standing stock, least-squares regressions were carried out on log-transformed density data of total weight and counts of "commercial" and "private" litter types per 100 m coast. There was no significant temporal trend in litter influx by total weight ($F_{1,60.1} = 2.98$, $p = .09$) (Fig. 4a), nor a difference in the mean influx between the inner and

Table 6

Results of non-parametric Mann-Kendall time series analyses combined with Sen-Theil slope estimations (month^{-1}) for temporal trends in the influx of different litter fractions to regularly cleaned beaches from 2011–2019. Significant trends are highlighted in bold. All densities are standardised per 100 m coast cleared. See Table 1 for sample size (# cleanup actions for weight and count data along the inner and outer shores).

Metric	Inner (fjord) coast			Outer (open ocean) coast		
	Slope	Lower 95% CI	Upper 95% CI	Slope	Lower 95% CI	Upper 95% CI
Total weight (kg)	-0.313	-0.611	-0.072	-0.833	-1.778	0.139
Commercial (#)	-0.225	-0.625	0.000	-0.388	-1.175	0.467
Private (#)	-0.148	-0.236	-0.001	-0.167	-0.422	0.348
Household (#)	-0.017	-0.056	-0.001	0.036	-0.081	0.128
Other (#)	-0.002	-0.008	0.000	-0.006	-0.016	0.003
Rope < 50 cm	-0.037	-0.278	0.016	0.159	-0.098	0.306
Beverage bottles	-0.033	-0.089	-0.013	-0.044	-0.199	0.017
EPS	-0.034	-0.153	-0.008	-0.040	-0.173	-0.004
Lids and caps	-0.056	-0.097	-0.010	-0.024	-0.092	0.193
Food packaging	-0.005	-0.042	0.003	0.033	-0.081	0.128
Buoys and floats	-0.013	-0.032	0.000	0.000	-0.033	0.007
Strapping bands	-0.063	-0.089	-0.002	-0.006	-0.169	0.017
Plastic bags	-0.016	-0.027	-0.003	0.012	-0.023	0.039

outer coasts ($F_{1,17.7} = 0.03$, $p = .87$) or an interaction between time and coast ($F_{1,60.1} = 0.69$, $p = .41$). The model residuals were normally distributed (Shapiro-Wilk W test: $p = .57$). Similarly, there was no temporal trend in influx of “commercial” litter types ($F_{1,60.4} = 2.03$, $p = .16$), nor a difference in the their mean influx between the inner and outer coasts ($F_{1,16.9} = 0.03$, $p = .87$) or an interaction between time and coast ($F_{1,60.4} = 1.50$, $p = .23$) (Fig. 4b). The model residuals were normally distributed (Shapiro-Wilk W test: $p = .53$). There was, however, a significant interaction of coast and time for “private” litter types ($F_{1,58.2} = 5.42$, $p = .02$). Consequently, we investigated temporal trends separately for the inner and outer coasts of the archipelago. There was a significant temporal trend in the influx of “private” litter over time along the inner coast of Lofoten ($F_{1,35.8} = 16.25$, $p = 0.0003$)

with an approximately 27% annual decline over time period. However, there was no evidence of a similar trend along the outer coast ($F_{1,22.3} < 0.01$, $p = 0.95$) (Fig. 4c). The model residuals of both models were normally distributed (Shapiro-Wilk W test: $p = 0.71$ and 0.16 for the inner and outer coasts, respectively).

The results of the Mann-Kendall time series analyses and Sen-Theil slope estimations showed similar results with significant declines in “private” litter types along the inner coast (Table 6) with an average total reduction of 12.4 items per 100 m from 2011 to 2018. However, these non-parametric analyses also showed a significant decline in total weight along the inner coast (Table 6), which amounted to an average total reduction of 26.3 kg per 100 m coast. Among the most common litter types, there were significant declines in plastic beverage bottles, EPS, lids and caps, strapping bands and plastic bags, all along the inner coast (Table 6). The only significant temporal trend along the outer coast was a decline in the influx of EPS (Table 6).

4. Discussion

4.1. Lofoten beach litter in decline

Volunteer cleanup data from the Lofoten archipelago in northern Norway show modest, but discernible declines in both influx (short-term accumulation) and standing stock (long-term accumulation) of litter on beaches over an 8–9-year period. The most pronounced decline has been in the “private” (“on the fly”) litter category, which covers litter types typically associated with the behaviour of individuals whilst outside the home (e.g., beachgoers, campers, fishermen). There are numerous sources of error in the citizen science data used to assess these trends, such as observer bias from various untrained persons, generally poor documentation of effort and cleanup location, estimation rather than counting, and a general lack of standardisation. These numerous sources of error, as well as generally high variability in litter loads among locations (Haarr et al., 2019b), are evident in the variability surrounding the observed trends. Nevertheless, the fact that relatively consistent negative temporal trends were discernible despite this provides compelling evidence that at least certain types of beach

