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Plastic litter from shotgun ammunition on Danish coastlines — Amounts and provenance☆

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ABSTRACT

Plastic litter in the marine environment is a major global issue. Discarded plastic shotgun ammunition shells and discharged wads are an unwelcome addition and feature among the top ten litter items found on reference beaches in Denmark.

To understand this problem, its scale and origins, collections were made by volunteers along Danish coastal shorelines. In all 3669 plastic ammunition items were collected at 68 sites along 44.6 km of shoreline. The collected items were scored for characteristic variables such as gauge and length, shot type, and the legibility of text, the erosion, and the presence of metallic components. Scores for characteristics were related to the site, area, and season and possible influences discussed.

The prevalence of collected plastic shotgun litter ranges from zero to 41 items per 100 m with an average of 3.7 items per 100 m. Most ammunition litter on Danish coasts originates from hunting on Danish coastal waterbodies, but a small amount may come from further afield. North Sea coasts are the most distinctive suggesting the possible contribution of long distance drift as well as the likelihood that such litter can persist in marine habitats for decades.

The pathway from initial discard to eventual wash-up and collection depends on the physical properties of plastic components, marine tides and currents, coastal topography and shoreline vegetation.

Judging from the disintegration of the cartridge and the wear and decomposition of components, we conclude that there is a substantial supply of polluting plastic ammunition materials that has and will accumulate. These plastic items pose a hazard to marine ecosystems and wash up on coasts for many years to come. We recommend that responsible managers, hunters and ammunition manufacturers will take action now to reduce the problem and, thereby, protect ecosystems, wildlife and the sustainability of hunting.

1. Introduction

Marine pollution by plastic litter is a major global environmental issue. Macro plastic items are a cosmetic and aesthetic problem that causes serious harm to marine animals that try to eat them (Lusher et al. 2013; Wilcox et al. 2015) or which become entangled by them (Laist 1997). Micro plastic particles or beads created by the decomposition of macro plastic items are ingested by small animals and filter-feeders, then accumulate up food chains and create hazards for ecosystems, other wildlife and human health. The issue is more thoroughly described in Derraik 2002, Thevenon et al. 2014, UNEP 2016, and Lamb et al. 2018.

Shotgun ammunition cartridges used for hunting are an additional unwelcome source of plastic litter in the marine environment. Empty cartridge shells cases (in the following called shells) may not be picked up by the hunter who fired them, or they may be irretrievably ejected into the sea on firing and not recovered. Plastic wads that serve to separate the propellant from the shot load, are invariably lost down-range when a shot is fired. Uncollected plastic shells and wads are distinct but avoidable sources of macro plastic pollution that in the later stages of decomposition break down into harmful micro plastic particles or beads (Andrady 2011).

Hunting in modern society is a valued recreational activity that benefits from broadly favorable but not uncritical political and public perceptions. Any avoidable negative impact on the natural

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environment, ecosystems and human health, risks undermining the perception of hunting and threatens its long-term sustainability.

Denmark's widespread coastal habitats located centrally on the Western European migratory bird flyway support a long-established tradition of waterbird hunting. The hunting takes place on open waterbodies from specially designed small boats as well as from adjacent private and state lands. Residents in Denmark enjoy a free right to hunt on such open salt and brackish waters known as the "the fishery territory". The total annual harvest of waterbirds in Denmark is approximately 800,000 (Christensen et al. 2017). Some 150,000[1] of these are taken during the free hunting on coastal salt and brackish water bodies. Based on the annual harvest and an estimated number of cartridges fired per bagged bird (estimated here at four[2]) we estimate a total annual discharge of some 600,000 cartridges while hunting in Danish coastal salt and brackish water bodies.

Denmark banned the use of lead shot for all hunting in coastal ecosystems in 1993, and steel shot is now the commonly preferred alternative.

A shotgun cartridge consists of a plastic cartridge shell containing the powder and the shot load. The cartridge's brand name and some specification details (cartridge type, gauge, shot size and shot type if not lead) are usually printed on the shell. When lost to the environment and subjected to abrasion the printed information becomes increasingly illegible and disappears over time. Cartridges that have lost all such marking cannot be identified and the only recordable indicator is its gauge and length. In some instances head marks may be stamped on the shell. The cartridge shell has a metallic base, commonly known as "the brass" which is, notwithstanding, mostly made from iron. A metallic primer is situated at the centre of the brass's baseplate. The gradual loss of printing and metal features provides clues to the length of time a cartridge shell has been subjected to abrasion and wear. The powder and shot are separated by a wad (also known as a shot cup). Wads come in different designs but they are insufficiently distinctive to enable them to be linked to a brand or type of cartridge. Wads have no labelling. Their gauge can however be recorded and the wad construction is indicative of the shot material used.

The predominant plastic material used for production of shells and wads used for hunting in wetlands is low density polyethylene (LDPE). This may show signs of abrasion but takes long time to break down completely. The shell plastic is colored, mostly black, red, blue or green, but colors cannot be used for identification. Wads are usually white/greyish.

Responsible hunters in normal circumstances take care to collect heir empty cartridges after shooting and later discard them. However, empty cartridges may sometimes be lost into the environment. The use of semiautomatic and pump action guns may accentuate this loss. The wads are invariably dispersed with the shot load and lost.

Systematic analysis of the plastic litter from hunting ammunition collected by volunteers in coastal habitats sheds light on its scale and provenance, and can help inform programs to counteract further dispersal. It may also contribute to wider understanding of movements and turnover of other plastic waste in marine habitats and ecosystems.

The principal objective of this study is to evaluate the amount and provenance of plastic waste from hunting ammunition washing up on Danish beaches. For this, we use litter characteristics (*inter alia* quantity, shot type, and wear) and relate this to site and season. We analyse possible movements of the litter types, and, finally, present some management perspectives for reduction of this pollution.

