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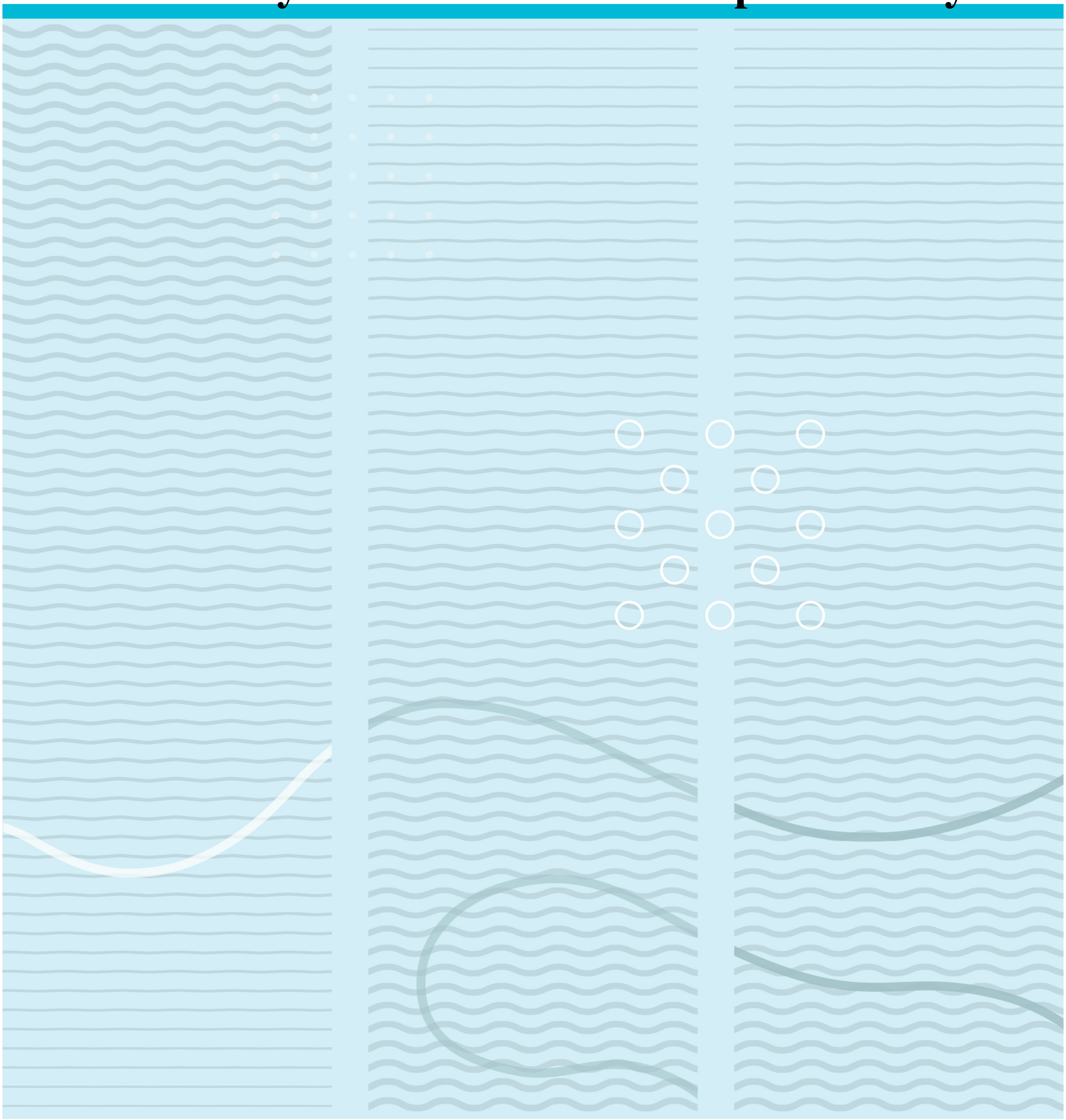
Vilde Sørnes Solbakken

Beach litter dynamics: A Mark-Recapture Study



A project in collaboration with SALT Lofoten AS

University of South-Eastern Norway
Faculty of Faculty of Technology, Natural Sciences and Maritime Sciences
Department of Natural Sciences and Environmental Health
PO Box 235
NO-3603 Kongsberg, Norway

http://www.usn.no

This thesis is worth 60 study points

ABSTRACT

A considerable portion of marine litter pollutes the world's coastlines. Its accumulation on beaches represents the product of deposition and retention, processes which are not well understood. A mark-recapture study of beach litter was performed with a two-week sampling interval at three sites in Lofoten, Norway. Deposition and retention vary over small spatial scales (approx. 13 km radius). No correlation was found among sites in the timing of high and low deposition events, suggesting these are governed by local factors. Contrastingly, a correlation was found among sites in the timing of high and low retention events, suggesting these are affected by regional factors. The results underline the importance of customising cleanup frequency for different beaches as spatiotemporal variation in the relative importance of deposition and retention dictate the optimal frequency for maximal removal of litter from circulation in the local marine environment, which cannot be discerned from accumulation (i.e., standing stock) alone.

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PREFACE

This master thesis concludes my Master in Environmental Science (MSc) at USN. The project "Beach litter dynamics: A Mark-Recapture study" was conducted in collaboration with SALT Lofoten AS, from May 2020 to May 2021. The field work was conducted from May until end of December 2020.

A great curiosity for the marine and coastal environment was my main motivation for studying Environmental Science at USN. With marine pollution as the main subject of interest, I was lucky enough to get in touch with SALT Lofoten AS, who luckily needed a curious master student on their team. I can now look back at the most intense year so far in my life, yet one of the best – I am so grateful, for the opportunity, all the experiences out in the field (there is no such thing as bad weather) and within the company, for countless of hours counting litter, for the steep learning curve it provided me, and for the people I got to meet.

Vilma, thank you for helping me open the door to the great field of marine pollution in the first place. Kjersti, thank you for accepting me for this project and welcoming me to "sail" with SALT. Thank you, every single one of you in SALT Lofoten AS for having me, discussing with me, laughing with me and for supporting me through the whole year. Benedikte, thank you for always being a sunshine in sun and rain through countless of hours cleaning the same three beaches over and over. Ane, Emil, Guri, Liz, Malin, Michael, Carl, Brita, Niclas, Kjersti, thank you all for being my field assistants. Gry, thank you for being my rock through the whole year. Emil, thank you for your help and support towards and over the finish line. And thank you to the rest of my family and friends, that accepted me moving somewhere far away from home. Again.
Synne, thank you for your support and your supervision through the whole process.
Marthe, to keep it short – this would not have been possible without you.

Svolvær, 17.05.21
Vilde Sørnes Solbakken

State-of-the-art synopsis

This is the state-of-the-art synopsis for the main manuscript "Deposition rates and retention time of litter varies among beaches in the Lofoten archipelago, Norway", which provides the theoretical background, a more detailed methods chapter and a discussion of the souces of errors in the study. The main manuscript is written by MSc candidate Vilde Sørnes Solbakken, with supervisors Synne Kleiven at USN and Marthe Larsen Haarr at SALT Lofoten AS and will be sent to the journal Marine pollution Bulletin [1].

1.0 Introduction

1.1 Marine Anthropogenic Litter

From the start of its production in the 50's, plastics have been a growing part of our everyday lives. With our growing dependence on plastics, its pollution of the marine environment has been growing alongside it. Most of the anthropogenic debris found in our oceans is made of plastic (Derraik, 2002). When discussing plastic pollution, it is generally categorized by size into nanoplastics (<0.01 mm), microplastics (<0.5 cm), mesoplastic (0.5-2.5 cm), macroplastic (2.5<1 m) and megaplastics (>1 m) (European Commission, 2019).Though often lumped into a single litter category, plastic is not one defined material but grouped into several different types of polymers with varying characteristics and made for different purposes. The most common types found in the environment are also those polymers often used in packaging and single-use plastic products including polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET) (Jambeck et al., 2020). This is unsurprising as plastic packaging makes up about 40 % of plastic production (Jambeck et al., 2020; United Nations Environment Programme, 2018). More and more countries in the world are banning single-use plastics, and was even banned within the European Union in 2021 (European Commission, 2020; United Nations Environment Programme, 2018) in an effort to curb its inflow into our oceans.

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[1] *Link to authorinformation: https://www.elsevier.com/journals/marine-pollution-bulletin/0025-326x/guide-for-authors*

There are still knowledge gaps in all the sources to litter in the oceans, but the major pollution sources have been defined to be municipal, agricultural (including aquacultural), industrial and maritime (Jambeck et al., 2020). Fishing gear and litter related to the fishing industry is also documented as a large contributor to the problem for the sea. The advantage with using plastic in fishing gear in durability and practicality, have increased the use of gear made of plastic, and contribute to a great degree to the composition of marine litter (Macfadyen et al., 2009). Plastic debris and foam have in different places of the world been found to be the most common litter types based on studies performed in sandy coasts of the Caribbean coast of Panama (Garrity and Levings, 1993), the Adriatic Sea in central Italy (de Francesco et al., 2018), and the Kenyan coast (Okuku et al., 2020).

8-13 mill tons of litter is estimated to enter the ocean from land yearly (Jambeck et al., 2015), but where all the litter ends up after this, is still a question unanswered as only 1% of this estimate is found floating in the ocean (Schwarz et al., 2019). Barnes et al. (2009) found a stabilized quantity of debris in the oceans since the 1990's, but an increase on shorelines. While some of the litter might be hiding under the ocean surface, or sink to the seabed, this might suggest that a considerable portion may wash in on our beaches.

1.2 Beach litter dynamics and accumulation of marine debris

While the exact proportion of marine litter that ends up beached may be unknown, it is clear that considerable amounts of litter get deposited and concentrated on shore. Beach litter density has, for example, been reported to exceed densities of nearby floating litter by an order of magnitude (Thiel et al., 2013). What is also clear, however, is that beach litter densities are highly dynamic and variable.

Different factors may influence the densities of beach litter. How long litter stays on the beach, or how long it is retained, is an important factor for how much litter a beach accumulates (Brennan et al., 2018). Together with deposition of fresh litter, those two processes work together on accumulation of litter (Smith and Markic, 2013). The whole composition of litter on a beach might experience a total turnover over short time e.g., if retention is low and deposition is high. If a beach is receiving a lot of new litter (high deposition rate) that is retained on the beach for a long time will accumulate a lot of litter over time. There are, however, spatial and temporal variations in beach litter densities, decided by different factors.

Spatial and temporal variations in litter densities are decided by factors as how close the beach is to urban areas and use by people, its geography, including the regions weather and currents (Barnes et al., 2009). For example, the beach characteristics like steepness and sediment type will determine what particles get stranded (van Sebille et al., 2020). Haarr et al. (2019) found that beaches are less likely to have high accumulation when the gradient are >35%, and Hardesty et al. (2017) and Williams and Tudor (2001) among others have documented more litter closer to urban areas. The total amount of litter on a given beach can be very dynamic. Litter will enter the beach from the ocean by wind and currents, and from land resuspend or be transported by wind or human activities on the beach. Within the beach, litter moves laterally and can be buried under beach substrate or wrack. After burial it can be exhumated back to the surface. In the same way, litter in the ocean can sink to the seabed, or resuspend from the seabed. Both on land and at sea, litter can degrade by exposure of wind, sun, water and pressure into smaller pieces and fragments, which might affect the object's ability to float or move. In the same way as litter enters the system, it can exit with wind and currents, or by beach cleaning on land. The whole beach system is never standing still, and the composition of what can be called 'the local litter population' is always changing (Critchell and Lambrechts, 2016) (illustrated in Figure 1).

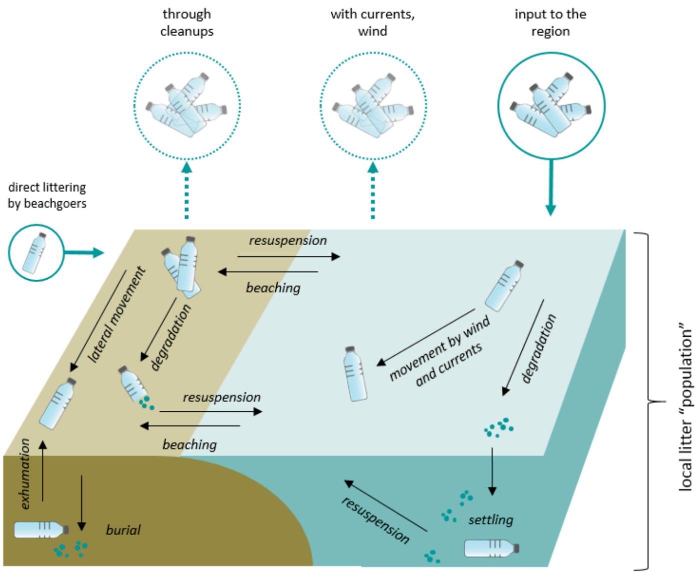

Figure 1. Varying processes affecting litter dynamics in a coastal system (Adopted from Haarr et al.,2020).

Van Sebille et al. (2020) did a review study on the physical, chemical and biological processes involved during transport of plastics at the ocean surface. There are many factors affecting the transport of marine debris at the ocean surface when it comes closer to shore, involving natural processes like coastal currents, internal tides, winds, surface waves and Stokes drift (van Sebille et al., 2020). Retention times of floating litter have been studied *in situ* on 1400 surface drifters in a study by Zambianchi et al. (2017); laboratory studies can provide information about beaching of plastic by studying hydrodynamics and motion of sediment particles (Alsina and Cáceres, 2011; van der Zanden et al., 2017); and remote sensing can provide information about dynamics and pathways of litter (van Sebille et al., 2020). When litter is reaching the coastal areas, there are still knowledge gaps how litter is transported and what decides where it accumulates. Based on the fact that there are many factors influencing litter dynamics on any given beach and given the large spatiotemporal variation in accumulation among beaches there is also reason to assume that there will be spatiotemporal variation in the dynamics on different beaches. One of the methods that have been used for studying beach litter dynamics, is the mark-recapture method.

1.3 Mark-recapture

The mark recapture method is a common research methodology in ecology, used to estimate population size and survival rates within a population, as well as to study animal behavior patterns. The method includes capturing individuals from the aimed study population, mark it and put it back into the ecosystem and return later recapturing/resighting the marked individuals (Hammond, 2009; Pollock, 2000). When a marked animal is recaptured or resighted at a different location than when last recaptured, it is obvious that it has moved from one place to another (Hammond, 2009). Mark-recapture method gives information of birth, death and movement and can be applied both in closed and in open populations, which is decided by if there is immigrants and emigrants in the studied population (open) or not (closed). Because the closed population does not change in population size, sampling is performed over a short time. In an open population, the population size is changing during the study, because new individuals are immigrating or emigrating. Individuals are often marked with unique marks to be able to report when they were last sighted and to detect movement of individuals within the population. Sampling events occur regularly with a constant interval between, with no maximum limit for study period (Krebs, 1999).