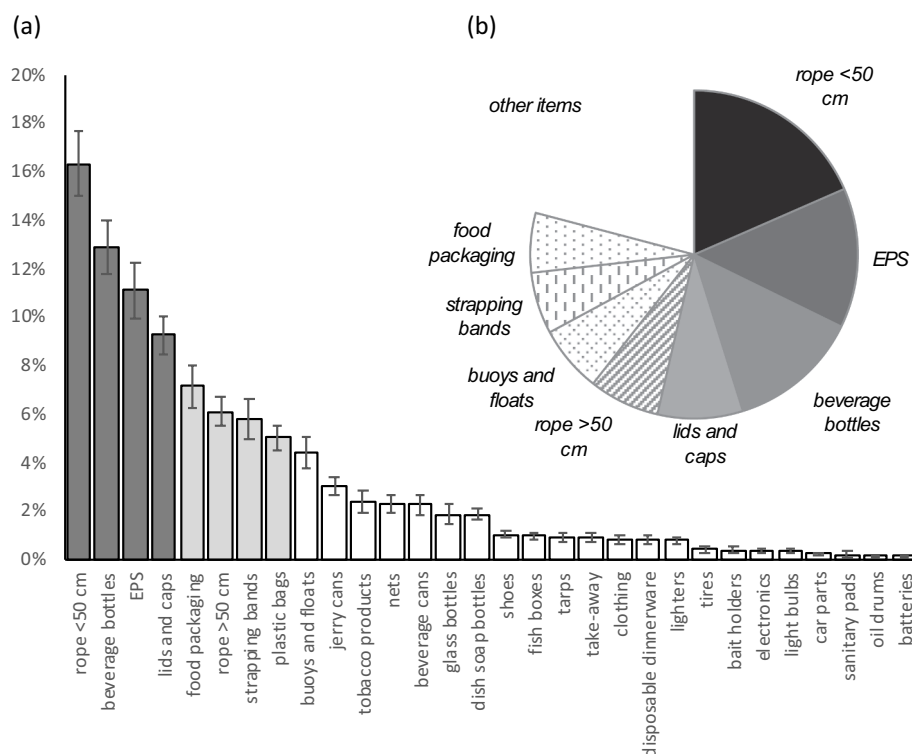


Fig. 2. Prevalence of different litter items. (a) The annual mean occurrence per cleanup action (i.e., the mean of the means). Error bars represent 95% confidence intervals. Litter types marked in dark grey constitute 50% of observations, on average. Combined with the litter types marked in light grey, these made up 75% of all registrations on average. (b) Proportions based on all litter types (all years and cleanup actions) pooled. Litter types shaded in solid colour make up just over half of all items. Combined with litter types with hatched shading these constituted 80% of all registered litter.

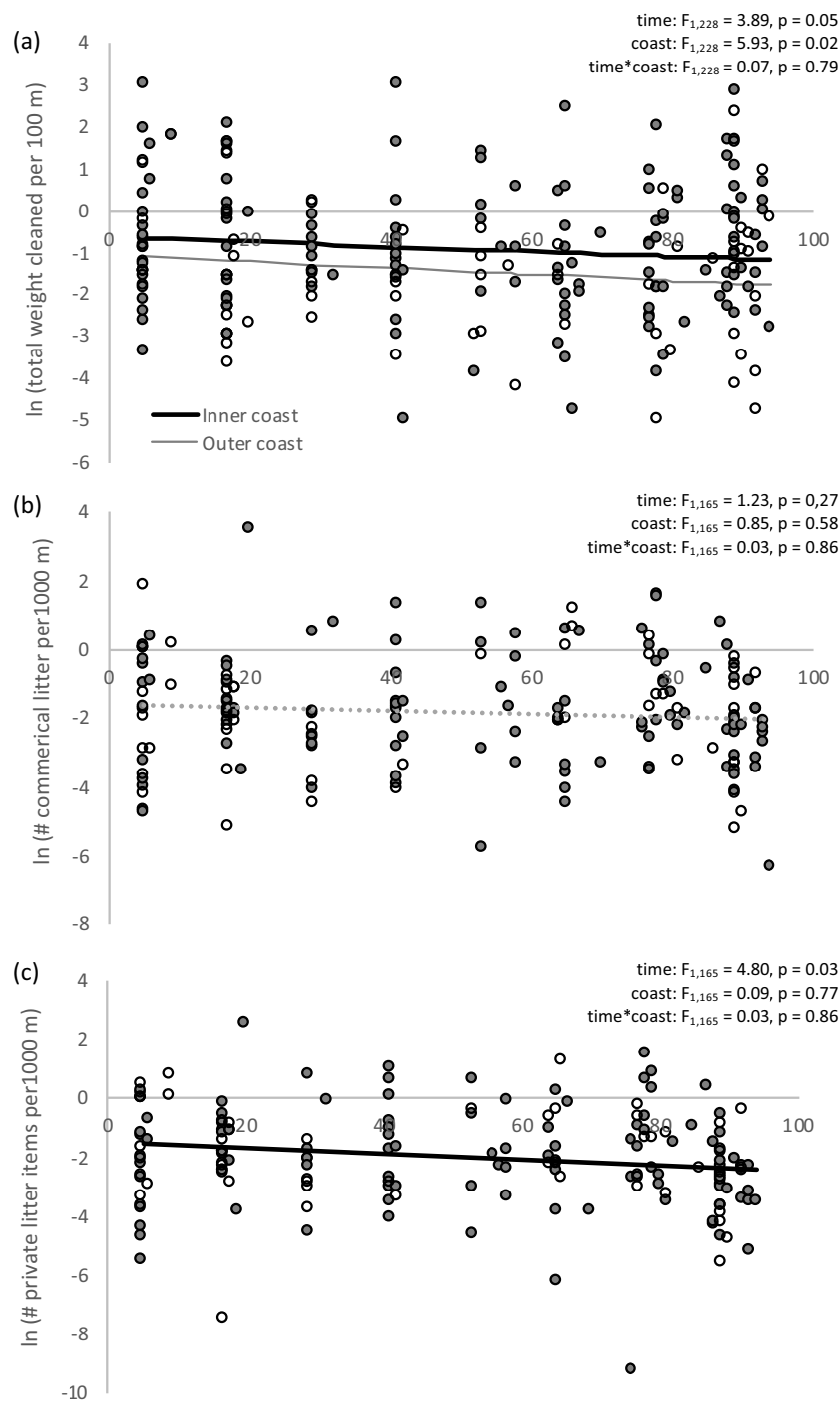


Fig. 3. Linear least squares regressions for litter standing stock (accumulated litter on beaches not previously cleaned) in (a) total weight, (b) abundance of “commercial” litter and (c) abundance of “private” or “on the fly” litter. See Table 2 for list of litter types in each category. Time is given in months from the start of time time period (1 = January 2011). Only solid trend lines are significant. Solid circles represents sites along the inner (fjord) coast of the archipelago, and open circles sites along the outer (open ocean) coast. Two lines of best fit are shown in a due to the significant difference between the inner and outer coast.

litter are in decline in Lofoten.