2. Materials and methods

2.1. Collection and registration of litter

From 2010 to 2017, volunteers associated with the Danish Nature Protection Society, as well as local clubs and individuals, collected shotgun ammunition litter from 68 sites along 44.9 km of Danish coastline. From 2010 to 2014 the collection was limited to two stretches of coast in the East Kattegat (Begtrup Bay and Ebeltoft Bay). In 2015 the collection was extended to 66 additional sites (Fig. 1). Based on the adjacent waterbodies we grouped each site as belonging to one of six areas with at least three collections within each area, except one with only one site (Roskilde).

For each collection, wads and shells found were retrieved and in most cases collection date, collector's name, site name, stretch length, and total number of plastic items in each batch was recorded. Items were registered individually and the following data, so far as possible, were recorded:

Shells: their gauge, brand, type, other text (labelling), text wear index (TW) (group 1 to 5, see caption Fig. 3), brass erosion index (BE) (group 1 to 5, see caption Fig. 3), presence of plastic bottom, and presence of primer. If possible, cartridges were categorised as "steel shot", "lead shot", "bismuth" or "unknown" depending on printed text, if present, or other indicative characteristics.

Wads: their gauge and design for use with "steel shot" or "lead shot" based on three distinguishing characteristics: volume of the shot cup, the construction and splitting of the cup wall, and design of the buffer forming the wad base. Remains of rusty pellets embedded in the wad cup base could also sometimes confirm a steel shot categorisation. Wads for bismuth or other soft shot types are the same as wads for lead shot, but due to *inter alia* price we expect that the use of bismuth for coastal hunting is negligible.

One single project staff (leading author Niels Kanstrup) carried out all registrations and categorisations centrally.

2.2. Metrics of litter samples and cartridge

The weight and volume of samples of empty cartridge shells and wads was measured, and mean weights and specific gravity calculated. In addition, the weight of components (shell plastic, shell metal, wad plastic, powder, and shot) of unfired standard cartridges was measured.

[1] The Danish waterbird wing survey programme was used to make this estimation after consultation with Aarhus University, Bioscience, Kalø. This programme suggests that some 10% of the dabbling duck and goose harvest is taken under hunting forms that relate to the free hunting right at sea. To this, we added the total harvest of all diving ducks and coot. On this background we suggest an overall estimation of 150,000 birds taken annually under the regime of the free hunting right on the Danish fishery territory.

[2] Noer et al. 1998 found for Danish duck hunters an average cartridge consumption at 3.6 per bagged duck (total 240 shots fired). The same study found for Eider Duck hunting a cartridge consumption at 2.5 per bagged bird (total 141 shots fired). However, this did not include shots to kill wounded birds. Noer et al. 2001 found for two groups of Danish duck hunters (dusk hunting) a cartridge consumption at 2.63 resp. 4.05 per harvested bird (total 390 shots fired). For goose hunting in Denmark the study referred to much higher levels of cartridge consumption, up to 8.0 (1996 estimates) and 8.7 (1997 estimates) depending on hunting form (shooting crossing birds or decoying). On this background and based on common practical experience we suggest a level of 4 shots per harvested birds as an average of the many different hunting forms that relate to the free hunting right on the Danish fishery territory.