Mark-recapture method have been performed in many different forms and combinations to study survival rates, abundance rates and/or behavioral patterns, introduced in multiple different environments. The method has been used in several studies on terrestrial populations ranging from studies on the population size of grizzle bears (*Ursus arctos*) (Mowat and Strobeck, 2000) using DNA profiling of bear hair, to analyzing dispersal of different species of herbivorous insects (Kareiva, 1983) based on multiple mark-recapture studies. The method has been frequently used within freshwater and marine ecology as well. To mention some; Smith et al. (1999) estimated abundance of the North Atlantic Humpback Whale (*Megaptera novaeangliae*) population by using photographic and skin-biopsy sampling, and Koivuniemi et al. (2019) used the method for estimating the population size of the endangered ringed seal (*Phoca hispida*) using photo-id, in Lake Saimaa in Finland. Siegwalt et al. (2020) studied the movement patterns of green turtles (*Chelonia mydas*) by satellite tracking. Guina dolphins's (*Sotalia guianensis*) population dynamics, and abundance and survival rates were studied by Cantor et al. (2012) through an 8-year study using photo-id as marking method.

During the last few decades, mark-recapture have been introduced to the marine pollution in several studies (Bowman et al., 1998; Brennan et al., 2018; Garrity and Levings, 1993; Johnson, 1989; Johnson and Eiler, 1999; Kataoka et al., 2013;

Williams and Tudor, 2001) to gain knowledge of beach litter dynamics and composition. Garrity and Levings (1993) used the mark-recapture method to study residence time and litter dynamics by registering positions of marked objects within transects at four study sites. They found that litter stays on average less than a year on beaches and that beaches with cleared litter abundance were back to 50% of original load after 3 months. Brennan et al. (2018) combined the method with litter input sampling and based on their findings they suggested that beaches with high accumulation not necessarily have high arrival of debris (influx), but rather retain litter for longer period. Bowman et al. (1998) studied beach litter dynamics, residence time and turnover period on six different beaches of different morphology by marking litter *in situ* and marking new litter in different "strips" of the beach with different colours.

Some studies have followed individual movement by tagging with numbered metal tags (Johnson, 1989) and radio-tags (Johnson and Eiler, 1999) and other studies have marked items, but not with individual marks (e.g., Brennan et al., 2018). While they have not been able to report individual movement and "survival" of each object, the marked litter still provide information of how much litter stayed between the samplings (Brennan et al., 2018). Waterproof painting of different color for each sampling have also been used to be able to differ old items on the site with new items (unmarked) (Williams and Tudor, 2001) or for marking litter of different strips of the beach to study movement patterns of beached litter (Bowman et al., 1998). The use of the methodology varies within the marine litter field, but provides an opportunity to study a previously little studied population.

1.4 The Lofoten archipelago and the objectives of this study

The Lofoten archipelago is a string of islands extending southwestwards from mainland Norway into the Norwegian Sea, and it presents an interesting case study for assessing variability in beach litter dynamics for several reasons. Firstly, Lofoten is known to be polluted by marine litter based on information from its high cleanup activity and the location surrounded by two ocean currents potentially bringing litter from near and far. Secondly, the coast is very heterogeneous and with great spatial variability in accumulation, suggesting different local factors and processes at play. Thirdly, local physical processes like currents, eddies and tides in the Vestfjord can be suggested to retain and circulate litter locally. Fourthly, the seasonal variations in weather and storms in the archipelago may influence the beach litter dynamics throughout the year.

The archipelago is affected by two oceanic currents; Norwegian Coastal Current (NCC) and Norwegian Atlantic Current (NAC). NCC goes along the whole Norwegian Coast until it divides into one pathway into the Vestfjord and the other part moves around Lofoten and continues going north parallelly to the NAC. The greater amounts of water that gets collected on the inner side of Lofoten compared to on the outer side creates strong tidal currents through the sounds going through the archipelago. In addition, eddy features are found present in the fjord (Mitchelson-Jacob and Sundby, 2001), which could retain debris from the Norwegian Coast that have been transported by NCC. NAC is going parallelly with NCC further out from the coast, which could potentially bring litter from (Haarr et al., 2020).

Spatial variation in accumulation of litter at very small scales have been reported in the Lofoten archipelago. In a study from 2019, Haarr et al. found a highly variable pattern of litter density among beaches in the region, where some beaches had no litter at all and others ranging up to 1.5 items per m^2. Most beaches had less than 0.2 litter items per m^2. These findings indicate local processes could play an important role in deposition and retention in the area (Haarr et al., 2019). Lofoten consists of beaches responsive to different local and regional factors, and are responsive to seasonal variations in weather and storms.

Meyer et al. (2018) found indications of considerable differences between sites whether deposition or retention is the dominant process. In addition, considering that it is a community with high beach cleanup activities (Haarr et al., 2020), it is an interesting case study to investigate in litter trends at different sites to gain more knowledge of characteristics of beach litter dynamics.

The objective of this study was to use mark-recapture methodology on stranded objects to study spatiotemporal variation in beach litter dynamics. Trends in accumulation of litter over time at three locations was assessed by looking at retention time of marked objects and deposition rate of new litter. To accomplish this, three sites with different physical characteristics was selected in relatively close proximity in the Lofoten *archipelago, Norway, which were monitored biweekly for a period of seven months (June through December 2020). Deposition is in this context defined as new litter arriving on shore over a specified time interval, retention as the length of time over which litter remains on shore once deposited, and accumulation as the sum of these two processes over time.*

2.0 Methods

2.1 Site selection

At the start of May 2020, the MSc candidate met with the team from SALT Lofoten AS to start the practical preparations and last decisions before the commence of the mark-recapture study. On beforehand of the meeting, SALT Lofoten AS had prepared a selection of possible beaches to visit and considered including in this study.

The beaches selected for the study were Klauva (68.194438°N, 14.035579°E), Storvika (68.279755°N, 14.147502°E), and Rekvika (68.279716°N, 14.147433°E) (Figure 2;Figure 3). The decision fell on the three selected beaches, based on physical differences like steepness, substrate, exposure level and size (Table 1). By including three sites of different size, we could study differences in the beach dynamics on a small, medium and a large-sized scale. Both Klauva and Rekvika are also known to accumulate litter, and there is some evidence to suggest contrasting scenarios of high deposition – low retention (Rekvika) and *vice versa* (Klauva) (Haarr et al., 2019; Meyer et al., 2018). There was no documented cleaning activity at Storvika (Haarr et al., 2020; Clean Up Lofoten, pers. comm. 2019), but the site was discovered with a high density of accumulated litter, and thus included under the assumption that some regular deposition must occur.

Table 1. Characteristics of the study sites Klauva, Storvika and Rekvika, displaying area (m^2), coordinates, description of substrate and typical physical properties, and the exposure level to the sea and beach aspect, which is the direction the bay is facing (relative to North, measured from the middle of the shore).

Study site	Area (m^2)	Coordinates (Latitude, Longitude)	Beach morphology	Exposure level to sea	Beach aspect
Klauva	1200	68.194438°N, 14.035579°E	Rock walls forming a gully with a narrow cobble beach at its end.	Protected by islets	S (193°)
Storvika	9200	68.279755°N, 14.147502°E	Wide cobble bay, with a rock wall and a rocky outcrop at each end and marshland area in the backshore.	Exposed to a between two islands	SE (159°)
Rekvika	4400	68.279716°N, 14.147433°E	Wide bay consisting of large boulders and sloping steeply towards the backshore.	Open coast	SW (209°)

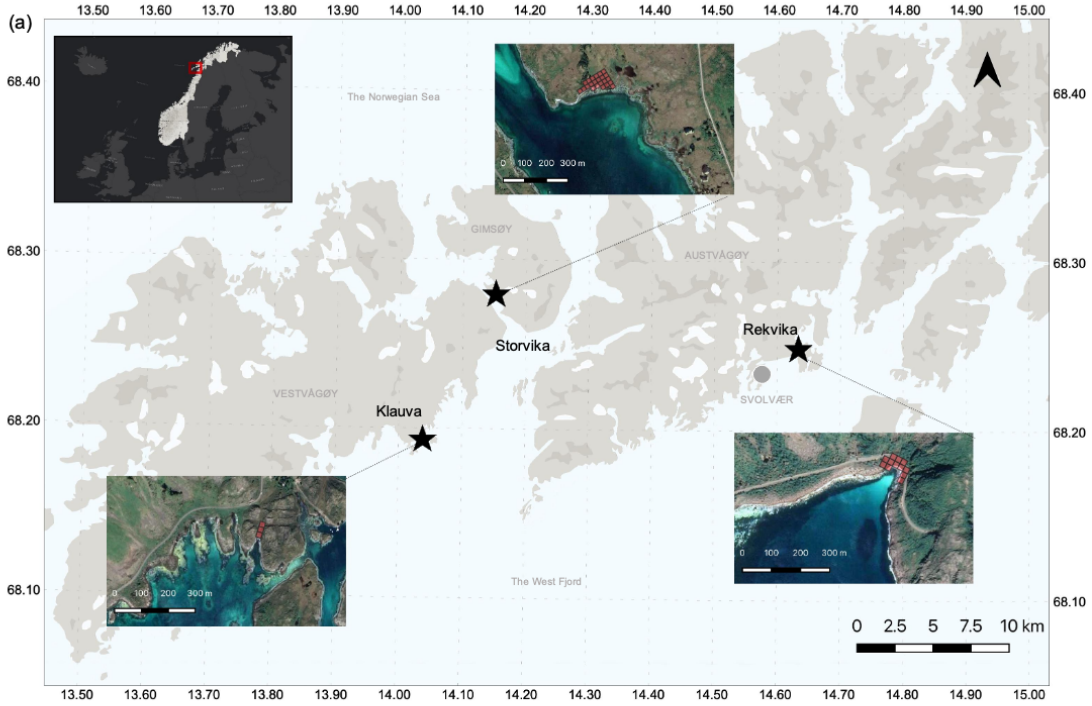

Figure 2. Maps of the study area. (a) Overview of site locations on the "inner" (West Fjord facing) coast of the three islands of Vestvågøy, Gimsøy and Austvågøy. The inset at the top right shows the location of the Lofoten Archipelago in Northern Norway. The other insets show the sampling sites and their immediate surroundings. (Base map: Esri, Ortophoto: Google).

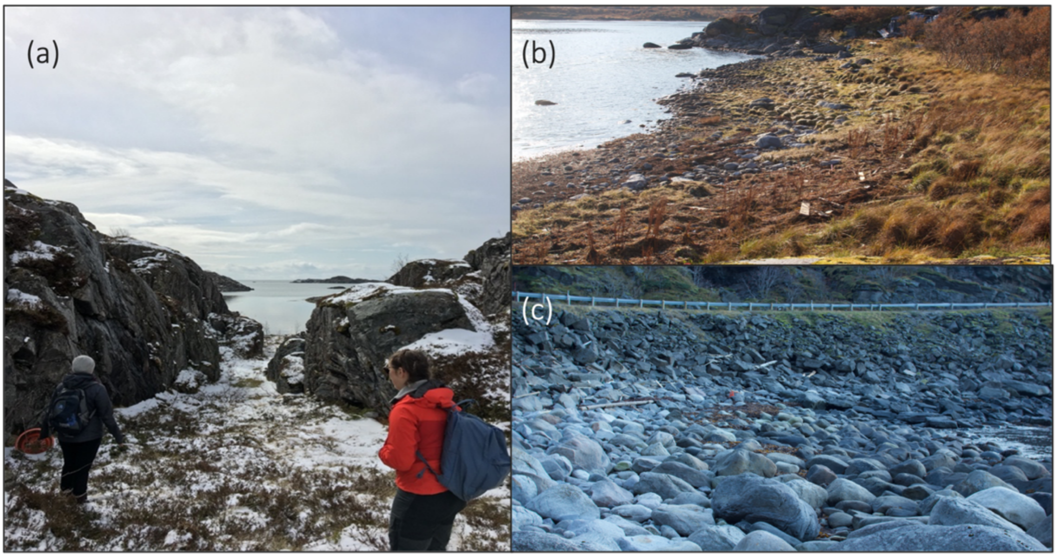

Figure 3. Photo of the study sites. (a) Klauva (b) Storvika (c) Rekvika. Photo: Vilde S. Solbakken.

2.2 Site preparation

The number of 20 m x20 m grid cells at each site was dictated by their size (as defined by natural limits), which determined the number of cells horizontally along the shoreline, and the distribution of litter, which determined the number of cells stacked vertically inshore as the site extended as far as did litter (Figure 4). All study sites started by the waterfront defined by the mean high-water mark.

The first six grid cells in Storvika were measured manually with a measure tape when preparing for the initial cleanup. The grid cells were later drawn in the software PenMap using a Trimble R2 GPS, and any necessary small adjustments was made in the field to match the cells in PenMap. When staking out a grid in PenMap, the lower edge of the first grid cell (*i.e.,* the line running parallel to the shore at the mean high-water mark) was first staked out with a measuring tape and the coordinates of the two corners recorded. These two points were then used to generate the first cell by creating its upper corners using a horizontal offset and build rectangles function in PenMap. The remaining grid cells were similarly generated by creating new points in PenMap using horizontal extensions and offset functions to place new points and a build rectangle function to connect these points to cells. The corners of each cell were then staked out in the field by using the GPS to accurately locate points. Grid cells in Klauva and Rekvika were made directly using the GPS and PenMap.

The initial clean-up was organized within the grid cells, where each cell had its own ID number. In each corner of the grid cells, spray-painted bamboo sticks were placed as markers during the clean-up. The markers made it easier to orientate during the litter collecting. Subsequently to the clean-up, the litter from each grid cell was sorted into categories, counted and weighted (as described in the main manuscript). The sorting was performed for each beach separately.

The clean-up was performed in teams of different number of persons on each site. The teams consisted of the MSc candidate and staff members from SALT Lofoten AS. Storvika (23 grid cells) (fig. 4c) was the largest bay and required five days of organized clean-up and was performed by a team of three or four persons each day. The smallest location Klauva (3 grid cells) (fig. 4a) required a smaller team and was cleared in one day by a team of two. The mid-sized bay Rekvika (11 grid cells) (fig. 4b) required two days, with a team of three persons one day, and two the last day. At the start of the clean-up, the litter were registered in situ after each grid cell was cleaned. After two days of testing this way of registering, a decision was made to mark the bags with the cell ID where the litter was collected and register it off-site after the clean-up. The decision was made to save time while in field and after experiencing some technical issues (with the software MagicDevice Forms first used for recording data) during the registration *in situ*. The technical issues made it necessary for us to change the way of registering, and we started registering the same directly into a Microsoft Excel form).

Figure 4. Study area shown in 20x20 m grid cells, in (a) Klauva, (b) Storvika and (c) Rekvika. The outline of each site is shown by the grid cells used during the initial cleanup and site preparation. Numbers and shading indicate litter density in number items re moved from each cell (i.e., n 400m^{-2}). (Ortophoto: Google).