The amount of marine litter in a region, such as surrounding the Lofoten archipelago, can be thought of in terms of a local population with a birth or growth rate (the input of new litter to the region), natural mortality (export of litter out of the region by currents and wind, and degradation to microplastics), exploitation (removal of litter through cleanups), and dispersal and movement patterns (Fig. 5). Population size is dependent on both litter entering and exiting the system. The distribution of litter within the population is also highly

dynamic. Beached litter does not necessarily remain beached or in the same location on the shore, and total turnover of litter on a beach can occur in only a few months (Bowman et al., 1988; Johnson and Eiler, 1999; Ryan et al., 2014; Smith and Markic, 2013; Williams and Tudor, 2001). The rates of beaching, resuspension, burial and degradation are all factors affecting the accumulation of litter along the shore (Critchell and Lambrechts, 2016) (Fig. 5). The amount of litter removed the first time a beach is cleaned (standing stock) reflects the net sum of these processes over a long time period (i.e., decades). In contrast, the litter

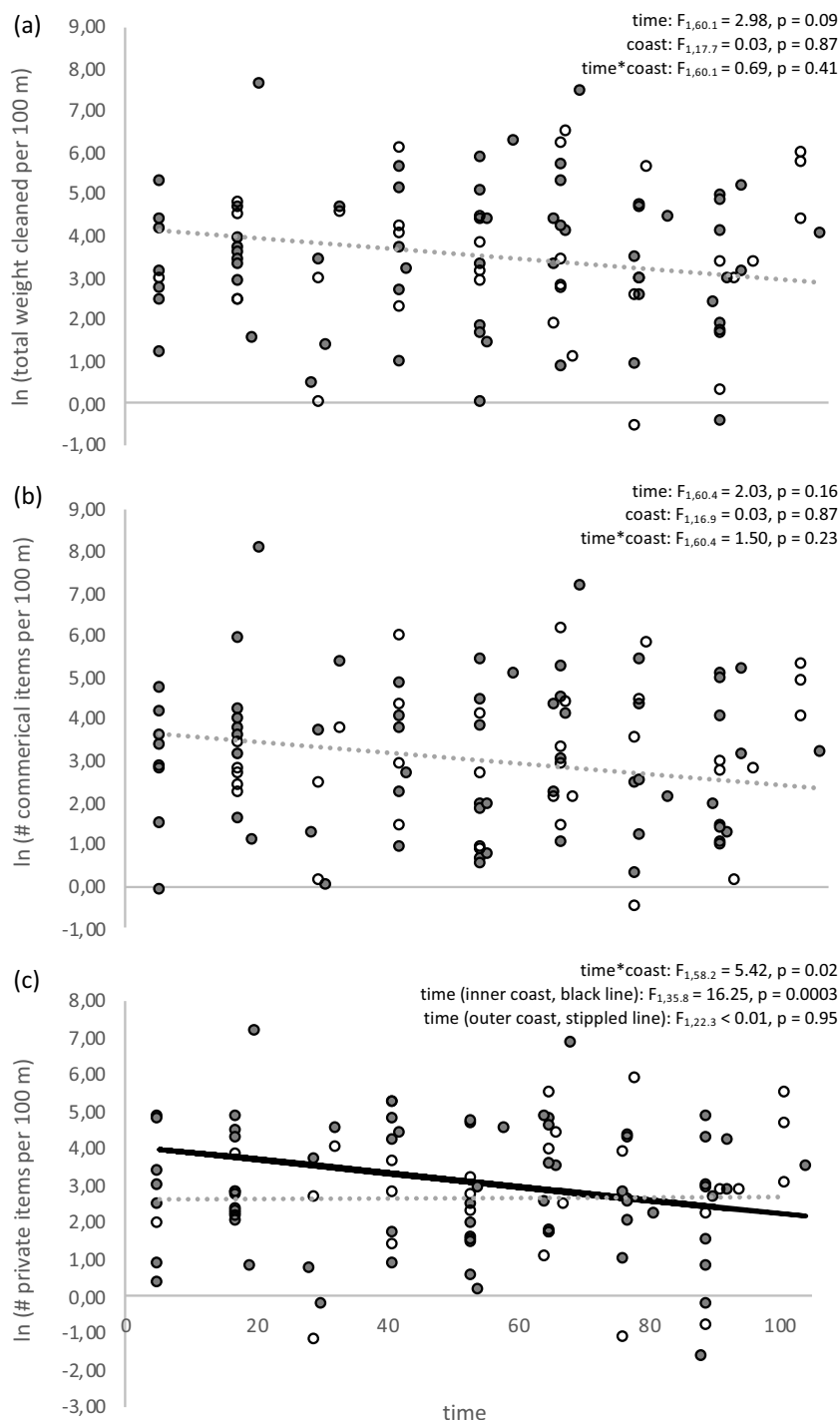


Fig. 4. Linear least squares regressions for litter influx in (a) total weight, (b) abundance of "commercial" litter and (c) abundance of "private" or "on the fly" litter to regularly cleaned beaches. See Table 2 for list of litter types in each category. Time is given in months from the start of time period (1 = January 2011). Only solid trend lines are significant. Solid circles represents sites along the inner (fjord) coast of the archipelago, and open circles sites along the outer (open ocean) coast. Site, while not shown in the graphs, was included as a random factor in each model. For a and b, a single line of best fit is shown due to the non-significant interaction terms and effect of coast. For c the line of best fit for the inner (solid line) and outer coast (dotted line) are shown separately given the significant interaction term in the full model.

removed from a beach during subsequent repeat cleanups (influx) reflects the net sum of these processes only over the short time period since the previous cleanup (*i.e.*, months/years). Both are subject to changes in the rates of beaching, resuspension, burial, exhumation, and movement of litter on the shore. However, as influx depends on the sum of these processes over a much shorter time period than standing stock, smaller changes should be detectable in the former compared to the latter. This assumption is consistent with our observation that declines in influx have been greater than those in standing stock. As declines were also observed in standing stock, however, this suggests substantial changes to beach litter dynamics in the area. There are multiple potential causes of these changes.