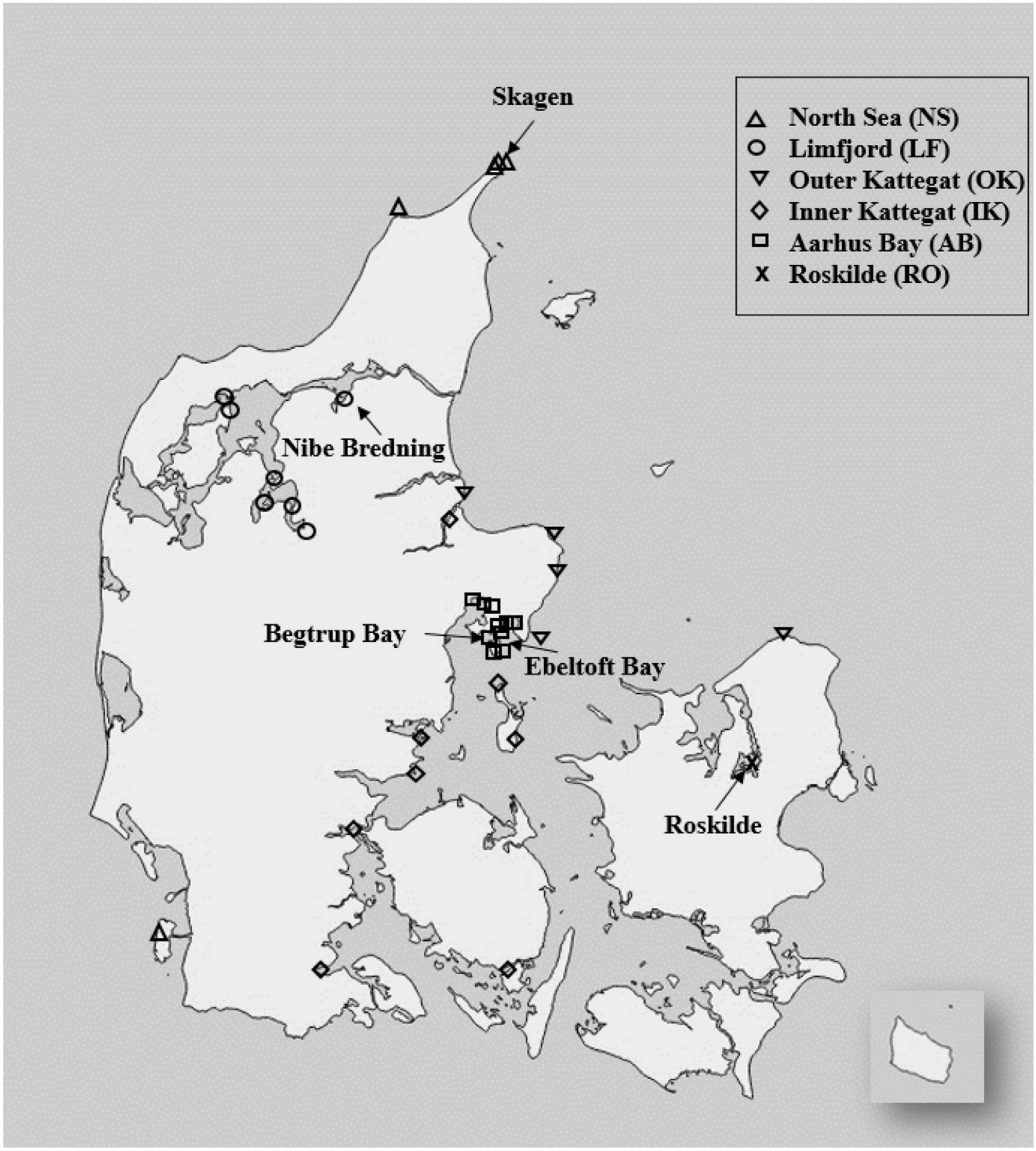

Fig. 1. Collection sites. Sites were organised in six different "areas" marked with symbols. Names with arrows refer to sites mentioned in the text.

2.3. Controlled wear and corrosion experiment

To assess the rates of wear of text and corrosion of the brass a sample of 10 empty steel shot cartridges were suspended (anchored on ropes and lines) 25 m from the shoreline at 1m depth in Begtrup Bay (approx. 2% salinity). This experiment started in 2015 and was extended in October 2016 by tethering 80 empty cartridges of five assorted steel and lead shot cartridge brands in the same locality. The amounts of wear and erosion were evaluated by frequent inspection, measurement of weights and observation of erosion until January 2018.

2.4. Statistics

We used a generalised linear model to test if the measures of wear and erosion of shells and the characteristics for the shells differed between the six areas. Measures of wear and erosion used an ordinal scale with up to five points for each, and hence we used a multinomial or a binomial distribution. We used least square means to conduct *post hoc* pairwise tests.

To determine whether occurrence of litter showed a periodic pattern and whether such pattern differed between cartridge shells compared to wads we recorded occurrence of litter per 100 m in January–March, April–June, and July–December. We used this division of the year as it provided a reasonable number of observations in each period. As the percentage was calculated for each site, we did not need to correct for site effects, but "area" was included as a random variable. We used a mixed model to test this. In addition, we used a random effects model to test if the seasonal variance in occurrence differed for shells and wads. All statistical analyses were conducted in SAS 9.4 (SASInstitute, Cary, NC) using proc genmod and proc glm.

3. Results

3.1. Density of shotgun plastic litter

The study involved 68 sites where systematic collections were made on shorelines with lengths between approximately 100 and 7000 m (total 44.6 km). In all 3669 pieces of plastic shotgun cartridge litter (2153 shells and 1516 wads) were collected. In some instances, collection was repeated on the same stretch. When repeated collections were excluded, the total number of “first time” collections were 53 covering a total stretch of 39.5 km producing 1468 plastic items or an average of 3.7 items/100 m coastline. Fig. 2 shows the distribution of densities on unrepeated (“first time”) collections.

3.2. Characteristics of litter

Most shells were 12 gauge (97.2%) and the remainder (2.8%) were of smaller gauge (16, 20 or 36 gauge). 90.0% of the shells were 70 mm chamber length. 3.3% were shorter (65 or 67 mm) and 6.7% were longer (75, 76 or 89 mm).

The majority (81.5%) of the shells showed a high degree of wear (TW groups 4 & 5). Surface text could be fully or partially distinguished on the remaining 18.5% (TW groups 1 to 3) (Fig. 3a). The