2.3 Preparing a sample of marked objects

2.3.1 Tags

The MSc candidate and Frode Bergan (head engineer at USN), conceptualised these marks in advance, and had evaluated numerous options for tagging objects in such a way that the tags would stay on and not degrade when exposed to weather, sunlight and salt water over the four contrast-filled seasons the Norwegian Arctic has to offer. Nail polish, paint and permanent markers were considered as marking method. GPS trackers were talked about but not really considered, as this was not an affordable option in this project. The decision fell on aluminium tags with numbers. The tags were hand made out of an aluminum plate approximately 1 mm thick, stamped with metal number stamps to make marks with unique numbers. The numbers were stamped into the plate by using a hammer on a hard and stable surface. Holes for the wire/attachment material were made using a drill with 3 mm drill bit. Cutting pliers were used to cut the tags from the plate (Figure 5).

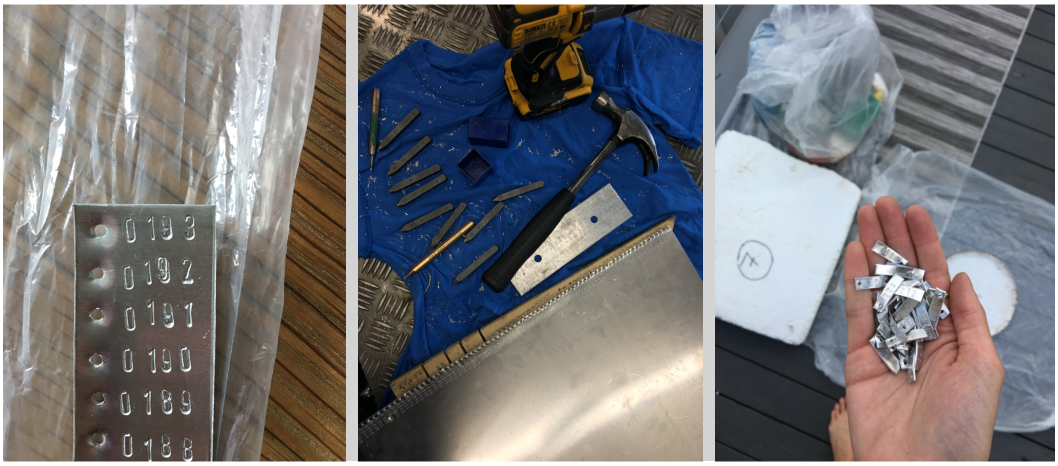

Figure 5. Aluminum tags and tools used to mark objects. Photo: Vilde S. Solbakken.

The premade marks were attached to the items with either zip-ties, brass wire or epoxy glue ("Quick Epoxy glue", bought from Biltema) (Figure 6). Type of attachment method were considered by the shape/form of the item. For example, on objects with a handle it was natural to attach the mark in a wire or a zip-tie though the hole that was already there. The selection of different length of zip-ties that thin (3mm holes in the marks) were limited, hence were wire used in cases where the zip-ties were too short. Zip-ties and brass wire were preferred as the glue required a clean surface on the item and time to dry in room temperature.

When attaching marks in the field later in the study hole pliers were used where the thickness of the material made it possible to make holes in the objects. Other objects had natural holes to insert the zip-tie or the wire, or a surface to mark with a permanent marker resistant to water and sun. The epoxy glue was not used for marking the objects in field, as the marking method required detailed handwork not practical under cold temperatures and unstable weather. In addition, the glue proved not to stick to the objects over the time of the study. Permanent marker replaced this marking alternative.

2.3.2 Selecting representative sub-samples of litter

The litter pieces picked out to represent each category in the sub-sample were selected haphazardly among the pieces that was suitable to mark and possible to bring back to the beach (Figure 3). The total sub-sample *n* was chosen to be 50 because it was a large enough number to represent a litter composition where some categories were more represented than others. At the same time, 50 were a small enough sample to include marking and sampling of new incoming litter in addition to the already marked items during field surveys.

Figure 6. Examples of marked objects in each item category: (a) beverage bottles, (b) buoys and floats, (c) EPS (mark attached w/brass wire) (d) food packaging, (e) lids and caps (mark attached w/ zip-tie), (f) ropes <50cm, (g) ropes >50cm, (h) strapping bands (i) other ("snus box" as an example, attached w/glue). *Photo: Vilde S. Solbakken.*

2.3.3 Data registered for each marked object

A kitchen scale with an accuracy of 1 g was used during registration. Some larger items were hard to weigh using the kitchen scale and were weighed with a handheld fish weight with an accuracy of 5 g. Weight for all items were wet weight either weighted *in situ* or stored wet in plastic bags until measurements were made.

Litter was stored between the initial cleanup and until the registration of all the litter from each beach was finished. When all the grid cells were registered on one beach, the distribution of the litter and categories was calculated, and a sub-sample were picked out as described above. As the litter was already collected, it was practical to mark and register the objects in advance of the placement of the sub-sample. By marking items in advance, the only thing we needed to register during placement was the GPS position of the objects. This was done using the Trimble R2 GPS unit.

2.3.4 Redistribution of marked objects *in situ*

The distribution of litter per cell for each category were not considered in the placement and were mixed independent to the results from the cleanup. The equipment used for the placement of the sub-sample on the beaches were the same as during the mark recapture field surveys.

2.4 Mark-recapture field routines

Two surveyors (the MSc candidate and one staff member from SALT Lofoten AS) conducted the field surveys every other week. For every field sampling at each site, a new project was made in Penmap with the name “STUDY-SITE_dd-mm-yy” (e.g., “Storvika_17-11-20), a new project with the template “Quickstart” was made and set up in UTM-zone 33. All positions of freshly marked, or recoveries of items were registered in this project. Measurements of the items (Table 2) were at the same time registered in an Excel form. Three events were reported during field sampling: mark, recapture, and survey.

Mark. Only litter suitable for marking was marked, meaning objects that was heavier and larger than the mark itself. These objects were placed where naturally deposited, after it was registered with the information needed for marked items. Table 2 shows the different measurements recorded during field surveys. Some measurements made (entanglement, biofouling, degradation, and buoyancy) was not analyzed and finished in the context of the master project, but are saved for further work and research.

Recapture. When recapturing marked objects while searching the sites, the position of objects was registered using the GPS. Positions were recorded in PenMap and linked to the object ID and the date recaptured (Figure 7). Additionally, information about the level of degradation, biofouling and entanglement of each object was also registered in the Excel form.

Survey. Newly deposited litter (*i.e.,* litter which had arrived since the previous sampling event), was recorded as ‘survey’ and removed from the site. *In situ*, litter was picked in two different bags, one marked with ‘entangled’ and one marked with ‘none’. Litter entangled in wrack, or in rocks was sorted in the ‘entangled’-bag, and surface litter, not entangled to anything, sorted in the ‘none’-bag. If an object was considered as 'partially buried', the object was manually noted to be considered 'partial burial' but collected in the 'entangled' bag. Litter was registered as 'survey' subsequently to the field surveys (Table 2).

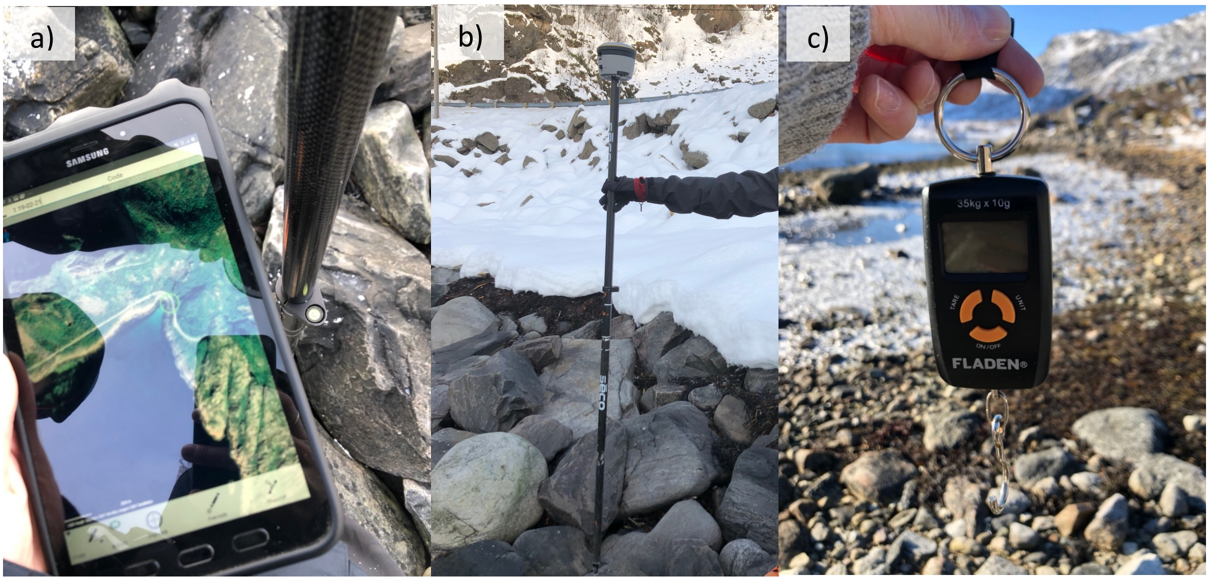

Figure 7. Equipment used during field surveys at the three beaches. a) the tablet using the Software Trimble Penmap, b) Trimble R2 GPS unit, and c) fishing weight used for weighing litter. Photo: Vilde S. Solbakken.

*Table 2. Measurements registered for individual items for each event. *Only items in the 'other'-category were given item description.*

Measurements	**Mark**	**Survey**	**Recapture**
Degradation	x	x	x
Biofouling	x	x	x
Entanglement	x	x	x
Item type	x	x	
Item description	x (*)	x (*)	
Material	x	x	
Size category	x	x	
Weight (g)	x	x	
Buoyancy	x	x	
Origin (natural/artificial placement)	x		
Tag attachment (wire/zip-tie/glue)	x		

2.5 Analyses of data

Weather data reported in the main manuscript was collected at www.Seklima.met.no, provided by the Norwegian Meteorological institute at weather station “Svolvær Flyplass (Helle)”. All coordinates collected with the GPS was converted to the coordinate system WGS84.

QGIS 3.10 was used for making figure 2 and 4. Tables were made in PowerPoint. Statistical analysis was performed in Excel (Chi Square tests), and the statistical software JMP (ANOVA, Pearson’s correlation coefficient) and in R (Time to event analysis NPLME, AIC, Weibull distribution).

3.0 Sources of error

3.1 Measurement error

Some small, light-weighted items (e.g., ropes under 50 cm) were affected by the mark in its ability to float and may have resulted in some error in measurements in these cases. The mark was made as small and light as possible, and no litter items smaller or lighter than the mark itself was marked and included in the study to minimize the chance of it to disturb or change movement or survival on the beach. To be able to study movement of small, light-weighted items they were included in the study, and buoyancy was tested with the mark on.

Of the few items that were marked with epoxy glue, the mark eventually fell off most of the marks – of those that were identified before mark was fully lost, they were remarked with a permanent pen supposed to resist both sunlight and water. The solution to the marking worked for a period but needed a new layer of marking (with the marker pen) after a period in the field. For a longer study period, another marking method for objects not suitable for marking with wire or zip-tie could have been studied further to be able to identify objects that could potentially be gone for a while and still hold a mark if it returns.

The accuracy of the R2 GPS is down to 7 cm, but not all data was collected with this quality. One of the sites, the smallest Klauva, is located within an area with “less mobile reception” than the other two sites. As the GPS is connected to “mobile net” during field surveys at sites, the precision was set not to exceed 0.5 meter. In light of the purpose of this study we were still be able to track large movements, and within 3 m, which was the minimal displacement that was further studied.

3.2 Human error and observer bias

Some observer bias was possible during the categorization of buoyancy, biofouling and degradation as litter items may have been interpreted differently by different observers during sampling. Observer bias was limited by the same person (i.e., the MSc candidate) was always present during sampling.

3.3 Procedural error

One can question that removal of litter from the study site could affect the study of beach litter dynamics. As for deposition of litter, it will probably happen to the same degree if litter on the beach is removed or not. Unless the litter densities were so large that it would change the beach morphology and make new “traps” by litter, removing new litter was considered unlikely to have any effect of the retention time and lateral movement of beach litter. As freshly deposited litter was removed with the same procedure among all the sites, this would occur to a similar degree on all the sites. Based on this, removing litter was not considered to be a big source of error, or bias in this study.

Litter densities varied among sites as they varied in size, and it was decided to “release” the same number of marked objects on all sites. This was decided based on the great differences in total litter counts on each site during the initial cleanup, which would lead to a great percentage of litter on two of the sites (Storvika and Rekvika), while the last one barely would have any litter to be released (Klauva) if the marked cohort were supposed to reflect those counts. For the purpose of the study, presence of litter at all sites were considered more important during a study of trends in dynamics than for the density to reflect the original composition.

3.4 Environmental error

Rekvika consists of large boulders constructing a bit more challenging terrain to move around in, and to search in between all the rocks. This could have affected our study in a way, if old litter that was not found or picked during the initial cleanup and showed up and registered later in the study. This could particularly be the case of EPS, as we experienced great amounts of EPS in Rekvika during the initial cleanup that we were not able to completely clear all of it from site.

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DEPOSITION RATES AND RETENTION TIME OF LITTER VARIES AMONG BEACHES IN THE LOFOTEN ARCHIPELAGO, NORWAY

Solbakken(1), V.S., Kleiven(1), S.and Haarr(2), M.L.

(1) University of South-Eastern Norway, Bø, Norway (2) SALT Lofoten AS, Svolvær, Norway.

ABSTRACT

A considerable portion of marine litter pollutes the world's coastlines. Its accumulation on beaches represents the product of deposition and retention, processes which are not well understood. A mark-recapture study was performed with a two-week sampling interval at three sites in Lofoten, Norway. Deposition and retention vary over small spatial scales (approx. 13 km radius). No correlation was found among sites in the timing of high and low deposition events, suggesting these are governed by local factors. Contrastingly, a correlation was found among sites in the timing of high and low retention events, suggesting these are affected by regional factors. The results underline the importance of customising cleanup frequency for different beaches as spatiotemporal variation in the relative importance of deposition and retention dictate the optimal frequency for maximal removal of litter from circulation in the local marine environment, which cannot be discerned from accumulation (i.e., standing stock) alone.