If growth (new litter input) and mortality (advection and cleanups)

in the population equal zero, one would expect a decline in beach litter over time simply due to the loss of macrolitter through degradation (*i.e.*, fragmentation to secondary microplastics). It is clear that weathering, especially whilst beached and exposed to sunlight, results in embrittlement of plastics, making them vulnerable to total fragmentation in the face of abrasion on the substrate caused by wave or wind action (Andrady, 2011). However, it is less clear how long this process takes on average, and whether it is likely to result in significant changes to local macroplastic supply in the time scale of this study. Evidence suggests it is extremely slow for floating and settled plastics in the water, although it does occur considerably faster when plastic is beached (Andrady, 2015, 2011). Some of the observed reductions in individual litter types, such as in food packaging and plastic bags but not

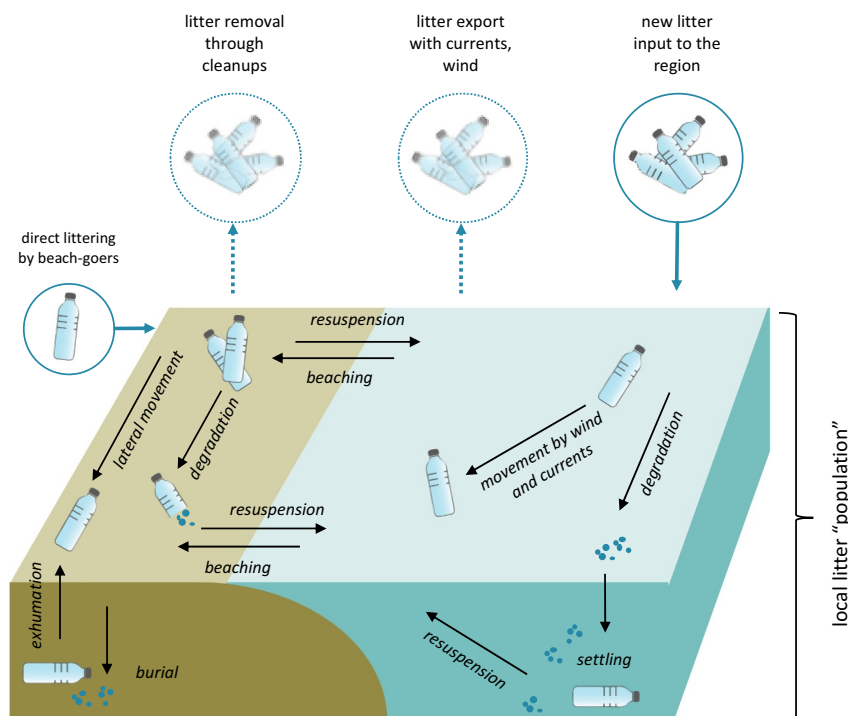


Fig. 5. Schematic of processes affecting litter on the beach and in a region. Modified from Critchell and Lambrechts (2016), with additions. Bottles represent *meso* and *macrolitter* (> 5 mm), and particles *microlitter* (< 5 mm).

in buoys and floats, could be partially the result of more rapid degradation of older pieces of thin plastic packaging material compared to the much more substantial plastic of e.g. trawl bobbins. Weathering and degradation have been attributed as the likely cause of an increase in unidentifiable plastic fragments documented by citizen scientists over a decade in the UK (Nelms et al., 2017). Given unidentifiable fragments were generally not registered under the LAS protocol, however, it was not possible to test for a similar correlation in Lofoten. In a no growth, no mortality scenario, a decline in accumulating beach litter may also occur due to a loss of litter in circulation as a result of continued settlement onto the seafloor with biofouling (Andrady, 2015). Such items may be resuspended if the biofouling organisms are removed through predation, meaning this loss is not necessarily permanent (Andrady, 2015), but again relatively little is known about the expected time frame of these processes and their likely relevance to the 8–9-year trends documented in Lofoten. A “no mortality” scenario is obviously not the case in Lofoten, and it is also extremely unlikely that there are no sources of new incoming litter to the region, yet it is nevertheless important to recognise that the above processes may contribute to (or confound) changes in dynamics and net accumulation of macro beach litter.

Changes in total population size (i.e., the total amount of litter circulating in a region) will almost certainly influence the net accumulation of beach litter. Even if the rate of each process (beaching, resuspension, burial, exhumation, lateral transport on shore, and degradation) stays constant, and a fixed proportion of the total population is expected to be beached at any time, an increase or decrease in population size would presumably result in a proportional change in the net accumulation of beach litter. Given the relatively consistent, and at times large declines observed in Lofoten it is highly likely that these reflect a similar change in the overall amount of litter in circulation in the region. Changes to total population size can occur by two mechanisms: changes to either the removal from, or the input into, the system.

Removal of litter from the population can happen either through advection by currents and wind, or through cleanup actions. For

temporal trends in net litter accumulation to result from changes to advection rates, this would imply corresponding changes to local current and/or weather patterns. While clearly not impossible, it is more likely that a significant removal effect result from the extensive local cleanup efforts in the region, which occur much more densely than the national average (Hartviksen and Gressetvold, 2018; Zimmermann et al., 2018). Coarse estimations of the total amount of litter present on Lofoten shores in 2018 (based on stratified random transect sampling) (Haarr et al., 2019a) suggest net accumulated litter at the time to within a range of 600–2300 tons along the region's coast. Volunteer cleanup actions in the same year removed approximately 41 tons of litter (Hartviksen and Gressetvold, 2018), which equates to 2%–7% of the total estimate. This removal rate is sizable, but still somewhat smaller than the observed annual per cent declines in accumulated litter. Assuming an approximately proportional relationship between changes to removal rates and changes in net accumulation in beach litter, the amount of litter removed, while considerable, is probably not sufficient to alone account for the observed declines.