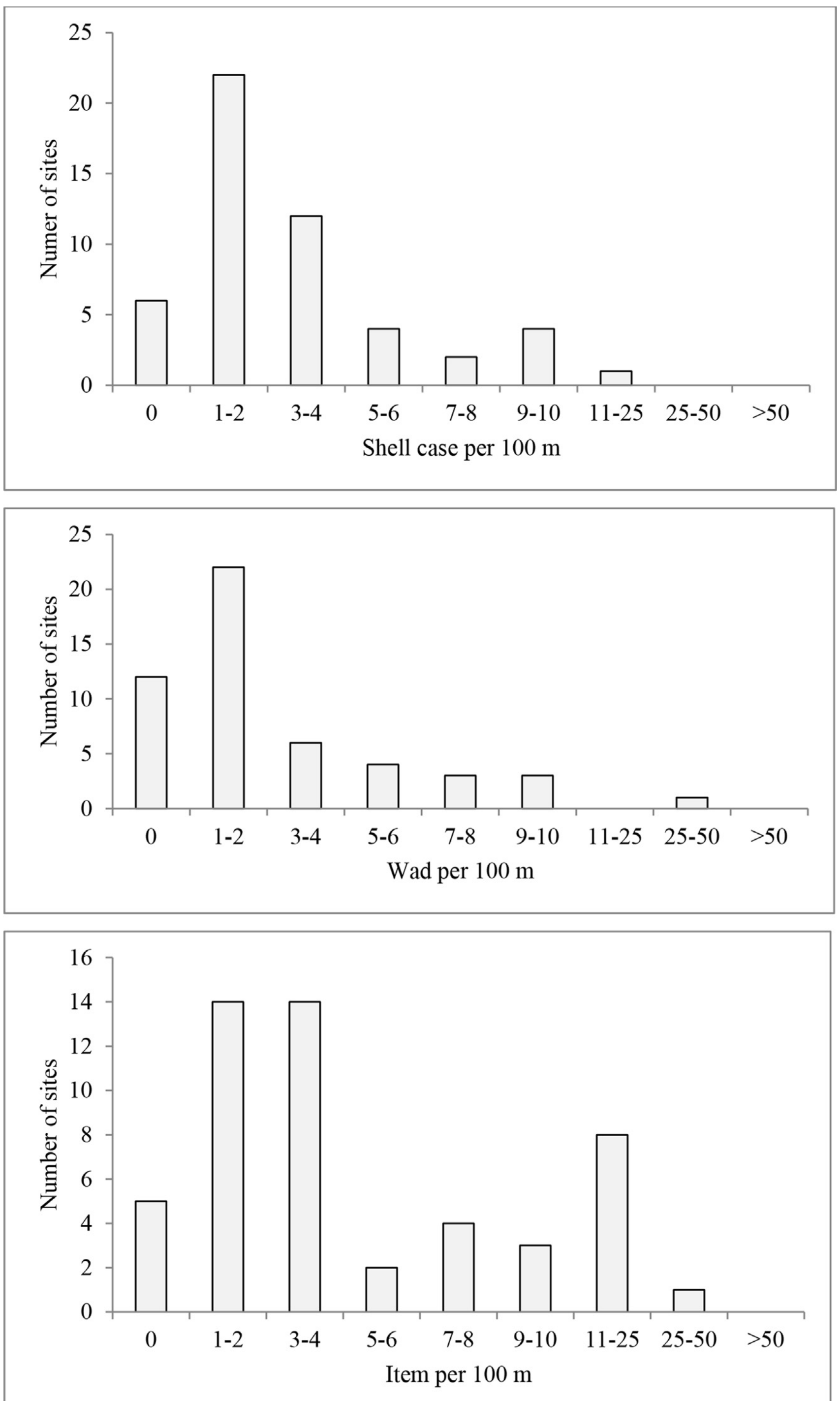

Fig. 2. Number of sites with different densities (number per 100 m), total 1468 items (only “first time” collection sites).

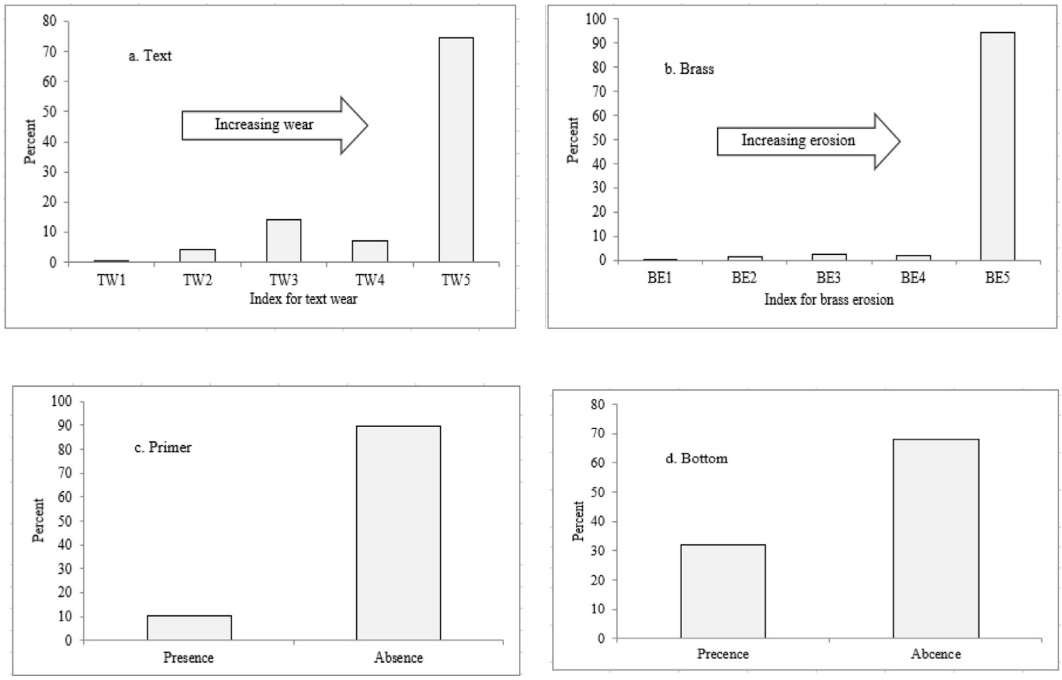

Fig. 3. Distributions of measures of: a. text wear (TW1 = intact text, TW5 = no text), b. brass erosion (BE1 = intact brass, BE5 = no brass), c. Presence/absence of primer, d. Presence/absence of bottom.

brass had completely disappeared (BE5) from 94.1% of the shells (Fig. 3b). Correspondingly, the primer was absent in 89.7% (Fig. 3c). The bottom of the shell was absent in 68.5% (Fig. 3d). Among all shells cases, 8.6% were categorised as "steel" and 13.8% as "lead", whereas 77.6% were indeterminate ("unknown"). One single shell could be determined to originate from a bismuth shot cartridge.

The majority (99.1%) of wads were from gauge 12 cartridges, with gauges 16, 20 and 28 (and one gauge 10) making up the remainder. Among the wads, 82.8% were judged to originate from steel shot cartridges and 17.2% from lead shot cartridges. The abrasive marine environment also causes wear to wads, but wear characteristics for wads showed minor variation so further analysis was not done.

3.3. Area differences

The four measures of wear and corrosion (text, brass, primer and bottom) and the three measures of cartridge type (gauge, length and shot type) differed between areas in most shells (Table 1).

The North Sea area's samples differed from all the other areas showing greater text wear, fewer bottoms present and a higher proportion of long or normal length cartridges (see supplementary material, Table S1). For text wear, presence of primer and shot type the *post hoc* pairwise comparisons showed significant differences among the four other areas (i.e. excluding the North Sea) (Table S1). For text wear, Outer Kattegat (OK) showed more erosion than other areas (except North Sea (NS)), and Aarhus Bay (AB) showed less text wear than other areas. Presence of primers differed between all areas except for North Sea. Shells from the areas Aarhus Bay (AB) and Inner Kattegat (IK) had more shells with retained primers than Limfjord (LF) and Outer Kattegat (OK). Limfjord (LF) had the lowest presence of primers. Most shot-type observations from shells were classified as "unknown", hence this material is less conclusive.