1. INTRODUCTION

Marine anthropogenic litter is a great global environmental concern of our time. It has been estimated that 8 million tons of plastic entered the ocean from land-based sources in 2010 (Jambeck et al., 2015). As the material degrades slowly or even never (Derraik, 2002), the problem continues to grow. Despite clear geographic trends in mismanaged plastic waste resulting in land-based leakages into the ocean (Jambeck et al., 2015; Lebreton and Andrady, 2019), marine litter has reached all corners of the world, including the Arctic, the Antarctic and remote oceanic islands (e.g., Barnes et al., 2010; Bergmann and Klages, 2012; Ryan et al., 2019). This global distribution of marine litter is partly due to direct leakages from ships (e.g., Deshpande et al., 2020; Ryan et al., 2019), and partly the result of redistribution by ocean currents (e.g., Cózar et al., 2017; van Sebille et al., 2020). A considerable amount of litter entering the ocean is later washed ashore (Gutow et al., 2018; Seo and Park, 2020) and may pollute beaches in staggering densities (e.g., Ambrose et al., 2019; Bouwman et al., 2016; Poeta et al., 2016).

The accumulation of litter on a beach is primarily dependent on two factors: (1) how much litter that beaches (i.e., deposition), and (2) for how long it stays beached (i.e., retention) (Hinata and Kataoka, 2016). There are, however, spatial and temporal variations in both deposition and retention, hence also in accumulation. Coastal location relative to population density (e.g., Galgani et al., 2015; Smith and Markic, 2013), availability to the sources of litter and ocean transport (Critchell and Lambrechts, 2016) have been described as important factors influencing the deposition of litter on beaches. Beach characteristics in terms of substrate and shape of the coast has been documented to influence retention (Brennan et al., 2018), which are also considered important factors for substantial heterogeneity of coastal litter (Galgani et al., 2015). Extreme weather events, wave energy (Williams and Tudor, 2001) and wind are also factors which affect the accumulation of litter (Hardesty et al., 2017). Consequently, coasts can be quite heterogeneous in accumulation even over small spatial scales (e.g., Haarr et al., 2019).

The beach system is highly dynamic, where litter is interacting with its surroundings (Critchell and Lambrechts, 2016). Beach litter may be moved to the backshore or laterally within the beach (e.g., Kataoka et al., 2013), get resuspended (e.g., Brennan et al., 2018) or end up getting buried under beach substrate or wrack (Williams and Tudor, 2001). Apparent recent deposits of litter may also be exhumed litter or litter that have moved from an adjacent place by land (e.g., Johnson and Eiler, 1999). The composition of beached litter may also rapidly change completely on beaches with high turnover rates (e.g., Blickley et al., 2016; Bowman et al., 1998). Studies have shown that the shorter the sampling interval, the higher the estimated daily deposition of litter (Eriksson et al., 2013; Ryan et al., 2014; Smith and Markic, 2013). These findings suggests that not all litter stays put over time, but there is a strong need for more knowledge of how beach litter behaves over time.

To study beach litter dynamics one can adopt a mark-recapture method, which is commonly used in ecological studies to estimate population size, survival and migration patterns, and which has been adapted to study beach litter dynamics in several studies (Bowman et al., 1998; Brennan et al., 2018; Garrity and Levings, 1993; Johnson, 1989; Johnson and Eiler, 1999; Kataoka et al., 2013; Williams and Tudor, 2001). The method gives information of birth (i.e., deposition), death (i.e., disappearance either through resuspension or burial), and movement of marked members of a population, at the cost of time and effort to collect sufficient data within the assumptions required for the studied population (Krebs, 1999). Individuals are marked with unique marks, and immigrants and emigrants to the study area are considered. The unique marks make it possible to study residence times as well as individual movement, by also recovering new positions of the individual for each sampling (Krebs, 1999).

The objective of this study was to use mark-recapture methodology on stranded objects to study spatiotemporal variation in beach litter dynamics. The Lofoten archipelago was considered a relevant case study as previous work has indicated that beaches here may differ considerably in whether deposition or retention is the dominant process (Meyer et al., 2018). We selected three study sites with different physical characteristics in relatively close proximity to each other, which were monitored biweekly for a period of seven months (June through December 2020). We then assessed trends in accumulation of litter during this period, by looking at retention time of marked objects and deposition rate of new litter. Composition and characteristics of the deposited litter was further studied to compare accumulation trends among the sites. We define deposition as new litter arriving on shore over a specified time interval, retention as the length of time over which litter remains on shore once deposited, and accumulation as the sum of these two processes over time.

2. METHODS

2.1 SITE SELECTION AND PREPARATION

The three study sites (Figure 1) were chosen to (1) include sites of significant litter accumulation, (2) ensure varying geomorphological and oceanographic characteristics, (3) capture a hypothesised range of deposition and turnover rates, (4) ensure ease of access for researchers, and (5) minimise the likelihood of interference from members of the public. The selected sites were of varying sizes; this was chosen over standardising site size in order to better capture natural variability in the geomorphology of areas of litter accumulation given the investigation of variability was one of key objectives. All three sites are located on the inner (fjord-facing) shore of the archipelago, and consequently all face a similar direction (south-east – south-west); sites meeting the above criteria were not found along the outer (open ocean-facing) shore.

Klauva (68.194438, 14.035579) is a narrow, funnel-shaped bay no more than 20 m across, and partially protected by islets (Figure 1b). The site is small (approx. 1200 m^2) and naturally defined by rock walls forming a gully with a narrow cobble beach at its end. The site is close to minor road (approx. 140 m), but not visible from it and surrounding terrain makes it fairly obscure. Rekvika (68.279716, 14.147433) is a wider, highly exposed bay (Figure 1d), consisting of large boulders and sloping steeply towards the backshore. The study area covered 4,400 m^2 and defined by expansive boulders flanking the sides. Rekvika is located immediately next to the archipelago's main highway and close to one of its main town centre Svolvær. To prevent the risk of outside interference at the site, the project was announced in the local newspaper and the local volunteer cleanup organisation (Clean Up Lofoten: www.cleanuplofoten.no) informed; a sign was also placed at the site. Storvika (68.279755, 14.147502) consists of a cobble beach situated within a larger bay in a strait separating two islands (Figure 1c). It was the largest site, covering an area of 9,200 m^2 and defined by a rock wall to the east and a rocky outcrop to the west. Storvika is located approx. 800 m from a minor road on one of the archipelago's smallest islands, and also considered fairly obscure and unlikely to be disturbed. All sites included the beach itself, as well as a considerable portion of vegetation beyond the backshore (see section 2.2).

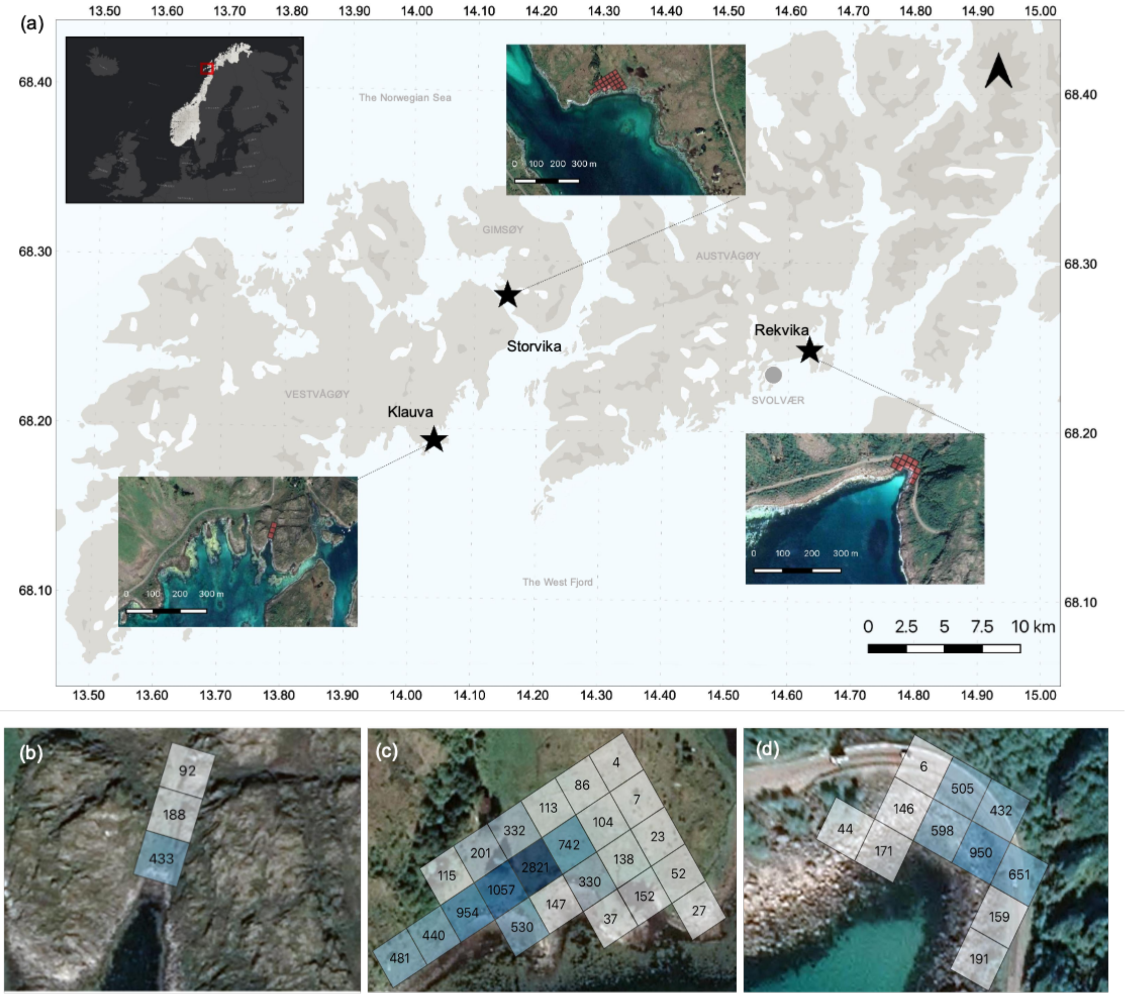

Figure 1. Maps of the study area. (a) Overview of site locations on the "inner" (West Fjord facing) coast of the three islands of Vestvågøy, Gimsøy and Austvågøy. The inset at the top right shows the location of the Lofoten Archipelago in Northern Norway. The other insets show the sampling sites and their immediate surroundings. The lower panels show a zoomed-in view of (b) Klauva, (c) Storvika and (d) Rekvika. The outline of each site is shown by the grid cells used during the initial cleanup and site preparation. Numbers and shading indicate litter density in number items removed from each cell (i.e., n 400m^{-2}). (Basemap: Esri. Ortophoto: Google).

Both Klauva and Rekvika are known to accumulate litter, and there is some evidence to suggest contrasting scenarios of high deposition – low retention (Rekvika) and *vice versa* (Klauva) (Haarr et al., 2019; Meyer et al., 2018). There was no documented cleaning activity at Storvika (Haarr et al., 2020; Clean Up Lofoten [https://www.cleanuplofoten.no], pers. comm. 2019), but the site was discovered with a high density of accumulated litter, and thus included under the assumption that some regular deposition must occur.

Each site was cleared of pre-existing surface litter prior to commencing the mark-recapture study, and analyses of this litter used to guide the initial marking of litter objects. Each site was divided by a 20 x 20 m grid (Figure 1) using a Trimble R2 GPS (7 cm accuracy) and the software Trimble PenMap prior to cleanup. It took between one (Klauva) and five days (Storvika) to clean and survey each site. These initial cleanups took place in early June, 2020. All anthropogenic macro litter over 5 cm was included in the study, except processed wood. A lower limit of 5 cm was chosen so as to avoid marking objects significantly smaller than the tags. Objects were categorised based on the eight most common item types comprising 80% of beach litter reported by volunteers in Lofoten (Haarr et al., 2020): 'Beverage Bottles', 'Buoys and Floats', 'EPS', 'Food Packaging', 'Lids and Caps', 'Ropes <50 cm', 'Ropes >50 cm' and 'Strapping bands'. Other items were simply classified as such ('Other') (Figure 2). Each piece of litter was also classified by size: small (5 - 20 cm), medium (20 – 50 cm), large (50 – 100 cm) and extra-large (>100 cm). All litter in each of the 36 categories (9 item types x 4 size classes) was pooled for a total count and wet weight by category. Storvika was the most polluted site during the initial cleanup, both in terms of the total amount of litter removed (8,893 objects *n* weighing 266 kg), and density (mean = 97 n 100m^{-2}and 2.9 kg 100m-^{2}) (See Appendix). Rekvika was the second most polluted in terms of the total amount of litter removed (2,778 objects weighing 44 kg), count density (mean = 63 n 100m^{-2}) and mean weight 1 kg 100m-^{2}. However, density by weight was lower in Rekvika than in Klauva (mean = 1.8 kg 100m^{-2}). A total of 713 objects weighing 22 kg were removed from Klauva, with a mean count density of 59 n 100m^{-}2.

2.2 MARK-RECAPTURE

A representative sub-sample of the litter collected during the initial cleanups was marked and returned to each site in mid-June, marking the start of the mark-recapture study. Sub-samples were selected to reflect the proportional frequency distribution of litter among the 36 item and size categories found in the initial cleanup. This was done at the site level; consequently, the composition of litter in the sub-samples varied among sites. We calculated the number of litter pieces to be sub-sampled within each category based on a total sub-sample n of 50. To avoid fractions, we chose to round all the resulting estimates up rather than round to the nearest integer so as to avoid rounding rarer categories to zero objects. Subsequently, the total number of marked objects 'released' at each site ranged from 61-65 (Table 1). Objects were marked with aluminum tags (approx. 25 x 7 mm, less than 1 g.) stamped with unique ID numbers and attached primarily by zip-tie or brass wire, or occasionally epoxy glue (Figure 2). The material type was recorded in addition to item type and size category. Objects were also weighed and photographed. Material type was categorized as rigid plastic, soft plastic, EPS/Foam, synthetic line/cord, rubber, textiles, metal, glass and other.