Changes to the population “growth rate”, or the annual input of new litter into the region, is likely to affect net litter accumulation in a similar, but inverse, manner to litter removal. The observation that beach litter declines in Lofoten are more evident for some litter types than others, strongly suggests a reduction in the input of these. Specifically, the especially evident declines of litter in the “private” (“on the fly”) category suggests that there has been a considerable decrease in new input of this type of litter to the Lofoten region. If the decline was due solely to removal of litter through cleanups one would expect the declines to be uniform across all types of litter. There is no reason to believe that cleanups would be selective, and especially not towards this category of litter, which while common is not the most common. It is furthermore likely that the reduction in “private” litter generally reflects a local reduction in littering. The much greater presence of foreign beverage bottles along the outer, open ocean coast of Lofoten supports the hypothesis that due to its greater exposure to the Norwegian Atlantic Current (NAC), an extension of the Gulf Stream, it is more exposed to long-transported litter than the inner coast, which is

primarily exposed to the Norwegian Coastal Current (NCC) (Falk-Andersson et al., 2019; Mitchelson-Jacob and Sundby, 2001; Skagseth et al., 2008). The relatively equal presence of Norwegian bottles along both coasts, however, indicate that both are exposed to similar levels of local, or at least Norwegian, plastic pollution. The decline in the accumulation of “private” litter, which includes beverage bottles, was particularly evident along the inner coast, which appears dominated by Norwegian litter. The additional, and greater, presence of foreign “private” litter along the outer coast may be sufficient to mask temporal trends in local litter input there. The presence of eddies and a certain level of retention of water masses within the West Fjord (Mitchelson-Jacob and Sundby, 2001), may also make a signal easier to detect along the inner coast as the “population” of litter may be more closed than along the outer coast.

In summary, the current study provides compelling evidence that beach litter is in moderate decline in the Lofoten archipelago in the Norwegian Sea. This decline is most likely due to a combination of a reduction in local “private” or “on the fly” littering, as well as volunteer cleanup efforts. The fact that some level of decline was observed in the long-term (decades) net accumulation of beach litter, and not only in short-term (months/years) net accumulation, suggests that the changes have either been going on for some time or have been quite large. It is possible that the temporal decline in long-term accumulation could have been caused by selective cleaning of the most affected beaches of the region in the early years. We believe this is unlikely to be the sole cause of the declines in standing stock, however, given that the per cent of the coastline cleaned annually is considerably lower than the proportion of the coastline believed to be significantly polluted based on randomised sampling (Haarr et al., 2019b).

4.2. Common litter types and composition

Half of all the litter items registered in Lofoten over the 7-year period 2012–2018 could be accounted for by only four items: rope fragments shorter than half a meter in length, plastic beverage bottles, EPS pieces, and various lids and caps. Combined with food packaging, rope pieces longer than half a meter, strapping bands, buoys and other floats, and plastic bags, these items accounted for 75%–80% of all litter registered. The remaining 22 items included on the registration form accounted for only a small proportion of observations. Unidentifiable plastic fragments were not consistently counted in Lofoten. Had they been, they would almost certainly have been one of the most common litter types registered, as evidenced elsewhere, including along the Norwegian coast in general (Falk-Andersson et al., 2019; Nelms et al., 2017; Watts et al., 2017). A large proportion of litter types being unidentifiable or unattributable to source is a common challenge in beach litter registrations due to weathering and degradation of litter (Watts et al., 2017).

There are both differences and similarities in the most common litter types registered in Lofoten and those elsewhere in the North-East Atlantic. However, direct comparisons of the prevalence of different litter types are challenging due to differing registration methods and variable levels of reporting (Browne et al., 2015). It is clear that “private” (“on the fly”) related litter types, such as beverage bottles and cans, lids and caps, and plastic bags, as well as various household related litter types, such as food packaging, are common also in the North Sea and elsewhere in Europe (Nelms et al., 2017; Watts et al., 2017; Williams et al., 2014). However, sewage related litter and a number of “on the fly” litter types, such as chips packets and sweet wrappers, are quite common in the North Sea and elsewhere in Europe (Nelms et al., 2017; Schulz et al., 2015; Storrer et al., 2007; Watts et al., 2017; Williams et al., 2014), but account for hardly any of the litter registered in Lofoten. These discrepancies suggest that while pollution through sewage and direct littering by beachgoers are undoubtedly also sources of marine litter Lofoten, these are likely less important sources than further south in Europe. This interpretation is consistent with the low

population density in the area, and similar patterns have been observed in remote areas of Scotland where population density is also low (Nelms et al., 2017). There is also evidence to suggest that litter types related to commercial activities are more common in Lofoten than further south in Europe, due to low population density coupled with intense fishing activity (Falk-Andersson et al., 2019). While ropes and EPS also constitute common litter types across the North Sea and European waters in general, the number of common litter types tied to commercial activities is typically somewhat less than seen in our study (Nelms et al., 2017; Schulz et al., 2017; Watts et al., 2017; Williams et al., 2014).

The attribution of different litter types to source categories can be challenging and sometimes involves considerable uncertainty. In our dataset, LAS (the Lofoten Waste Management Company, which organises cleanups and data collection) has made different attributions based partially on local knowledge and expertise. Given different potential sources of the same litter types, using local and source-specific expertise can be a useful method by which to attribute litter types to different sources (Falk-Andersson and Strietman, 2019). Nevertheless, a large degree of uncertainty remains regarding source attribution of several litter types. Lids and caps, for example, have been attributed to direct littering by beachgoers in some studies and as unknown in others due to numerous possible origins and uses (Falk-Andersson et al., 2019; Nelms et al., 2017; Watts et al., 2017). Polystyrene can also stem from a variety of sources and it may not be accurate to attribute it in its entirety to commercial activities (Schulz et al., 2013). The litter types categorised by LAS as being “private” in origin, also referred to as “on the fly”, match well with litter types attributed to recreational activities or public littering in other studies (Nelms et al., 2017; Storrer et al., 2007). Dish soap bottles are a classic household item, yet LAS has identified these as primarily originating from fisheries as dialogue with local fishermen revealed that these are frequently used onboard vessels to clean up minor oil spills (Falk-Andersson et al., 2019). Presumably it is more likely that dish soap bottles are lost from vessels directly into the ocean, than that they indirectly make their way there through managed household waste streams. However, by this logic a number of “private” (“on the fly”) and “household” litter types should also be reclassified as stemming from fishing (“commercial”) activities. Beverage bottles, food packaging, tobacco products, etc., are also used on board vessels and will likely have a higher probability of entering the ocean directly from a vessel than indirectly through loss whilst on land (unless directly deposited on the shore by beach-goers), making it highly likely that a considerable proportion of these litter types in reality stems from fishing activities. This interpretation is consistent with another recent study concluding that a significant proportion of plastic bottles stem from vessel traffic (Ryan et al., 2019).