From the collected wads, the average steel to lead shot ratio was 85:15. The North Sea (NS) sample showed the lowest steel to lead ratio (Fig. 4) but this was not statistically significant (General linear model $\chi_3 = 1.83$, $p = 0.608$). 99.1% of the wads originated from gauge 12 cartridges.

Table 1
Test of difference between the areas with various measures of corrosion of shotgun shells. We used a generalised linear model with a multinomial or binomial distribution to test differences between areas.

	df	Chi-square	p
Text wear	4	355.9	<0.0001
Brass erosion	4	87.1	<0.0001
Primer (present/absent)	4	199.4	<0.0001
Bottom (present/absent)	4	102.0	<0.0001
Shot type (Lead, steel or unknown)	4	236.6	<0.0001
Gauge (normal or different)	4	16.1	0.0028
Length (short, normal or long)	4	37.4	<0.0001

3.4. Seasonal pattern

The percentage of wads relative to the total number of collected items (i.e. wads and shells together) per 100 m differed between seasons (General linear model $F_{3,69} = 8.43$, $p < 0.0002$). Post hoc pairwise comparisons showed that the percentage of wads found in January–March was significantly higher than found in other periods (least square means $p \leq 0.0032$). The percentage of wads differed significantly between the three seasons (Fig. 5, Mixed model $F_{2,45} = 5.60$, $p = 0.0067$). The period from July–December showed significantly lower percentages than the periods January–March and April–June (Least means square $t_{45} \geq 2.18$, $p \leq 0.035$).

The variance in the number of shells and wads per 100 m differed between the three seasons (Random effects mixed model, wads: $F_{2,59} = 5.58$, $p = 0.006$; shells: $F_{2,59} = 3.61$, $p = 0.033$).

3.5. Shot sizes

The shot size could be determined for 312 (17%) of all collected

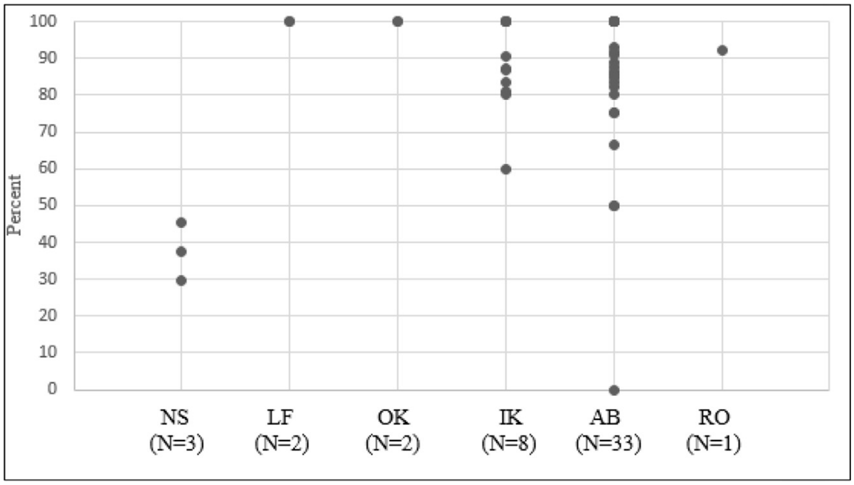

Fig. 4. Percentage of wads originating from steel shot cartridges showed per collection site distributed on areas. Sites with zero wads are not included. North Sea (NS) has the lowest steel shot percentage, but the difference is not statistically significant (p = 0.608).

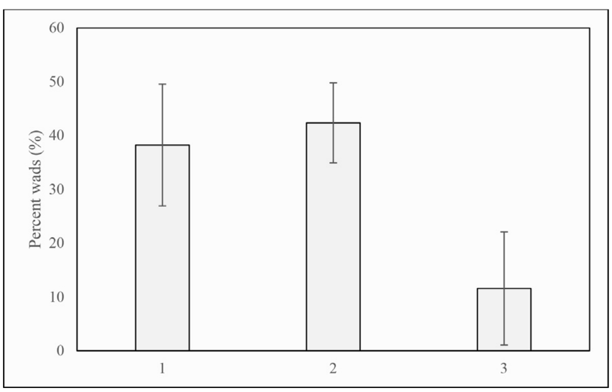

Fig. 5. Percentage of wads relative to total number of items per 100 m distributed on the three annual seasons, 1 = January–March, 2 = April–June, 3 = July–December. Estimates are least mean squares.

shells. 39.7% originated from US shot size 3 (3.5 mm) and 77.8% from cartridges with shot size 2–5 (3.75–3 mm).

3.6. Metrics of shotgun ammunition and litter

Average metrics of the main components of a selection of standard 12 gauge shotgun cartridges for chamber length 70 mm is shown in Table 2. Metrics vary with gauge and chamber length, solidity of wad etc. Magnum loads (e.g. gauge 12/76) may contain up to 30% more powder and shot. However, the weight of the plastic components was not significantly greater.

Table 2
Basic metric data for cartridge components of standard shotgun ammunition gauge 12/70 with a 30 g steel shot load.

		Weight (g)	Volume (cm^3)	Spec. gravity (g/cm^3)
Shell	Plastic	4.3	4.6	0.93
	Metal	3.3		
Shell total		7.6	5.1	1.49
Wad (steel shot)	Plastic	3.1	3.3	0.94
Powder		3.1		
Shot load	Metal	30		
Cartridge		43.8		

Given the estimated annual consumption of 600,000 cartridges, these data indicated an annual dispersal of plastic wads during the free hunting in coastal habitats of some 1860 kg. The total amount of plastic from shells in the equivalent number of shotgun cartridges would be 2580 kg of which an unknown but not negligible proportion was inadvertently lost in the natural environment during hunting.