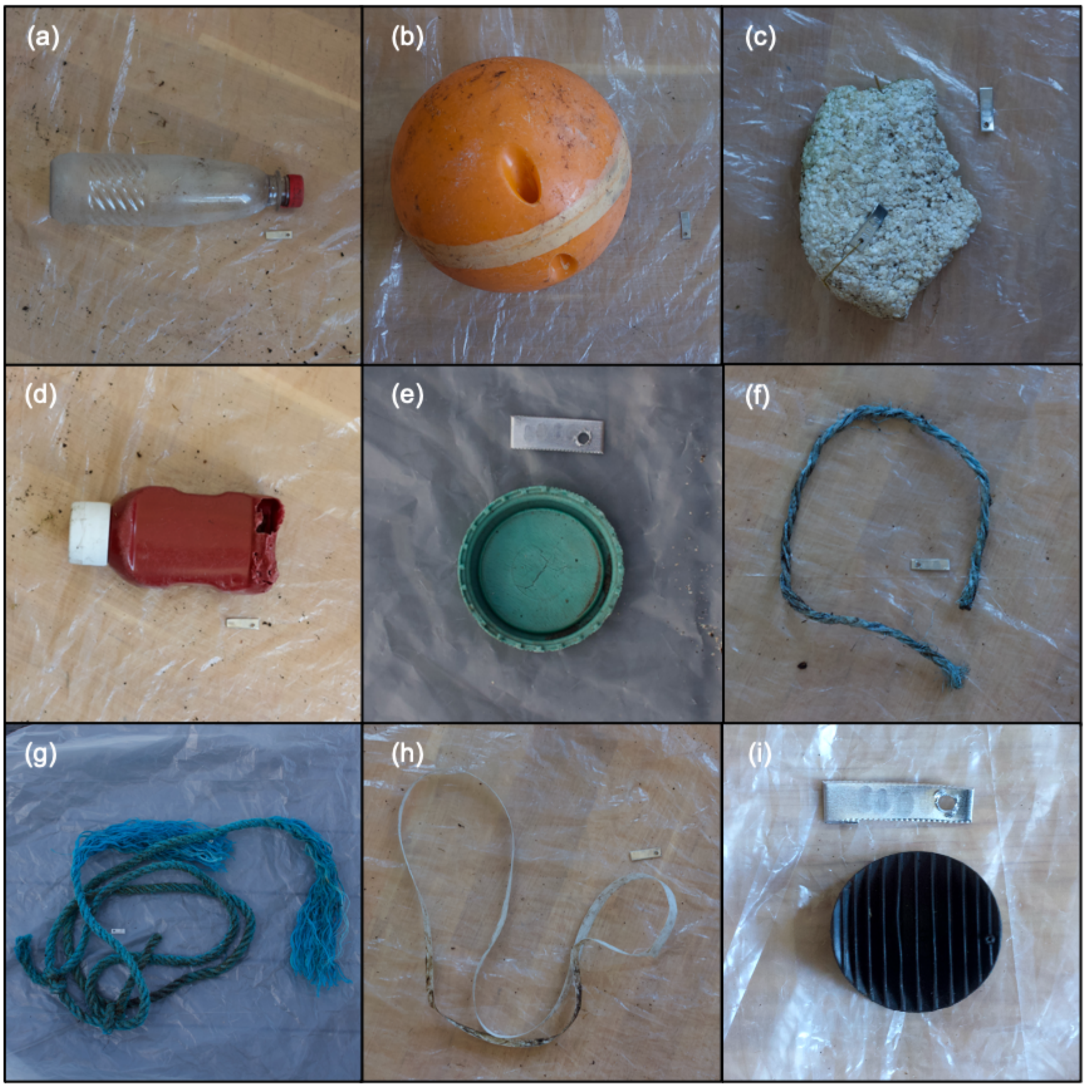

Figure 2. Examples of marked objects in each item category: (a) beverage bottles, (b) buyos and floats, (c) EPS, (d) food packaging, (e) lids and caps, (f) ropes <50cm, (g) ropes >50cm, (h) strapping bands (i) other (bio carrier used as an example). Marks (aluminum tags) are shown for scale.

Table 1. Summary of the number of freshly deposited litter objects surveyed, and of objects marked, during the 7 month period of the study.

Litter		**Klauva**	**Storvika**	**Rekvika**	**Total**
Fresh deposits		303	3,448	2,976	6,727
Marked objects (initial cohort)*		61	62	65	190
Marked objects (running cohort)†		22	54	44	120
Marked objects (post-storm cohort)‡		38	42	46	126
Marked objects by item (all cohorts pooled)	Beverage bottles	3	2	4	9
	Bouys and floats	2	2	5	9
	EPS	1	2	31	34
	Food packaging	10	7	8	25
	Lids and caps	6	5	10	21
	Ropes <50 cm	21	33	14	68
	Ropes >50cm	6	8	13	27
	Strapping bands	7	10	6	23
	Other	64	89	64	217

* The initial cohort consists of objects marked and distributed on each site following the initial cleanups and site preparations (date 19-25).

† The running cohort consists of objects marked *in situ* on a continual basis as they were deposited on each site during the first 6 weeks of the study.

‡ The post-storm cohort consists of items marked in order to replenish the supply of marked objects on each site following a storm on week 39, which removed 47-76% of the marked items on each site.

Objects were returned to the site by haphazardly scattering litter in the same relative density among grid cells as in Figure 1. The number of objects scattered in each grid cell reflected the proportion of the total litter removed from each cell during the initial cleanup. The exact location of each litter object was recorded with 7 cm accuracy using the Trimble R2 GPS. The marked objects were placed in Storvika on June 19th, in Klauva on June 23rd, and In Rekvika on June 25th, 2020. Any litter which had arrived on site since the initial cleanup was removed to ensure only marked objects were present at the start of the study. The three sites were surveyed every other week until the end of December 2020, for a total of 14 surveys per site. A two-week interval was chosen partially for practical reasons, and partially to be comparable to other similar studies (*e.g.*, Williams and Tudor, 2001).

During each survey, the sites were searched systematically from the mean high-water mark to the back edge of the uppermost grid cells (note that the grids themselves were only used during the initial cleanups and to place the first marked objects). The locations of marked objects recovered during each survey were recorded. New incoming litter was marked (i.e., ‘running cohort’) *in situ* on a continual basis as they were deposited until a maximum of 100 objects were marked per site during the first 6 weeks of the study. Only litter sufficient to be marked based on size and weight relative to the mark was marked. When the number of marked objects at a site had reached 100, new objects were simply registered as new deposits and removed from the site. For ‘other’ items it was also noted in detail what these objects were.

2.3 STATISTICAL ANALYSES

Deposition rates were estimated based on the number of new items found during each sampling event divided by the number of days since the previous sampling. This rate was further standardized per 100m^2 as the sites were of different sizes. Variation in the magnitude of deposition rates among sites was tested with a single factor ANOVA followed up by a Tukey-Kramer post-hoc test (test assumptions of normality of residuals and homogeneity of variances were not violated; results not shown). Pearson’s correlation coefficients were used to assess whether high and low deposition events coincided among sites.

The retention of marked objects on each site were compared using time-to-event analyses. Firstly, comparisons were first made using nonparametric maximum likelihood estimations (NPMLE) for interval censored data given the two-week interval between surveys; significance was assessed using an asymptotic weighted log-rank test (Fay and Shaw, 2010). Secondly, exponential and Weibull parametric regression models were fitted to the data, and the model of best fit determined based on minimising the AIC score (Akaike, 1974; Zhang, 2016). All analyses were done using the “survival”, “interval” and “SurvRegCensCov” packages in R (RStudio v 1.4.1106) (Fay and Shaw, 2010; Zhang, 2016). In this study, “retention” is a collective term covering everything related to how long or how well objects are retained once beached. In the analyses, the time-to-event analysis assessed residence time, and the parametric regression both residence time and hazard (i.e., the risk for loss at any time during the study). In addition to time-to-event analyses, the percentage of possible marked objects recovered was estimated for each sampling event (i.e., the number of marked objects present during the previous sampling event divided by the number of marked objects recovered during the relevant sampling event) for each site and compared among sites using Pearson's correlation coefficients. This was done to assess whether periods of high and low retention of marked objects coincided among sites.

The displacement of objects whilst beached was estimated based on GPS positions recorded each sampling using the following formula:

$$D = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

where D is displacement in meters, x is longitude, y is latitude and z is meters above sea level. This was calculated for each marked object between consecutive sampling events when it was located, and the maximum displacement between sightings of each object identified. A frequency distribution of maximum displacement is strongly right-skewed; subsequently, the interquartile range (IQR) in the spread of maximum displacement values among objects was determined, and objects which maximum displacement was greater than 1.5 the IQR were classified as outliers. Outliers were considered to have shown substantial displacement, while the remainder of objects were considered to have experienced limited displacement and have remained relatively stationary.

Two-way chi-square tests were used to test for associations in object counts among variables. Variables tested for associations included: (1) the loss status of marked objects (*i.e.,* the frequency of objects permanently lost, temporarily lost and never lost) *versus* site, (2) the frequency of marked objects remaining stationary and those showing substantial displacement *versus* site, (3) the loss status of objects *versus* their displacement category (limited or substantial), (4) the temporarily loss of objects (*i.e.*, the frequency of objects temporarily lost) *versus* the length of being gone, (5) the temporarily loss of objects *versus* substantial displacement, (6) the size class of deposited litter *versus* site (7)Weight class of deposited litter *versus* site, (8) item category of deposited litter *versus* site, (9) the ‘other’ item category among deposited litter *versus* sites, and (10) the occurrence of different plastic types of deposited litter *versus* site.

An alpha of 0.05 was used to determine significance in all statistical tests. Mean values are reported +/- 95% confidence intervals.

3. RESULTS

3.1 LITTER DENSITY

A total of 6,824 items were registered as fresh deposits during the six months of the study. Approximately half of these were deposited each in Storvika and Rekvika (3,485 and 3,012, respectively); only 327 items were deposited in Klauva (Table 1). The mean deposition rate was significantly higher in Rekvika (mean = 0.37 n 100m^{-2} day^{-1}) than in Storvika and Klauva (mean = 0.2 n 100m^{-2} day^{-1} and 0.16 n 100m^{-2} day^{-1}, respectively) ($F_{2,35}$=6.6219, p=0.0036, Tukey HSD Post-Hoc) (Figure 3). Deposition rates also varied considerably among sampling events within sites. Fresh litter was always found, but the deposition rate varied from 0.5–8 items per day (0.04 to 0.48 n 100m^{-2} day^{-1}) at the lowest to an order of magnitude greater with 5 (Klauva) to 40 (Storvika and Rekvika) items per day (0.05 to 0.86 n 100m^{-2} day^{-1}). This temporal variation in deposition rates did not coincide among the sites as there were no significant correlations among them (Figure 4a), indicating that high and low deposition events generally did not occur during the same sampling periods across sites.

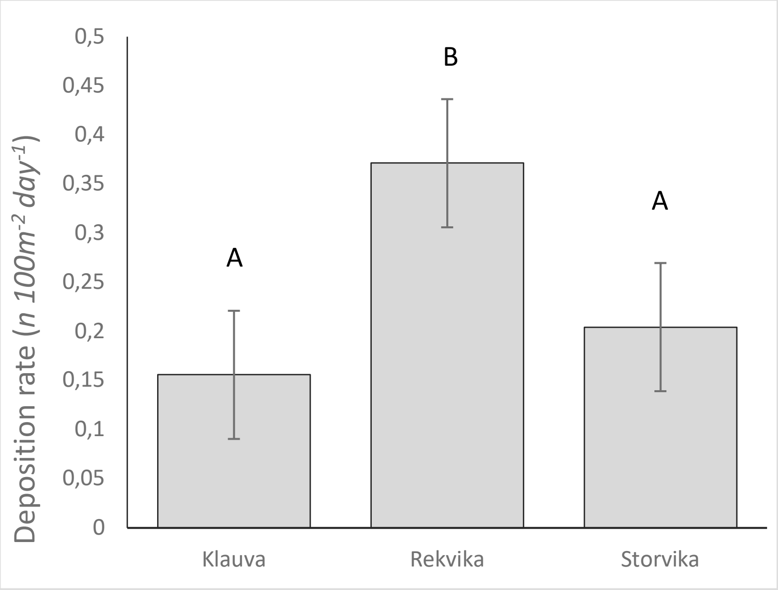

Figure 3. Histogram showing the mean deposition rates on each study site (n 100m-2day-1) (F(2, 35)=6,6219, p=0.0036). Error bars represent 95% confidence intervals. Locations not connected by the same letter are significantly different at alpha = 0.05 (Tukey HSD Post-Hoc test).

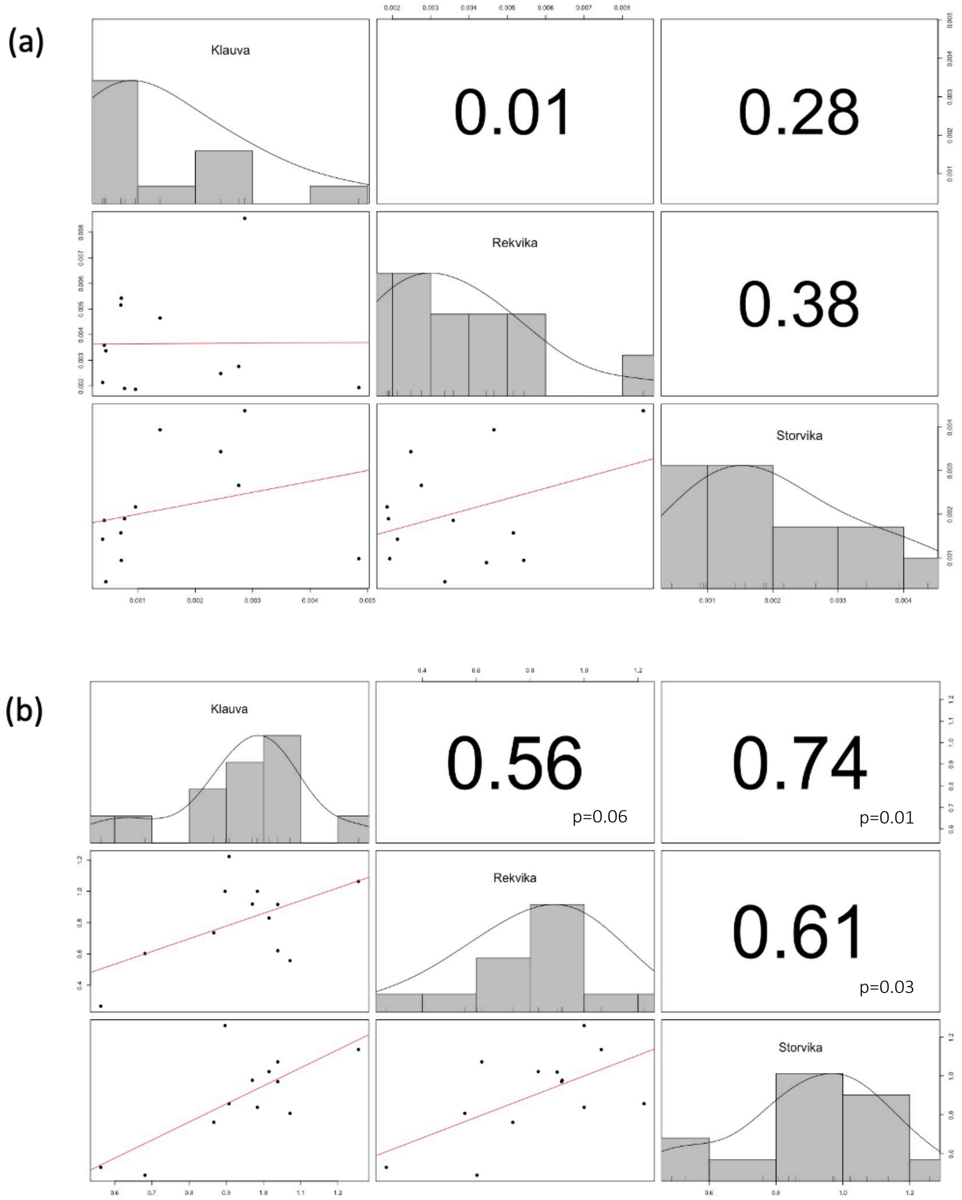

Figure 4. Pair-wise scatterplots showing the temporal correlation among sites in (a) deposition rates (n m^{-2} day^{-1}) and (b) retention (proportion of marked items present on previous sampling recovered during the current sampling). Each data point represents a sampling event standardized to calendar week. Histograms along the diagonals show the frequency distribution of (a) deposition and (b) retention at each site. The values of the Pearson correlation coefficient and their corresponding p-values for each pairing are shown above the diagonals.