4.3. Recommendations for continued citizen science

Challenges utilising citizen science data include the at times low data quality and generally limited documentation of cleanup locations. This limits the types of analyses that can be applied to the data and subsequently the hypotheses which can be tested. It is also a source of considerable error, reducing statistical power and making small changes near impossible to detect (Nelms et al., 2017). Even on strictly delineated beaches cleaned at regular intervals by professionals, power analyses show that as many as 12 surveys (three years with four annual surveys) are necessary to detect a change of 40–50% in total litter influx to a particular location (Schulz et al., 2019). Detecting trends for individual litter types is even more challenging, requiring as many as 16–20 surveys (4–5 years with four annual surveys) per location to detect a 30% change (Schulz et al., 2019). Studies have also shown that power is greatly reduced when data are merged from multiple locations due to considerable small-scale spatial variation (Schulz et al., 2019, 2017, 2013). Voluntary cleanup actions rarely occur repeatedly in precisely the same location, particularly not with greater than annual temporal resolution, necessitating the consideration of multiple sites

simultaneously if seeking to utilise these data. Although this is partially augmented by the generally much greater number of locations with data than during professional monitoring.

One key source of error in the LAS dataset, as in many datasets collected by citizen scientists, is uncertain density estimates given imprecise estimations of the length of coastline cleaned (Nelms et al., 2017). An erroneous recording of 400 m as 500 m, for example, will cause the resulting density estimate to be 20% lower than reality. Correctly localising cleanup locations was also challenging as locations were represented by a single point only, regardless of the length of the stretch of coast cleaned. Particularly when this point was frequently estimated at a later date by cleanup coordinators. This poses a challenge for time series analyses as it can be difficult to determine which sites have been cleaned previously and which have not, as well as for spatial analyses to assess geographical trends and their drivers except over very large scales (Falk-Andersson et al., 2019). However, these limitations can be mitigated in large part through improved documentation by volunteers, such as through a map tool where one draws up the location cleaned whilst still on site (coastline length at a minimum, but possibly also area). Others working with volunteer cleanup data have also suggested standardising the size of area cleaned during each action (Nelms et al., 2017), although it can be difficult to enforce this and to impress its importance upon volunteers. However, such standardisation would be particularly useful for locations cleaned repeatedly. Stricter requirements for recording date and duration of cleanup actions would also reduce error in temporal analyses and better enable analyses of litter deposition patterns related to for example wind events. If some of this error can be reduced, it may drastically improve the potential applications of citizen science data.

If a request for increased documentation during cleanup actions are perceived as discouragingly onerous by volunteers, one may consider simplifying the litter registration requirements somewhat. As eight litter types accounted for 75–80% of registered litter, it would be possible to maintain most of the resolution in the dataset with a more limited protocol. Total weight measures would still serve as an indicator of the trends in total amounts of litter, while easily recognizable objects from presumably different sources could serve as indicators of trends in pollution from said sources without the need to register a large number of different objects. It is also challenging to assess trends in relatively uncommon litter types due to high frequency of zero counts, which hinders analyses (Schulz et al., 2013). Extensive litter registration protocols asking volunteers to identify and source less common and less recognizable litter types also pose a considerable potential error source as volunteers may be unsure of identification. Other areas outside of the Lofoten archipelago will presumably also have similar “worst offenders”, which may form the basis of a simplified registration protocol. However, these would first need to be identified through more extensive registrations.

A key strength of the LAS dataset is that it includes total weight cleaned, which has been noted as a weakness of citizen science data by others (Nelms et al., 2017). However, it is not possible to investigate the relative importance of different source categories (or litter types) based on count *versus* weight data as different types of litter is not weighed, not are all litter types counted. Doing so would be add considerable workload for the volunteers collecting the data as it would involve counting all litter items and/or bringing a scale to the shore and weighing litter categories during registrations (as opposed to simply weighing in during delivery to the waste management facility). Doing so, however, would likely yield different conclusions regarding the key litter types and sources upon which to focus mitigative and preventative measures (Falk-Andersson and Strietman, 2019; Haarr et al., 2019a), thus providing better nuanced information for management.

4.4. Implications for management

Analyses of citizen science data as done in this study can provide

valuable information for management. Extensive monitoring programs are highly expensive, particularly if attempting to achieve sufficient replication to be representative for a region. Consequently, monitoring programs, such as OPSAR in the North-East Atlantic, frequently have too few locations per region to be considered representative, often necessitating analyses and interpretations at the beach level unless the coastline in question is highly homogeneous in nature (Falk-Andersson et al., 2019; Schulz et al., 2019). While such professional monitoring programs obviously provide data of higher quality, the sheer volume of data provided through volunteer beach cleanup data can be a valuable addition. This study has shown that citizen science data can be used to assess whether there are temporal trends in regional litter dynamics, despite the errors and limitations associated with this type of data. It has also shown that such analyses can be used to inform managerial decisions on preventative and mitigative measures. The observation that “private” litter has declined in Lofoten, and likely as a result of reduced (relatively) local inputs, suggests that the considerable efforts to raise awareness in the region has had a positive effect. This positive effect likely reflects reduced littering of “on the fly” items both by beachgoers and by fishermen. Similarly, the less evident declines in “commercial” litter indicates that further efforts to reduce the input of litter originating directly from commercial activities (primarily fishing) will likely be an effective measure to further reduce marine litter in the region. Particularly as litter in the “commercial” category was the most prevalent. It is worth noting that a general reduction in the influx of fisheries related litter to beaches has been documented in the North Sea and more southern parts of the North-East Atlantic (Schulz et al., 2015). As this was less evident in Lofoten, there is still potential for fisheries in the region (and upstream) to reduce their contributions to marine litter. Analyses of citizen science data can also be used to indicate which litter types may be most suitable for monitoring in different regions (Nelms et al., 2017; Storrier et al., 2007).