3.7. Wear and corrosion

Fig. 6 shows the weight loss of samples of shotgun shells tethered in a typical Danish marine environment (Begtrup Bay), a *Littorina* coast (salinity 2%). The samples showed a weight loss that was not linear over time. For most types of cartridge including both steel and lead shells, the weight reduced by some 50% to approximately 4–5 g over 460 days. At this weight the shell began to become positively buoyant and may float. The measurements were supplemented by a visual inspection of the wear and corrosion. Shells lost text after 47 to 113 days depending on brand. After 460 days all brass metal parts had disappeared on all five brands. However, the primer was still left in four of the five brands. Based on weight loss trends, we estimated that shells would achieve a weight to refloat after approximately 18 months of exposure.

4. Discussion

The dispersal pathway from the location of initial wad discharge and empty cartridge case discard on a given hunting or shooting day to the place where they eventually come to rest (Fig. 7) is multifactorial and needs consideration. Depending on weather conditions (waves) discarded shells may float for a short while, but when swamped by waves they sink and will thereafter embedded in sediment or driven by bottom and tidal currents. The wads are positively buoyant and remain floating at the surface. The sunken shells, if not filled with silt and embedded in marine sediments, refloat once the metal parts (brass and primer) have corroded sufficiently (in our study after approximately 18 months). The plastic litter's ability to float seems to be of some importance to the eventual location of wash-up. Of the 2153 shells collected during the study 2027 (94.1%) had lost their metal components (brass and primer). This points to the possibility that the brass had corroded away sufficiently for the shell to refloat. Shells retaining a small amount of metal and having a specific gravity greater than 1 g/cm^3

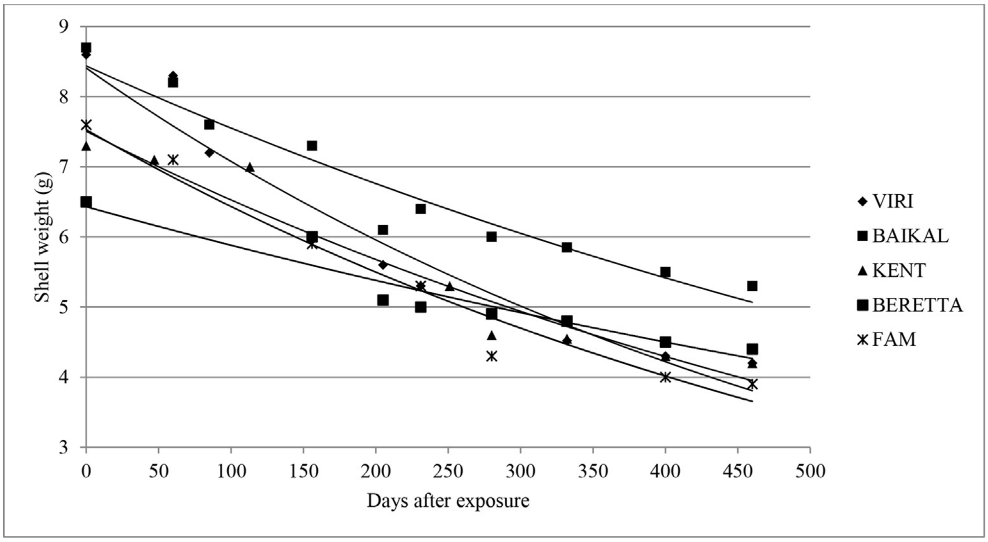

Fig. 6. Weight of samples of shotgun shells from five brands tethered in Begtrup Bay from October 2016 to January 2018.

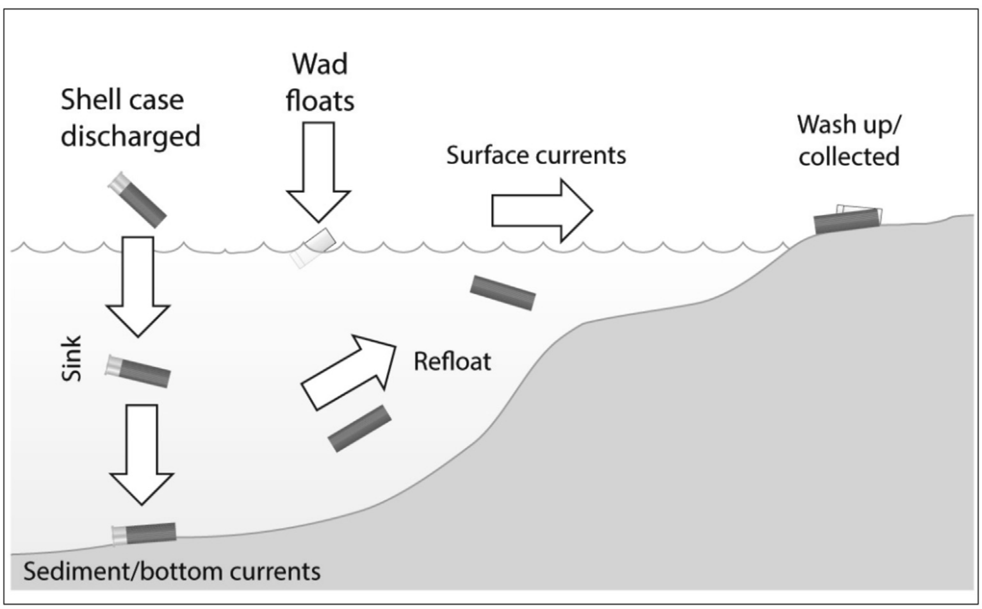

Fig. 7. The flow of ammunition litter when dispersed during hunting in coastal areas. Shells may be retrieved by the hunter and disposed of with household garbage.

were unlikely to wash up. Floating litter follows surface currents dependent on wind conditions, tide etc. The likelihood of litter washing up on a given shoreline depends on multiple vectors and influences including near-coast currents, wind, tide, and shoreline topography and vegetation. Washed-up litter may become embedded in the shore sediment or hidden by saltmarsh vegetation, dead seaweed and other detritus. The likelihood of discovery and ultimate collection depends on intensity of search, experience of volunteer collectors, and the intrinsic visibility of the litter. Colorful litter (typically shells) are more easily found than relatively small white/grey items (typically wads). This may explain why the number of collected shells was greater than the number of wads, although the opposite could be expected as shells sink and hunters cannot retrieve the wads. Another possible explanation is that some of especially the older shells in our sample may originate from a period when shells were made from plastic whilst the wads were made from felt.