A total of 433 objects was marked over the course of the study: 120, 155 and 158 in Klauva, Rekvika and Storvika, respectively. Following the initial cohort of approx. 60 items per site (see Methods; Table 1) a running cohort of 106 objects (20, 46 and 40 in Klauva, Storvika and Rekvika, respectively) were marked as they were deposited through the study until 100 items were marked in total (insufficient deposition to reach 100 in

Klauva). Additionally, as 76% of items in Rekvika and 47% in Storvika got lost from between samplings in week 38 and 40, 50 new items were marked to replace them at each site during week 44. Because of logistical and safety limitations primarily related to weather events, the sampling interval ranged from 11-18 days (mean = 14 +/- 0.46), with the exception of one missing sampling in Klauva. A clean-up was accidentally started at Klauva by a local actor (MARINENVIRON) and the site was subsequently not sampled on Sept. 17th (week 38). The clean-up was discovered and aborted prior to completion, so some marked litter was left uninterrupted (n=43); all removed litter was recovered and marked items given a new ID and haphazardly replaced on the beach (n=35). However, this interruption meant the cohort of objects with the potential to remain on the beach long-term was reduced. A small amount of marked litter (n=12, 2% of total) was at different times accidentally removed from the sites during sampling. In such instances, each object was given a new ID and replaced on the beach at new positions later in the study. Because of issues with the equipment, coordinates could not be recorded at all sites in week 42 and at Klauva in week 28.

Most marked litter (n= 261, 60%) was (eventually) lost and never recovered (Figure 5a). A quarter of the marked items were temporarily lost but later recovered (n=115, 26%). Most of these items (56%) failed to be located for a single sampling event and were recovered during the subsequent one and may thus simply have been missed rather than truly lost (*i.e.,* sampling error). This occurred in equal frequency across all sites (X^2_6=2.17, p = .90). The remaining 41% of temporarily lost items were lost for multiple consecutive sampling events (range = 4-22 weeks, mean = 7 weeks +/- 1.32). These items were presumed to have either been buried and exhumed or resuspended and later redeposited on the same beach. This generally happened once during study period (81% of temporarily lost objects) but did occur repeatedly (up to 4 times) for some objects.

Two-thirds of marked objects (64%) had less than 1 m as its maximum displacement between sightings, although some moved as far as 80 m (Figure 5b). Items which moved more than 3.73 m were classified as outliers based on being greater than 1.5 times the interquartile range (Walfish, 2006), and accounted for 15% of marked items. The proportion of items showing substantial displacement (*i.e.,* the outliers) varied among sites (X^2_1 = 20.40, p <.00001) with largest proportion occurring in Storvika (61%), followed by Rekvika (27%) and rarely in Klauva (11%).Of the 63 outliers, 23 were temporarily lost for an extended period and all but one showed substantial displacement upon recovery. There was a significant association beween whether objects were temorarily lost for an extended period and whether they showed substantial displacement ($X^2_1 = 41.94$, $p < 0.00001$). Of the marked items which remained reasonbly stationary whilst beached (*i.e.,* moved <3.73 m), 93% of them were consistently recovered until permanently lost (Table 2). Contrastingly, this was the case for only 63% of items showing substantial displacement, of which 37% of objects were temporarily lost and later reappeared. Of the objects which were temporarily lost for an extended period of time, 51% showed substantial diplacement upon recovery (Figure 5c). In comparison, only 12% of of objects consistently recovered (*i.e.,* not temporarily lost) showed substantial displacement between sampling events. Objects temporarily lost and recovered without substantial displacement were assumed to have been buried and exhumed, while it was assumed that there is a high probability that objects recovered a susbtantial distance from where they were last seen had been resuspended and subsequently redeposited on the same beach.

Table 2. Contingency table showing the relationship between marked litter that went missing or not, and whether they showed substantial displacement or not (X21 = 41.94, p <0.00001).

	Gone missing	**Stationary**	**Sum**
The distribution of marked litter that went missing or stayed statinary at site within the group of litter that showed substantial displacement.			
Showed substantial displacement	37%	63%	1
No substantial displacement	7%	93%	1

The distribution of marked litter that showed substantial displacement or not among the objects that went missing, and for those that did not ('stationary').			
Showed substantial displacement	51%	12%	
No substantial displacement	49%	88%	
Sum	1	1	

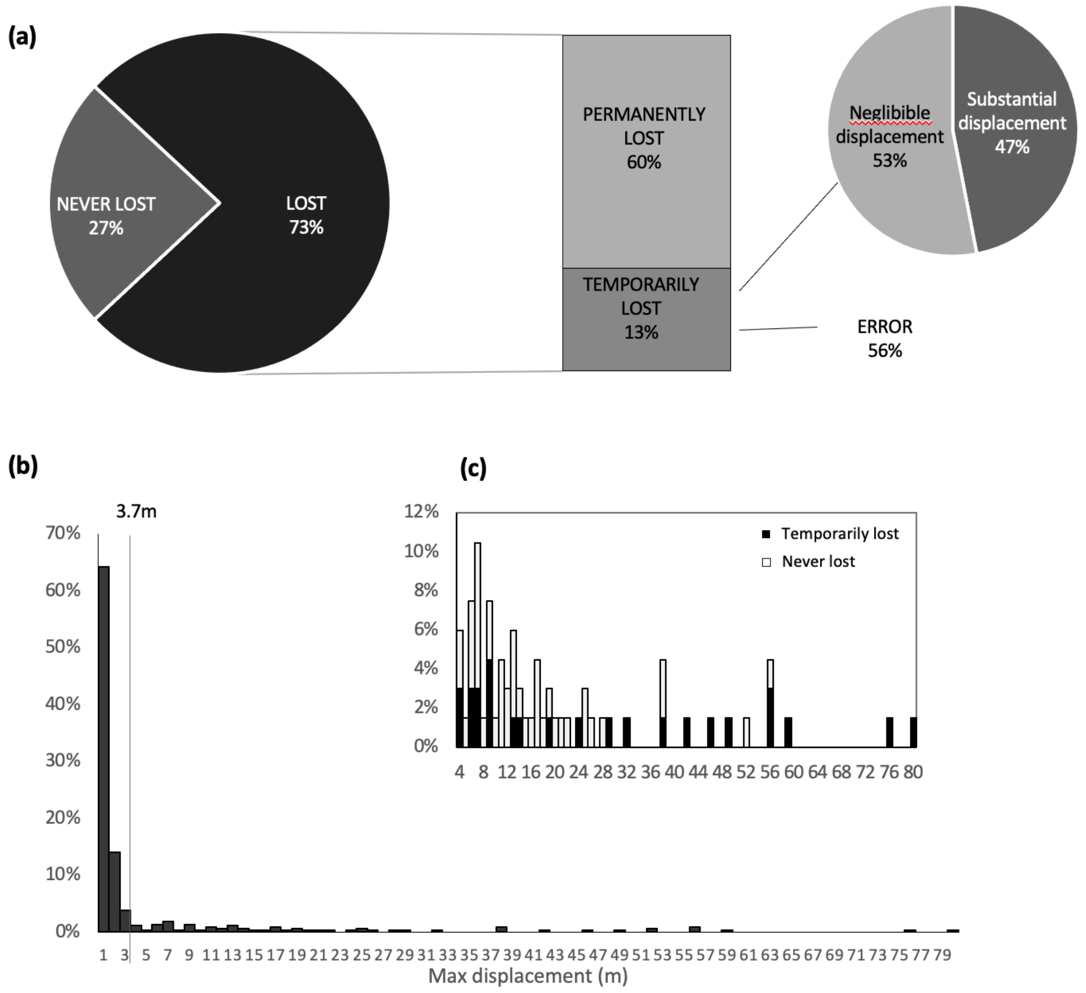

Figure 5.The fate of marked objects: (a) Breakdown of objects remaining on the beach at the end of the study (i.e., never lost, right censored data) vs. those that were lost (went missing), followed by a breakdown of the duration for which objects were lost. Objects that were lost for a single sampling event were considered as sampling error (56% of the temporarily lost objects). Objects that were lost for a minimum of two sampling periods (i.e., 4 weeks) and later got recovered were designated as temporarily lost. Permanently lost objects were lost and not recovered by the end of the study. The far-right pie chart shows the relative displacement of temporarily missing objects when they reappeared. (b) Frequency histogram showing the maximum displacement between sightings of objects. The stippled line indicates x1.5 the interquartile range (i.e., beyond which objects were considered outliers);"substantial displacement" in panel a refers to objects which displacement was in the outlier range upon reappearance. The inset graph shows the frequency distribution of displacement among the outliers, separated by whether or not the objects also went temporarily missing between the two sightings of maximum displacement.

Table 3. Quantiles from the parametric Weibull test of retention of marked litter (days until the quantile percentage of items are expected to have been lost).

Site	**.25**	**.5**	**.75**	**.95**	**.99**
Test 1: The temporary disappearance and later recovery of some objects ignored (equivalent to Fig. 6a).					
Klauva	98	160	237	367	468
Storvika	70	115	171	264	337
Rekvika	47	76	113	174	222
Test 2: Temporarily lost objects showing substantial displacement upon recovery considered as two separate objects (assuming resupension and redeposition) (equivalent to Fig. 6b).					
Klauva	69	111	161	245	309
Storvika	63	101	147	223	281
Rekvika	46	73	107	162	205

The time interval until marked objects got lost differed significantly among the three sites (log-rank test: p<.0001) (Figure 6a). Of the parametric models, the Weibull (AIC=1,092) was a better fit than the exponential (AIC=1,177). The Weibull scale parameter was 0.566, indicating that the hazard increases with time. The hazard ratio (i.e., the risk for loss at any time during the study) was nearly four times higher in Rekvika (HR=3.73), and nearly twice as high in Storvika (HR=1.79), when compared to Klauva. The residence time was approximately 53% shorter in Rekvika (event time ratio (ETR) = 0.47), and 28% shorter in Storvika (ETR = 0.72), than in Klauva (Figure 6a). Klauva retained litter better than the two other sites, of which the risk of loss/departure of litter in Rekvika was about four times higher than the risk in Klauva, and almost the double in Storvika. Klauva was estimated a loss half of its composition within 160 days, more than double the time for the same event in Rekvika (76 days), and in Storvika in between (115). Similarly, Klauva was predicted to lose 99% of its litter composition within 468 days, again more than double the time that was predicted in Rekvika (222 days) and after 336 days in Storvika (Table 3). These results changed relatively little in nature if objects temporarily lost for a prolonged period and later recovered at a considerable distance (>3.7 m) from where they were last observed were considered as newly deposited items upon recovery, but the differences among the sites were reduced albeit remained significant (log-rank test: p < .0001) (Figure 6b). The hazard ratio relative to Klauva was reduced to 2.13 for Rekvika and 1.19 for Storvika. Similarly, the estimated residence times of objects in Rekvika and Storvika were reduced to 44% (ETR=0.66) and 10% (ETR=0.91) lower in Revika and Storvika, respectively. The median time in Klauva (111 days) was reduced the most and came close to the median residence time in Storvika (101 days), and the least changes were in Rekvika (73 days). Almost all litter (99%) was expected to be lost within 309 days in Klauva, 281 in Storvika and 205 days in Rekvika (Table 3). Although the residence times among the beaches varied, there was a significant correlation among sites in the percentage of marked items retained from one sampling event to the next throughout the study period (Figure 4b). No items marked on sites were recovered at another during the study.

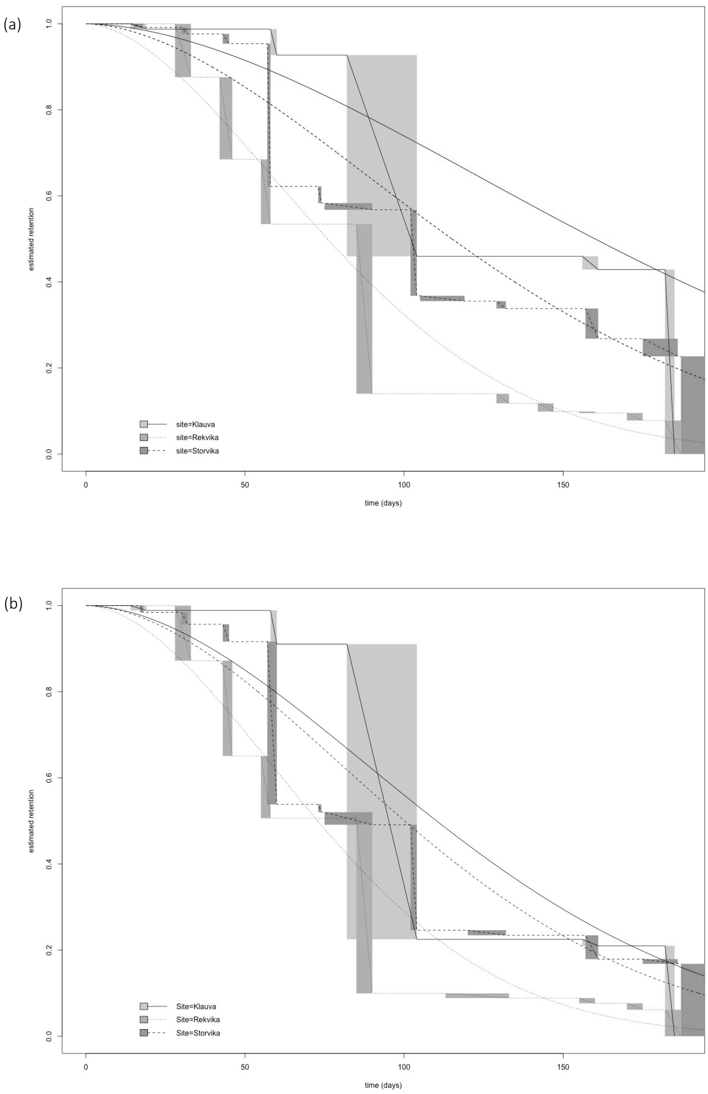

Figure 6. Time-to-event analyses showing residence time at each site. Each plot shows a nonparametric minimum likelihood estimation (NPMLE) fitted to each site, with parametric Weibull regressions overlaid. The shaded areas of the NPMLE plots indicate uncertainty due to interval censoring (i.e., 2-week sampling intervals); the very large interval at Klauva is due to the accidental cleanup action disrupting sampling at the site. The two panels show the results of (a) the raw analysis with no consideration of whether items went temporarily missing during their the period they were beached, and (b) the follow-up analysis in which objects temporarily missing and later recovered a substantial distance from where they were last seen (see Figure 5) where considered as new objects upon their return under the assumption that these had been resuspended and later redeposited. Sites were significantly different in both analyses (p < .0001) indicated by the results of a log-rank test.