Another important implication of this study is that perhaps tonnage cleaned should not be the key metric used to identify success of cleanup actions or programs; the length of coastline cleaned may serve as a better metric. There is considerable funding for beach cleanups in Norway through for example the Norwegian Environment Agency and the Norwegian Retailer's Environment Fund. Generally, these require tonnage to be reported, and also often asks for predicted tonnage to be estimated during the proposal phase in order to fund the presumably most successful cleanup actions and programs. However, if highly effective cleanup programs succeed in removing sufficient litter from a region to reduce the local litter “population” and thus also the new accumulation of litter on beaches, these programs would over time be deemed inefficient (or less efficient) as a function of their success. Similar effects would be anticipated in regions where new litter input is decreasing, perhaps due to improved personal habits brought about through attitude changes resulting from the participation in cleanup actions (Wyles et al., 2017). Punishing the most effective interventions is clearly an undesirable consequence of measuring success primarily in tonnage cleaned.

CRediT authorship contribution statement

Marthe Larsen Haarr: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Michael Pantalos:** Methodology, Formal analysis, Writing - review & editing. **Monica Kleffeldgård Hartviksen:** Conceptualization, Data curation, Writing - review & editing, Funding acquisition. **Marit Gressetvold:** Conceptualization, Data curation, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We extend our sincere thanks to the Norwegian Retailers Environment Fund for providing the funding to carry out these analyses, as well as the numerous volunteers who have collected data through the years.