4.1. *Amounts*

On some of the investigated coastal stretches, we found up to 41 pieces of shotgun plastic litter per 100 m, which is almost one per every second meter. The average density was 3.7 items per 100 m (total 37.8 km). Given the number and total length of investigated coast stretches we consider that this amount of pollution substantial. Strand et al. 2016 place cartridge shells and wads (OSPAR Code 43 = “shotgun cartridges”) among the top ten items in the North Sea/Skagerrak and the Baltic Sea/Inner Danish waters, based on 2015-data from the Danish reference beaches.

Overall the sites differed significantly in number of shells and wads per 100 m and on some stretches (total 4.9 km of the 44.9 km) we found no ammunition litter. A basic condition for ammunition litter wash-up is its presence in the nearby waterbodies, as demonstrated by research and monitoring programs and campaigns (McCord, pers. comm., Rame Peninsular Beach Care 2017, Strand et al. 2016). However, there were regional differences, as certain coastal waters are not exposed to the direct disposal of ammunition litter from local hunting. This seemed to be the case for the Danish North Sea coast, where hunting is far from intensive. Nonetheless, high densities of hunting litter were found there (Skagen). It is likely that the origin of it is not local but connected to movements of North Sea and Atlantic currents.

Similar to this Danish study, Shetland colleagues in 2017 collected a sample of 84 pieces of shotgun ammunition litter on a 70 m stretch at Burwick located on the west coast of mainland Shetland. This was a higher density than found at any Danish site. Shetland colleagues suggested that the hunting tradition at Shetland does not indicate local discharge and that the litter may have an Atlantic, perhaps transatlantic origin. The high density found on this shoreline was probably due to onshore currents and prevailing winds that increased the wash-up of plastic litter of all kinds including that from ammunition (McCord, pers. comm.).

Marine, tidal and estuarine currents influence the likelihood of litter washing up. The high density of ammunition litter collected at Skagen may have been due to local sea currents at the confluence of the Skagerrak and Kattegat (just as coastal circulations were suspected to have contributed to the findings at Burwick, Shetland). This rationale is supported by Strand et al. 2015 who demonstrated that the general circulation of the currents in the North Sea and Skagerrak, which includes the Atlantic Gulf Stream waters, passes Shetland and continues along the Norwegian coast.

Shoreline profile and topography combine with tidal movements and the saltmarsh vegetation to filter and retain litter and influence the degree to which plastic items remain on the shoreline. Cartridge shells and wads are normally found with other (plastic) litter in wash-up zones with short vegetation, and/or along the tideline fringe where there is dead algal, seaweed and other detritus.

The orientation of the shoreline to prevailing wind direction plays a role. Forty seven percent of the total cartridge litter sample was collected in Begtrup Bay. This was probably due not only to the relatively long and intensive collection effort, but also to the shoreline conditions which favoured wash-up. This shore is located on the east of Aarhus Bay where hunting from boats is notably intensive and the dispersal of ammunition litter correspondingly high. The prevailing wind direction is onshore from the west and the shoreline is thereby exposed to wash-up. Begtrup Bay has a steep and narrow intertidal zone with a characteristic intermittent fringing of seaweeds and short, stiff retentive vegetation. At Nibe Bredning on the other hand, where waterbird hunting from boats and adjacent land is similarly intensive, very few items of plastic ammunition litter were found. A possible cause may be that the shoreline here is often covered by dead and stranded eel grass (*Zostera marina*) that could hide any stranded litter items.

Some of the above-mentioned influences may be seasonal, due for example to different tidal and estuarine currents as well as wind conditions. There was a clear seasonal difference in the wash-up of cartridge shells compared to wads. This was probably due to different physical characteristics affecting their dispersal. Shells sink and get embedded in sediment or follow bottom currents until sufficient corrosion of the brass makes them buoyant again, whereas the wads float and disperse more quickly in surface currents.

4.2. Provenance

A central question is the extent to which ammunition litter comes from local hunting activities and there are several ways to look at this.

We have estimated that the annual dispersal of plastic wads into Danish coastal waters is some 600,000 pieces. Since wads float they are likely to wash up on shorelines nearby in Denmark or in neighbouring countries depending on dispersal site and sea currents. If all 600,000 were to wash up on Danish shorelines it would amount to some 7 wads per 100 m of coastline, given a total coast length of approximately 8500 km (Geodætisk Institut, 2017). This is far greater than the average density of wads collected during this study (1.7 wads per 100 m). This comparison must also take account of the likelihood that wads will have accumulated over multiple years and are not the product of the immediately preceding or current hunting seasons. Although this is, admittedly, a very rough estimation the potential dispersal of wads in terms of quantity is consistent with the collected wads to originate from hunting in Denmark. It should also be noted that 82.8% of the collected wads were estimated to have come from steel shot cartridges. This supports the likelihood that the main source is hunting in the Danish territory, as neighbouring countries have not regulated against lead shot for open sea hunting.

Tracing the origins of cartridge shells was more complex. It was possible to determine the brands and types of some shells collected. These were consistent with their source being Danish as the brands are typical for types that have been marketed in Denmark in recent decades. Additionally, 97.2% of cartridge cases were 12 gauge, which corresponds with experience that hunters are unlikely to use gauges smaller than 12 gauge for coastal hunting (Simonsen, pers. comm.). Shot sizes found in the collected material were those commonly used for coastal hunting in Denmark.