3.2 LITTER COMPOSITION

Synthetic polymers (including EPS) dominated the litter deposited during the study (97% of items). However, there was a significant association between site and the relative distributions of the different types of plastic categories ($X^2_{16} = 1199.95$, $p < .00001$). Soft plastics (sheeting, etc.) and synthetic line and cord was less common among deposited litter in Rekvika than in Storvika and Klauva. Contrastingly, EPS was more common in Rekvika than in Storvika or Klauva (Figure 7a).

Most items deposited during the study were small. There was no significant difference in the relative distributions of newly deposited items in different size classes among the three sites ($X^2_6 = 6.27$, $p = .39$), and items <20 cm constituted 72%-74% of deposited items at all three sites (Figure 7b). Items 20-50 cm were the second most common deposited (20-21%) and larger items were relatively rare (Figure 7b). Furthermore, over two-thirds of all deposited items weighed less than 5 g, although here there was an association with site ($X^2_2 = 391.17$, $p = 1.15$) where the proportion was somewhat lower in Rekvika compared to Storvika and Klauva (Figure 7c).

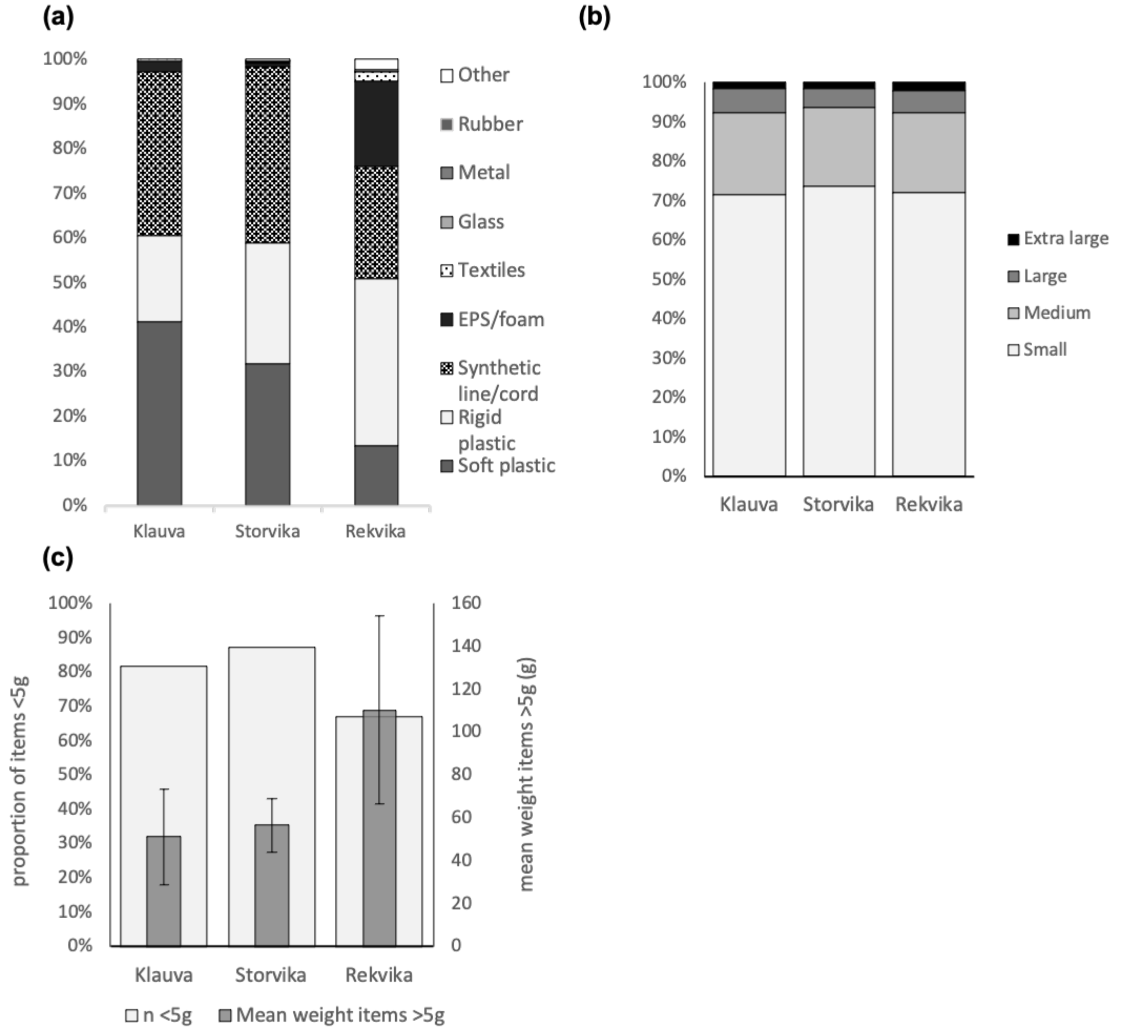

Figure 7. Composition of all deposited litter pooled. Proportions of (a) material type, (b) size categories, (c) weight <5 g and mean weight of items >5g +/- 95% confidence intervals.

The different types of litter deposited during the study varied among sites ($X^2_{16} = 954.27$, $p < 0.00001$). EPS' was the most common classified category in Rekvika (18%) (Figure 8a). Small ropes were the most common in Storvika (30%) and Klauva (28%), and accounted for a sizeable proportion in Rekvika also (16%) (Figure 8a). "Other" litter dominated at all three sites constituting 44% of objects in Rekvika, and 54% in both Storvika and Klauva (Fig. 8a). Pooling all litter within the "other" category (n=3376), fragments of soft and rigid plastics were the most common; sheeting, bio carriers and detonation cords were also common (Figure 8b). There was a significant association among site and the composition of litter within the "other" category ($X^2_{10} = 815.02$, $p < 0.00001$). Unidentifiable fragments in soft plastic were most common in Klauva (51%) and Storvika (41%), compared to a dominance of various intact unidentified objects in Rekvika (50%).

The great occurrence of biocarriers found in Storvika (Figure 2i), and considering they were of enough volume to carry marks, made it relevant for our study to include the item as an exception to the limit of 5 cm set for the study. Storvika furthermore differed from the other two sites in that all biocarriers recorded (n=278) were deposited there, accounting for 15% of all “other” fresh deposits there. These biocarriers were regularly deposited in Storvika and 3-51 fresh deposits were recorded during all but one sampling.

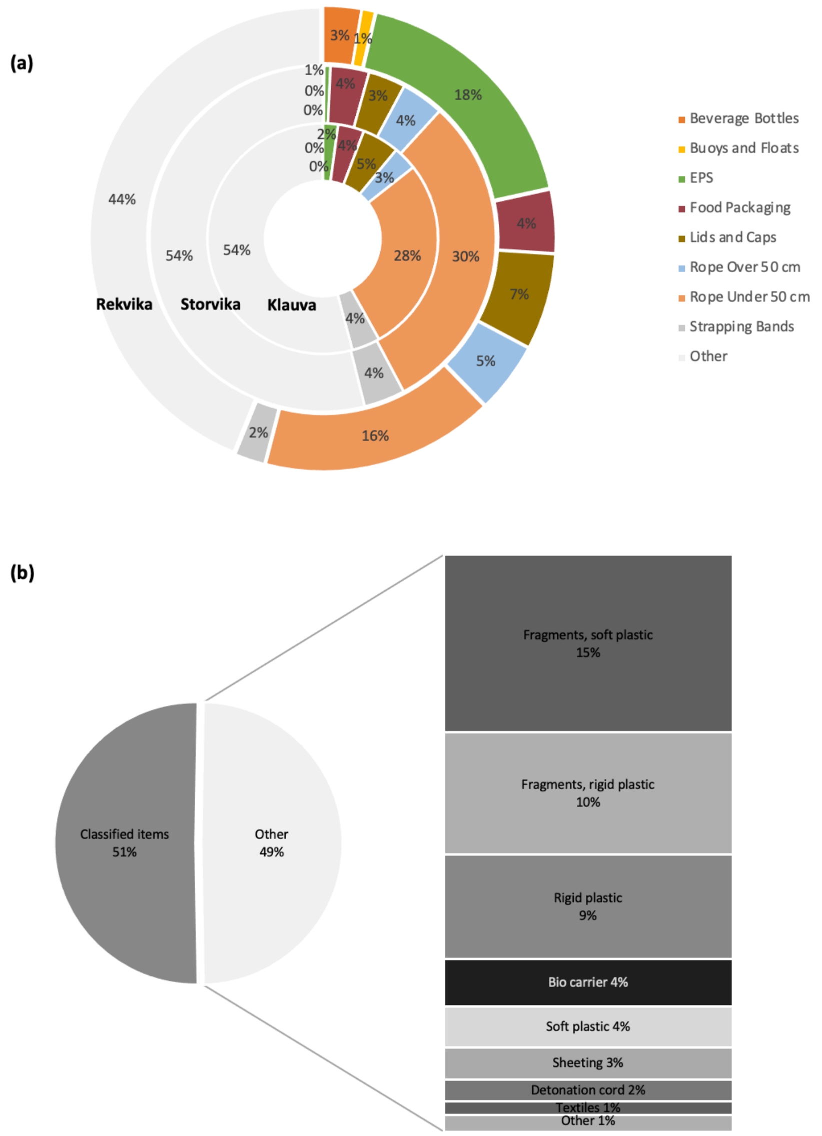

Figure 8. (a) All deposited litter grouped by item category at each study site. (b) The pie chart shows the proportion of classified vs. non-classified litter items among all deposited litter. Common non-classified litter types are presented to the right. Pieces of litter that clearly were fragments of larger objects in soft or rigid plastic, were registered as ‘fragments’. Bio carriers (shown in figure 2(i)) are used in water treatment systems and were frequently found in Storvika.

4. DISCUSSION

4.1 DEPOSITION AND RETENTION OF BEACH LITTER

The accumulation of beach litter in a location over time will depend primarily on two factors: the rate at which new litter is deposited on the beach and the retention time of litter once beached (Hinata and Kataoka, 2016). Additionally, beach cleanups may interrupt these processes. The retention, and inversely the removal, of beached litter encompasses both resuspension (*i.e.,* litter is washed back out to sea), alongshore movements repositioning litter to adjacent locations (Brennan et al., 2018), and burial on site (Williams and Tudor, 2001). The long-term accumulation of litter along the shore will be a function of the equilibrium reached between litter deposition and its residence time. The two processes can either augment each other to accumulate considerable amounts of litter if deposition is high and the litter relatively stationary once beached, or accumulation may be limited by one or both processes. If retention is poor, for example, even a high deposition rate may not lead to significant accumulation. In these cases the turnover (*i.e.* full replacement of existing litter population) would be high (Bowman et al., 1998). The relative dominance of these processes will vary in both space and time. This study clearly demonstrated spatial variation over relatively small spatial scales (Euclidean distance among beaches 6-26 km) in both deposition rates and residence times of beached litter, as well as temporal variability within sites.

On average, around twice as many items (0.37 $n\ day^{-1}\ 100m^{-2}$) were deposited daily per unit area of beach in Rekvika compared to the Storvika and Klauva (0.20 and 0.16 $n\ day^{-1}\ 100m^{-2}$, *respectively*). This is consistent with other studies showing that deposition rates vary among beaches within a region (*e.g.,* Blickley et al., 2016; Chitaka and von Blottnitz, 2019; Lee and Sanders, 2015; Watts et al., 2017). It is challenging, however, to compare results across studies to infer variability over larger spatial scales as both the standardization of area and the sampling frequency varies widely among studies. A number of studies report accumulation rates by linear distance rather than area *(e.g.,* Blickley et al., 2016; Chitaka and von Blottnitz, 2019). Converting this study's results to linear units based on the coastline length of each site results in deposition rate estimates of 9-16 n day^{-1} $100m^{-1}$, which is comparable to, and slightly higher than, estimates from Hawaii within the North Pacific Central gyre based on monthly sampling (site means of

1-7 n day^{-1} 100m^{-1}) (Blickley et al., 2016). It is, however, considerably lower than deposition rates reported following daily sampling of South African beaches (site means of 40-3,000 n day^{-1} 100m^{-1}) (Chitaka and von Blottnitz, 2019). However, varying sampling intervals pose a substantial challenge for comparing estimated daily accumulation rates (*i.e.,* deposition) among studies as it is known to vary negatively with sampling interval (Eriksson et al., 2013; Ryan et al., 2014; Smith and Markic, 2013), presumably due to the loss of beached litter over time. As both deposition and retention are continuous processes, estimated daily deposition rates are confounded with retention time for the majority of studies unless sampled daily, and this confound increases with increasing sampling interval (Eriksson et al., 2013; Ryan et al., 2014; Smith and Markic, 2013). Consequently, it is not currently possible to compare studies to assess large-scale spatial variation in litter deposition rates. Note also that the deposition rates recorded in this study were in fact the product of deposition and item retention (*i.e.,* accumulation) over two-week periods rather than pure deposition. Consequently, the difference in deposition rates of litter between Rekvika and the other two sites was probably even greater than recorded as it also had the lowest retention time.

Litter retention also varied considerably among the three sites with the hazard nearly four times greater, and the expected residence time half the length, in Rekvika compared to Klauva. This small-scale variation in retention is in contrast to the results of a mark-recapture study on the Caribbean coast of Panama which reported similar residence times among four sites within a larger study area (max. distance between sites approx. 50 km) (Garrity and Levings, 1993). Kataoka et al. (2013) estimated a mean residence time of 209 days on a Japanese beach, and also estimated a mean residence time of 104 days for the four Caribbean sites surveyed by Garrity and Levings (1993). The estimated median residence time for Rekvika (76 days) was considerably shorter than both these estimates. The estimated median residence time for litter in Klauva (160 days), which clearly showed the greatest retention of the three sites, was also considerably shorter than the average 209 days estimated by Kataoka et al. (2013). Contrastingly, the estimated 99% quantiles suggest maximum residence times of approximately 7-16 months in Lofoten, which is comparable to the maximum retention of 9-15 months reported by Garrity and Levings (1993). This suggests that while the general turnover in Lofoten may be relatively fast compared to some regions, the maximum retention is more comparable. However, retention is, as deposition, challenging to compare among studies due to different types and sizes of items being marked, varying site sizes and delineations (e.g., transects vs. entire beaches), different study durations and sampling intervals and, varying analytical approaches (e.g., Garrity and Levings, 1993; Kataoka et al., 2013; Williams and Tudor, 2001; Bowman et al., 1998; Brennan et al., 2018).