References

- Andrady, A.L., 2011. Microplastics in the marine environment. *Mar. Pollut. Bull.* 62, 1596–1605. <https://doi.org/10.1016/j.marpolbul.2011.05.030>.
- Andrady, A.L., 2015. Persistence of plastic litter in the oceans. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), *Marine Anthropogenic Litter*. Springer International Publishing, Cham, pp. 57–72. https://doi.org/10.1007/978-3-319-16510-3_3.
- Bowman, D., Manor-Samsonov, N., Golik, A., 1988. Dynamics of litter pollution on Israeli Mediterranean beaches: a budgetary, litter flux approach. *J. Coast. Res.* 14, 418–432.
- Browne, M.A., Chapman, M.G., Thompson, R.C., Amaral Zettler, L.A., Jambeck, J., Mallos, N.J., 2015. Spatial and temporal patterns of stranded intertidal marine debris: is there a picture of global change? *Environ. Sci. Technol.* 49, 7082–7094. <https://doi.org/10.1021/es5060572>.
- Critchell, K., Lambrechts, J., 2016. Modelling accumulation of marine plastics in the coastal zone: what are the dominant physical processes? *Estuar. Coast. Shelf Sci.* 171, 111–122. <https://doi.org/10.1016/j.ecss.2016.01.036>.
- Deshpande, P.C., Philis, G., Brattebø, H., Fet, A.M., 2020. Using material flow analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway. *Resources, Conservation & Recycling*: X 5, 100024. <https://doi.org/10.1016/j.rcrx.2019.100024>.
- Falk-Andersson, J., Strietman, W.J., 2019. Svalbard Beach Litter Deep Dive (SALT Report No. 1033), SALT Report. SALT Lofoten AS.
- Falk-Andersson, J., Berkhout, B.W., Abate, T.G., 2019. Citizen science for better management: lessons learned from three Norwegian beach litter data sets. *Mar. Pollut. Bull.* 138, 364–375. <https://doi.org/10.1016/j.marpolbul.2018.11.021>.
- Galgani, F., Fleet, D., Van Franeker, J.A., Katsanevakis, S., Maes, T., Mouat, J., Oosterbaan, L., Poitou, I., Hanke, G., Thompson, R., Amato, E., Birkun, A., Janssen, C., 2010. Marine Strategy Framework Directive: Task Group 10 Report Marine Litter (No. 58104), JRC Scientific and Technical Reports.
- Galgani, F., Hanke, G., Maes, T., 2015. Global distribution, composition and abundance of marine litter. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), *Marine Anthropogenic Litter*. Springer International Publishing, Cham, pp. 29–56. https://doi.org/10.1007/978-3-319-16510-3_2.
- Haarr, M.L., Falk-Andersson, J., Johnsen, H.R., Bay-Larsen, I., 2019a. Marin plastforsøpling fra fiskeflåten (No. 1039), SALT Report. SALT Lofoten AS.
- Haarr, M.L., Westerveld, L., Fabres, J., Iversen, K.R., Busch, K.E.T., 2019b. A novel GIS-based tool for predicting coastal litter accumulation and optimising coastal cleanup actions. *Mar. Pollut. Bull.* 139, 117–126. <https://doi.org/10.1016/j.marpolbul.2018.12.025>.
- Halsband, C., Herzke, D., 2019. Plastic litter in the European Arctic: what do we know? *Emerging Contaminants* 5, 308–318. <https://doi.org/10.1016/j.emcon.2019.11.001>.
- Hartviksen, M.K., Gressetvold, M., 2018. Sluttrapport 2018: Strand og kystrydding av marint avfall i Lofoten (Annual Report). Lofoten Waste Management Company.
- Hidalgo-Ruz, V., Thiel, M., 2015. The contribution of citizen scientists to the monitoring of marine litter. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), *Marine Anthropogenic Litter*. Springer International Publishing, Cham, pp. 429–447. https://doi.org/10.1007/978-3-319-16510-3_16.
- Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. *Science* 347, 768–771. <https://doi.org/10.1126/science.1260352>.
- Johnson, S.W., Eiler, J.H., 1999. Fate of radio-tagged trawl web on an Alaskan beach. *Mar. Pollut. Bull.* 38, 136–141.
- Kühn, S., Bravo Rebolledo, E.L., van Franeker, J.A., 2015. Deleterious effects of litter on marine life. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), *Marine Anthropogenic Litter*. Springer International Publishing, Cham, pp. 75–116. https://doi.org/10.1007/978-3-319-16510-3_4.
- Macfayden, G., Huntington, T., Cappell, R., 2009. Abandoned, lost or otherwise discarded fishing gear. In: (No. 185), *UNEP Regional Seas Reports and Studies*.
- Mitchelson-Jacob, G., Sundby, S., 2001. Eddies of Vestfjorden, Norway. *Cont. Shelf Res.* 21, 1901–1918. [https://doi.org/10.1016/S0278-4343\(01\)00030-9](https://doi.org/10.1016/S0278-4343(01)00030-9).
- Nelms, S., Coombes, C., Foster, L., Galloway, T., Godley, B., Lindeque, P., Witt, M., 2017. Marine anthropogenic litter on British beaches: a 10-year nationwide assessment using citizen science data. *Sci. Total Environ.* 579, 1399–1409. <https://doi.org/10.1016/j.scitotenv.2016.11.137>.
- Newman, S., Watkins, E., Farmer, A., Brink, P., ten, Schweitzer, J.-P., 2015. The economics of marine litter. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), *Marine Anthropogenic Litter*. Springer International Publishing, Cham, pp. 367–394. https://doi.org/10.1007/978-3-319-16510-3_14.
- OSPAR Commission, 2014. *Marine Litter Regional Action Plan*.
- Ryan, P.G., Lamprecht, A., Swanepoel, D., Moloney, C.L., 2014. The effect of fine-scale sampling frequency on estimates of beach litter accumulation. *Mar. Pollut. Bull.* 88, 249–254. <https://doi.org/10.1016/j.marpolbul.2014.08.036>.
- Ryan, P.G., Dilley, B.J., Ronconi, R.A., Connan, M., 2019. Rapid increase in Asian bottles in the South Atlantic Ocean indicates major debris inputs from ships. *Proc. Natl. Acad. Sci. U. S. A.* 116, 20892–20897. <https://doi.org/10.1073/pnas.1909816116>.
- Schulz, M., Neumann, D., Fleet, D.M., Matthies, M., 2013. A multi-criteria evaluation system for marine litter pollution based on statistical analyses of OSPAR beach litter monitoring time series. *Mar. Environ. Res.* 92, 61–70. <https://doi.org/10.1016/j.marenvres.2013.08.013>.
- Schulz, M., Clemens, T., Förster, H., Harder, T., Fleet, D., Gaus, S., Grave, C., Flegel, I., Schrey, E., Hartwig, E., 2015. Statistical analyses of the results of 25 years of beach litter surveys on the south-eastern North Sea coast. *Mar. Environ. Res.* 109, 21–27. <https://doi.org/10.1016/j.marenvres.2015.04.007>.
- Schulz, M., van Loon, W., Fleet, D.M., Baggelaar, P., van der Meulen, E., 2017. OSPAR standard method and software for statistical analysis of beach litter data. *Mar. Pollut. Bull.* 122, 166–175. <https://doi.org/10.1016/j.marpolbul.2017.06.045>.
- Schulz, M., Walvoort, D.J.J., Barry, J., Fleet, D.M., van Loon, W.M.G.M., 2019. Baseline and power analyses for the assessment of beach litter reductions in the European OSPAR region. *Environ. Pollut.* 248, 555–564. <https://doi.org/10.1016/j.envpol.2019.02.030>.
- Skagseth, Ø., Furevik, T., Ingvaldsen, R., Loeng, H., Mork, K.A., Orvik, K.A., Ozhigin, V., 2008. Volume and heat transports to the Arctic Ocean via the Norwegian and Barents seas. In: Dickson, R.R., Meincke, J., Rhines, P. (Eds.), *Arctic-Subarctic Ocean Fluxes*. Springer Netherlands, Dordrecht, pp. 45–64. https://doi.org/10.1007/978-1-4020-6774-7_3.
- Smith, S.D.A., Markic, A., 2013. Estimates of marine debris accumulation on beaches are strongly affected by the temporal scale of sampling. *PLoS One* 8, e83694.
- Storrier, K.L., McGlashan, D.J., Bonellie, S., Veler, K., 2007. Beach litter deposition at a selection of beaches in the Firth of Forth, Scotland. *J. Coast. Res.* 234, 813–822. <https://doi.org/10.2112/04-0251.1>.
- Watts, A.J.R., Porter, A., Hembrow, N., Sharpe, J., Galloway, T.S., Lewis, C., 2017. Through the sands of time: beach litter trends from nine cleaned north cornish beaches. *Environ. Pollut.* 228, 416–424. <https://doi.org/10.1016/j.envpol.2017.05.016>.
- Wilcox, R.R., 2010. *Fundamentals of Modern Statistical Methods*. Springer New York, New York, NY. <https://doi.org/10.1007/978-1-4419-5525-8>.
- Williams, A.T., Tudor, D.T., 2001. Litter burial and exhumation: spatial and temporal distribution on a cobble pocket beach. *Mar. Pollut. Bull.* 42, 1031–1039.
- Williams, A.T., Randerson, P., Alharbi, O.A., 2014. From a millennium base line to 2012: beach litter changes in Wales. *Mar. Pollut. Bull.* 84, 17–26. <https://doi.org/10.1016/j.marpolbul.2014.05.017>.
- Wyles, K.J., Pahl, S., Holland, M., Thompson, R.C., 2017. Can beach cleans do more than clean-up litter? Comparing beach cleans to other coastal activities. *Environ. Behav.* 49, 509–535. <https://doi.org/10.1177/0013916516649412>.
- Zimmermann, I., Pindsle, F., Gulbrandsen, L.K., 2018. Strandrydderapporten 2018 (Annual Report). Keep Norway Beautiful.