Of the total sample of cartridge shells (2153) the shot material type could be ascertained in only 23%, of which 9% were steel and 14% were lead. These figures were consistent with the view that most shells stem from steel shot cartridges shells dispersed in Denmark, if combined with a contribution of lead shot shells dispersed before their prohibition in 1993 and some illegal use thereafter. The likelihood of some continued illegal use was indicated by the fact that a considerable number of the identified lead shot shells had readable printing similar to those with less than one year's corrosion as indicated by our controlled trial (including the same brands, e.g. Baikal). However, the picture was complicated by several changes related to both the types of ink used as well as the printing techniques used by most modern cartridge manufacturers, where there was a general tendency towards less durable printing on shells compared to older types (Larsen, personal comm.). This change in printing technology overlapped with the introduction of non-lead shot types. It was therefore reasonable to suspect that steel shot cartridges were under-represented in the above proportions and over-represented in the sample of non-identified shells.

The North Sea (Skagen) samples showed significant differences in most of the key characteristics, e.g. wear, corrosion, prevalence of small calibers, and shot type (shells). Although not statistically significant, the Skagen wad samples had a higher lead to steel ratio compared to all other samples (Fig. 4). In one of the Skagen samples, we found a single gauge 10 cartridge wad. This gauge is not legal in Denmark and this isolated finding could possibly suggest that some of the litter may originate from neighbour countries that allow such calibres. These special characteristics suggest that some of the North Sea (NS) litter may not all originate from Denmark but possibly from other countries as North Sea (NS) current systems may have carried ammunition litter to Danish coasts. This finding corresponds with findings of litter on North Sea (NS) coasts in the Shetlands that was unlikely to have originated from local sources (McCord pers. com.).

4.3. Age and fate of ammunition litter

Cartridge shells and wads are made from LDPE, though wads for some types of non-toxic shot may be produced from high density polyethylene (HDPE). These plastics are not biodegradable under normal environmental conditions. Ultra violet light and other physical impacts stimulate degradation, but even with such exposure breakdown can take hundreds of years. With no exposure such plastic items may persist indefinitely.

From this perspective, it is possible that some of our samples of ammunition litter might have originated from dispersal at the very beginning of production of modern shotgun cartridges with plastic some 50 years ago. The level of text and metal corrosion confirmed that the shells in general were older than one year, but an absolute age estimation of the material was not possible or when it had been dispersed. However, due to solid labelling of shells (melting combined with painting) we identified some cartridge types that have not been produced since the 1980's, for example cartridges produced by HK (Hærens Krudtværk); a legendary Danish factory that stopped production in the 1960's. We also identified rather large numbers of the Russian brand "Baikal" (e.g. one type "Baikal Super") and the Czech brand "SB" (Sellier & Bellot, particularly the type "Plastik") that previously were popular among Danish hunters but which have not been on the Danish market since the lead shot ban in the mid 1990's. Such old cartridges could have been stockpiled by hunters and not used until recently. However, it is possible that a significant share of the cartridge shells was dispersed many years ago. This suggests that much plastic ammunition litter has accumulated in the marine environment for decades and will remain a further accumulating source of plastic pollution for many years to come.

Plastic compounds used for the manufacture of cartridge components do not degrade at a significant rate, and the final fate of the litter from hunting ammunition and other sources is worth considering. The most plausible option is that shells and wads will in time be covered over and layered in sediments – either at the sea bottom or along the intertidal shoreline. Here they may rest unchanged for centuries unless exposed by shoreline erosion. Some items may remain floating for many years and be subject to erosion and wear due to contact with rocks and stones, and become micro plastic particles and beads. The roughness of the coast may speed this process, as indicated by the difference in wear and corrosion we found in litter from Danish west and east coasts. Any micro plastic residues may be ingested by invertebrate life (to their detriment) and accumulated in filter feeders and predators (to their detriment also) at higher trophic levels.

4.4. Management

Compared to the other sources of plastic litter in natural habitats and ecosystems, litter from hunting ammunition could be regarded as a relatively minor hazard that can be disregarded. However, plastic ammunition litter features high on lists of litter types found on the Danish reference beaches where litter has been monitored. We believe that hunters in general, once made aware of the scale and duration of problem for which they are responsible, will dismiss any such *laisser faire* attitude. We therefore suggest that responsible managers and hunters will consider the following points.

First, hunters must do more to retain/retrieve empty shotgun shells during hunting so as to discard them later with their household waste. This is a simple question of attitude and respect for existing codes of conduct, but the evidence suggests there is more to be done, including a campaign to ensure greater effort and compliance by all.

Regulatory and civil society actions could support such a campaign, for example through implementation of a deposit system for used empty cartridges, as known for other potential waste items e.g. plastic or glass bottles. Hunters and their clubs could also initiate or get actively involved in existing beach clean-up programmes.

Wads require a different approach as hunters cannot retrieve wads when hunting. The only way to prevent dispersal of wad-plastic is to switch away from plastic to wads made from marine biodegradable or soluble materials that are not harmful in the marine environment. Technology for this is already in place and several products are available on the market and used in a variety of cartridges. However, progress is driven by user-demand as well as by forward-looking, innovative cartridge manufacturers and loaders developing improved and profitable biodegradable wads that meet technical, environmental and health standards.

Owners of private and state hunting land request increasingly hunters to use non-plastic wads. As for hunting in public areas such as the Danish fishery territory a switch from plastic to biodegradable wads will need a clear management strategy led by hunters, their organisations and governmental bodies.

5. Conclusion

Litter from hunting ammunition is a significant source of plastic pollution in nature, and in some Danish coastal areas one of the most common single types of macro pollution. Samples from different areas show various levels of wear and corrosion, which indicates the likelihood of extended length of time since dispersal. Gauge, shot type, and other characteristics also differ between areas indicating that plastic litter occurs in different "populations", with North Sea being the most distinct.

Most ammunition litter on Danish coasts originates from hunting on Danish coastal waterbodies. The North Sea samples may provide some exceptions that suggest that ammunition litter may have come from neighboring countries or even further afield.

Judging from the likely age of the litter collected and slow decomposition rates of plastic, a substantial quantity of plastic ammunition litter will expose coastal habitats to a harmful source of pollution for many years to come.

We recommend responsible managers and hunters to take action now to help reverse this problem and thereby safeguard ecosystems, wildlife and the sustainability of hunting.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envpol.2018.02.087.

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