In addition to departing the beach through resuspension (or burial), litter may also be displaced through lateral (or vertical) movements on the shore (e.g., Johnson, 1989; Johnson and Eiler, 1999; Kataoka et al., 2015). Kataoka et al. (2015) concluded that lateral movements, or diffusion, played a significant role in the accumulation dynamics of litter on their study site as it would consistently move north along the beach before concentrating in a convergence zone prior to resuspension by nearshore currents. However, most (64%) of the marked objects in this study moved less than 1 m between sightings (Figure 5), suggesting that diffusion of beached litter plays a relatively small role in its distribution on the beaches studied. Nevertheless, several objects did move considerably among sightings, some as far as 80 m, and the prevalence of these events varied among the sites. Varying degrees of movement among sites is consistent with differing observations on adjacent beaches in Alaska (Johnson, 1989; Johnson and Eiler, 1999). The most movement was observed in Storvika, which as the widest bay also held the greatest potential of lateral movement without leaving the defined study area, but also for alongshore movements in general. Klauva is a very small site, which limits the movement which could be detected. However, with its defined rock walls, any considerable movement of litter in Klauva would naturally be limited to perpendicular to shore unless very close to the water’s edge. In both Klauva and Rekvika, boulders or crevices may form natural litter traps in the terrain, thus limiting movement; such features were rare in Storvika.

A number of marked objects went missing to be recovered at a later date. Objects which failed to be recovered for a single sampling events were assumed to be the result of sampling error. However, objects missing for longer periods of time were assumed to have either been buried or resuspended. If the missing object reappeared in close proximity to where it was last seen, it was assumed to have been buried in the substrate, wrack or vegetation (e.g. Brennan et al., 2018; Johnson and Eiler, 1999) and exhumed upon reappearance (Williams and Tudor, 2001). Heavy vegetation (mostly tall grasses) covered large parts of Storvika and Klauva during the summer, which may have hidden objects. In addition, exhumation may have contributed to deposition at the sites. For example, during the initial cleanup, the great prevalence of EPS at Rekvika made it impossible to remove it all as great amounts was trapped under large boulders and hard to reach. EPS was also the most commonly deposited litter in Rekvika, which may have been driven partially by exhumation. Contrastingly, when objects vanished and later reappeared a substantial distance from where they were last seen it is reasonable to assume that these were resuspended, remained floating in nearby waters and been redeposited; litter mixed in with floating wrack was particularly common in Rekvika and Klauva, with single objects observed floating off Storvika. Making this assumption resulted in a smaller magnitude of differences in the time-to-event analyses among sites, suggesting more even turnover among the sites.

How the processes of deposition and retention interact will determine how rapidly litter accumulates on a beach, and also the accumulation potential over time. If both deposition and retention are high, a beach is expected to continue to accumulate litter indefinitely. However, if deposition is high but retention is low, the two processes are likely to balance each other and reach an equilibrium which limits accumulation; these are sites with high turnover rates (e.g., Blickley et al., 2016; Bowman et al., 1998; Smith and Markic, 2013). Rekvika is likely an example of such a scenario. If both deposition and retention are low, limited amounts of litter are likely to accumulate even over prolonged periods of time. Locations with low deposition but high retention may continue to accumulate litter indefinitely, but gains will be slow. Klauva is likely such a case. The site is known to accumulate beach litter as it was the most densely polluted location of 27 sites surveyed in the Lofoten archipelago in 2017 (Haarr et al., 2019), yet deposition rates were not particularly high at the site. Consequently, the very high density of litter reported by Haarr et al. (2019) was most likely the result of slow accumulation over a very long period facilitated by the long residence time of litter once deposited.

Irrespective of the dominant balance between deposition and retention at a site, this relationship undoubtedly varies over time and extreme events may have significant impacts on accumulation. For example, the extremely high litter density reported in Klauva by Haarr et al. (2019) may have been the result not only of slow accumulation over a long period of time, but also of an extreme depositional event (Bastesen et al., 2021; Falk-Andersson et al., 2020; Gündoğdu et al., 2018; Murray et al., 2018). Similarly, the significant accumulation of litter on a site where both deposition and retention are high may be reset by a cleanup action or storm surge washing litter out to sea. All three sites retained more than 92% marked litter during the first month, but over the same two weeks during fall, Storvika and Rekvika lost 47% and 76%, respectively, of the total of objects marked at site at the time. It illustrates that though deposition rates can sometimes be very high, a great sudden loss of litter on beaches can occur. The likelihood and prevalence of extreme events may vary over time and thus affect the hazard function of beached litter. Kataoka et al. (2013) fitted exponential time-to-event models to their own and Garrity and Levings (1993) data, indicating a constant hazard function where the probability of being removed from the beach is independent of the time an object has been beached. This study, however, found a Weibull model to be a better fit, indicating that the hazard increases the longer an object has been beached. This could be related to seasonal changes throughout the study and the increased prevalence of storm events in the fall. Seasonal variation in litter deposition and retention have been demonstrated in other studies (Bowman et al., 1998; Brennan et al., 2018; Garrity and Levings, 1993). More movement of litter out of study sites during dry season was documented by Garrity and Levings (1993), which they hypothezised was caused by differences in forces like high onshore winds, less rain and heavy waves. This is similar to the findings by Bowman et al. (1998) that found cleaner beaches during winter storms, suggested to be a result of waves washing litter off the beaches.

4.1 THE SCALE OF FACTORS INFLUENCING ACCUMULATION

The spatiotemporal variation in deposition and retention, and thus accumulation, of beach litter may be driven by a variety of factors, such as beach morphology and gradient, weather, and season. These factors furthermore operate over different scales, thus potentially driving both variability and similarities among and within sites over time. Factors with highly localized impacts on beach litter accumulation include substrate and gradient (Brennan et al., 2018; Haarr et al., 2019). In contrast, factors such as weather and tides impact beach litter dynamics on a larger scale (although the magnitude of these impacts may vary locally).

Small-scale spatial variability in deposition is at least partially independent of physical site characteristics as (1) the smallest site consisting of a narrow cove and gully (Klauva) did not differ significantly from the largest and most open site (Storvika), and (2) all three sites lie on the same inner shore of the archipelago and face a similar direction (south-southeast to southwest) making them all prone to common southern and southwesterly fall and winter storms (although fetch and wave exposure almost certainly varies among them). Nevertheless, some of the observed differences in deposition and retention may be related to the physical characteristics of each site. Wave energy typically correlates positively with grain size (Oak, 1984); thus wave energy (and disturbance) is expected to be greater in Rekvika (cobbles and boulders) than at the other two sites (cobbles, pebbles and vegetation). High wave energy, wind speed and tidal heights generally increase deposition (Blickley et al., 2016; Eriksson et al., 2013; Johnson and Eiler, 1999; Williams and Tudor, 2001). High wave energy can also reduce retention (Garrity and Levings, 1993; Williams and Tudor, 2001), potentially explaining the low retention in Rekvika. The steep hill consisting of large boulders at the backshore could also function as a litter trap as objects smaller than the substate grain size are readily buried (Williams and Tudor, 2001), leading to an apparent reduction in retention even though objects are still technically retained on site (Bowman et al., 1998; Brennan et al., 2018). Interestingly, there are some striking similarities between Rekvika (lowest retention) and Klauva (highest retention). Both coves have considerable fetch in their facing direction and thus have potential for similar high exposure, and both are shaped in such a way that there is only one direction of entry and exit, creating a funnel; the primary difference is in size (Klauva is smaller). Furthermore, Klauva is shaped as a gully with steep cliffs on each sides, which may create a wind shadow and shield litter from being moved by wind, and increasing retention (Brennan et al. 2018; Critchell and Lambrechts, 2016). However, a storm surge could potentially bring a lot of water through the gully and wash litter back to sea (Brennan et al., 2018; Garrity and Levings, 1993). Storvika (medium retention) has relatively low fetch compared to the other sites, but lies in a strait assumed to have strong tidal currents (Moe et al., 2002), which may impact litter dynamics (van Sebille et al., 2020). Tides can contribute to higher deposition above the intertidal area (i.e., the lower part of beach that is under water during high tide), but even higher tides can remove litter back to sea (Blickley et al., 2016). Litter characteristics may also impact retention. The low density of EPS, for example, makes more susceptible to wind than higher density objects (Schwarz et al., 2019), which may negatively impact its retention (Kataoka et al., 2013) and its prevalence in Rekvika may partially account for the low retention at the site.

The relative magnitude of deposition rates and retention time among sites clearly suggests a degree of highly local influences on both metrics. However, there were among-sites correlations in the retention of marked objects from one sampling event to the next. In other words, despite differences in magnitude, the timing of periods with relatively high or low retention within a site would coincide across sites. This is consistent with the results of Garrity and Levings (1993) from the Caribbean and suggests that variability in one or more common factor(s) have a considerable impact on litter retention across sites within a region. Tides and weather patterns are likely candidates for such factors. All three sites face a similar direction and are roughly affected by the same weather patterns (*e.g.,* southwesterly fall storms). While the strength and impact of tides and weather events may vary among sites, as the magnitude of litter retention does, the timing of events will coincide regionally. Strong tidal currents and heights have been shown to reduce litter retention (Blickley et al., 2016; Dixon and Cooke, 1977), and storm surges causing wave action abnormally high on the beach are likely to have the same effect. During the study period, particularly one storm resulted in a great loss of litter among the sites, and new litter was required on two of the sites. However, the timing of the events appears governed by more local factors for deposition and more regional factors for retention.

Contrastingly, litter deposition appears to be primarily influenced at a highly local level because (1) there were no significant correlations in timing among sampling sites (i.e., time periods of high and low deposition did not coincide among sites), and (2) there were differences in the composition of litter arriving at each site. Litter availability is a likely factor and could be governed by current patterns transporting and concentrating litter to varying degrees close to each site, or by highly local sources and release points of litter (Haarr et al., 2020; Halsband and Herzke, 2019). A certain type of black bio carrier (2,5 cm in diameter, equivalent to these: https://www.cleantechaqua.com/en/biological-method-mbbr/) (fig. 2i) were prevalent in Storvika and found as fresh deposits there on all but one sampling event (mean = 21 new bio carriers biweekly, total deposits = 277). However, apart from a single one in Rekvika, these bio carriers did not occur at the other two sites. This clearly suggests a highly local source of bio carriers in Storvika, and the water purification system of a small aquaculture facility located approximately 6 km away from the site (Leiknes and Ødegaard, 2007) is a likely candidate. Similarly, EPS was common only in Rekvika. The use of EPS is common in a variety of both land-based and marine activities, making it difficult to source. However, general deposition and accumulation patterns tend to increase with decreasing distance to urban areas (Barnes et al., 2009; Garrity and Levings, 1993; Ryan, 2020) and its prevalence in Rekvika may be partly explained by its proximity to the Svolvær town center with its ports, fish reception facilities and land-based construction activities. Rekvika also stood apart from the other two sites in terms of greater diversity in litter characteristics, which may also reflect a greater diversity of local sources given its proximity to a population center.

The disappearance and reappearance of litter items on the same site but on a new location within it suggests that local current patterns may also play an important role in litter availability and thus also deposition. During the study, litter that was temporarily gone were so for periods from 1 to 5.5 months before returning. While the disappearance and reappearance of litter objects through burial and exhumation has been documented in other studies (Johnson, 1989; Williams and Tudor, 2001), this explanation for the reappearance of objects is less likely when the object does not reappear in roughly the same location. The litter that was gone for the longest period can illustrate that litter does not necessarily move far away from the original beach even if it disappears from study site. Litter (new and marked litter we could recognize) was observed floating close to shore at high tide at all sites. At two of the sites, Klauva and Rekvika, great amounts (more than 20 items) were observed floating in wrack patches, approaching the beach on rising tides. Single litter objects observed floating were also common in Storvika, and the majority of objects which disappeared and reappeared with considerable displacement did so at this site. This may be a study design construct given it was also the largest site with the greatest potential for observing considerable movement, but Storvika is also situated on a strong tidal current as water passes through the strait between the islands of Gimsøy and Vestvågøy betwen the Vest Fjord and the Norwegian sea (Mitchelson-Jacob and Sundby, 2001) which could slosh litter back and forth in the vicinity.

Despite an overall local influence on deposition rates, likely related to litter availability in nearby waters, there is also evidence to suggest that certain types of events or conditions can have regional impacts on it as well as on litter retention. Though there was no general correlation among periods of high and low deposition among the sites, the peak deposition event at each site did occur during the same two-week period. During this period (Sept. 17th – Oct. 2nd) there was a severe storm event with max wind gusts of 125 km/h (data retrieved from the Norwegian Meterological Institute's online portal: seklima.met.no). Interestingly, this also coincided with the minimum recorded retention and left two of the sites (Storvika and Rekvika) with <30% of their marked objects remaining. Consequently, all three sites lost a lot of litter during the same two-week period they also received a lot of new litter, indicating a simultaneous exchange of the litter composition (i.e., turn-over). However, there were other severe fall storms as well, but without the same unified response across sites, highlighting our continued need to better understand how weather patterns influence beach litter dynamics.

CONCLUSIONS

This study documented small-scale spatial variation in deposition rates and residence times of beached litter among three sites within a relatively small radius (approx. 13 km) in the Lofoten Archipelago, northern Norway. Fresh litter was routinely recovered at all sites during biweekly sampling, particularly in Rekvika which differed significantly from the other two sites. The residence time of beached litter varied significantly among all three. Based on temporal correlations, or lack thereof, among high and low deposition and retention events, it appears as though the deposition of beach litter is governed at least in part by local factors (e.g., litter availability), while the retention and residence time of litter once beached appears more heavily influenced by regional factors (e.g, weather pattens).

The prevalence of unclassified litter (*i.e.,* the item category “other”) suggests that the proportion of cleaned beach litter counted and registered by volunteers in Clean Up Lofoten (Haarr et al. 2020) is considerably lower than perhaps assumed. Haarr et al. (2020) concluded that 75-80% of registered litter in Lofoten consisted of only eight items, and which constitute the item categories used in this study. Given that unclassified litter constituted 44% - 54% of deposited litter and 30% - 72% of litter removed during the initial cleanup and site preparations, these eight items seem to be less dominant than thought based on citizen science data from the region. Plastic fragments in particular were highly common.

Further research into the impacts of weather and tidal patterns on deposition and retention would greatly enhance our understanding of spatial and temporal variation in beach litter dynamics. The accuracy of the assumption that temporarily lost litter later recovered in a different location on the beach has been resuspended and redeposited should also be verified as it has considerable ramifications for the study of litter circulation and transport patterns. Similarly, the importance of highly local sources and their general importance should be further investigated. The study’s findings provide further evidence that the regular removal of litter on beaches with high turnover will remove more litter from the local marine environment than beaches that accumulate more over time, highlighting the importance of being better able to identify these beaches as accumulation (i.e., standing stock) alone is not necessarily an adequate predictor.

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"Deposition and retention of litter varies among beaches in the Lofoten Archipelago"

Appendices

Appendix: Composition of litter during the initial cleanup May/June 2020