Widespread ingestion of synthetic micro-particles by geese across Great Britain and Ireland

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Abstract

Scant consideration has been given to the ingestion of synthetic micro-particles (*e.g.* plastic particles such as micro-fibres and micro-fragments 0.5–5 mm in size) by non-marine waterbirds, such as geese, residing in coastal and inland areas. In the present study, we therefore assessed the occurrence of micro-particle ingestion for five goose species across multiple locations throughout the United Kingdom and Ireland. Micro-particle recovery was inclusive of synthetic micro-fibres and micro-fragments, as well as treated textile micro-fibres such as dyed cotton fibres. Goose faecal samples were collected opportunistically between May 2018 and October 2019. At least one micro-particle was detected in 46.5% of the samples (n = 809 samples in total; 0–21 micro-particles per sample), which were collected from Greater

White-fronted Geese *Anser albifrons* (*n* = 31 samples; 41.9% yielded micro-particles), Greylag Geese *A. anser* (*n* = 256; 58.6%), Pink-footed Geese *A. brachyrhynchus* (*n* = 66; 42.4%), Canada Geese *Branta canadensis* (*n* = 298; 36.6%) and Barnacle Geese *B. leucopsis* (*n* = 158; 48.1%). Time of year and distance from the coast had significant partial effects on the abundance of micro-particles recovered, with fewer micro-particles recovered during winter months and from locations > 70 km from the coast. Overall, it appears that the ingestion of synthetic micro-particles is a widespread and frequent occurrence, albeit in low quantities, in different goose species. Further research is however needed to ascertain the extent of absorption and subsequent impacts of chemical contaminants derived from synthetic micro-particles and textile fibres, especially in relation to bird health and developmental life stages.

Key words: Anthropocene, micro-fibre, micro-fragment, plastic pollution, wetland bird.

The proliferation of anthropogenic debris within natural environments, and their subsequent ingestion by a variety of wildlife, has become one of the most topical environmental issues of the 21st century (Gall & Thompson 2015; Cunningham *et al.* 2020). In particular, the production levels of plastic now exceed 413 million tonnes per year worldwide (Plastics Europe 2024), while the input of plastic waste into Earth's oceans is estimated to be between 4.8–12.7 million tonnes on an annual basis (Jambeck *et al.* 2015). Given the downstream movement of anthropogenic debris within river catchments (Kooi *et al.* 2018), along with coastal areas also being prone to the ingress of oceanic plastic debris due to tidal forces (*e.g.* Kurniawan & Imron 2019), coastal locations appear to be particularly susceptible to the accumulation of synthetic debris. The ingestion of synthetic debris (*i.e.* debris composed fully or partially of synthetic polymers) by wildlife can lead to greater levels of morbidity and mortality (*e.g.* Baulch & Perry 2014). For the most part, the detrimental effects of debris ingestion have been attributed to physical damage, reduced digestive capacity and appetite, and blockage of the gastrointestinal tract caused by large synthetic items (> 5 mm in length: *e.g.* Pierce *et al.* 2004; Lavers *et al.* 2014). Yet, the ingestion of synthetic micro-particles (≤ 5 mm) by wildlife can also result in deleterious effects due to the bioaccumulation and biomagnification of toxic chemical contaminants (Tanaka *et al.* 2013, 2020). Despite concerns for potential wide-ranging environmental impacts, most studies have focussed on the occurrence and effects of synthetic micro-particles in marine rather than freshwater or terrestrial ecosystems (O'Hanlon *et al.* 2017; Windsor *et al.* 2019; Wong *et al.* 2020). Nonetheless, substantive evidence indicates that synthetic micro-particles can widely occur in surface waters and terrestrial habitats (de Souza Machado *et al.* 2018; Wong *et al.* 2020). For the most part, it appears that synthetic micro-particles enter the environment through inadequate waste disposal practices, with higher concentrations generally being linked to greater human population densities and urbanisation (de Souza Machado *et al.* 2018; D'Souza *et al.* 2020). Nevertheless, little is known about the ingestion of synthetic micro-particles by many species residing within these environs.

While seabirds are frequently used as sentinel species for anthropogenic pollution, the ingestion of synthetic debris by other bird species remains poorly studied (Holland *et al.* 2016; Gil-Delgado *et al.* 2017; Rossi *et al.* 2019). To date, only a handful of studies have begun to explore synthetic debris ingestion by non-seabird species of waterbirds (*e.g.* Gil-Delgado *et al.* 2017; Coughlan *et al.* 2020; D'Souza *et al.* 2020). As a result, the occurrence and frequency of synthetic debris ingestion by other waterbird species, such as the Anatidae (ducks, geese and swans), remains largely unknown. Conversely, the accidental ingestion of non-synthetic anthropogenic debris by Anatidae, such as spent gunshot and discarded anglers' weights, has been well documented with a clear determination of their associated deleterious effects (O'Halloran *et al.* 1988; Mateo *et al.* 2007; O'Connell *et al.* 2009; Wood *et al.* 2019). Geese are obligately herbivorous, and the inadvertent ingestion of synthetic particles by Anatidae has been linked to their tendency to ingest grit to aid the mechanical breakdown of food items within the gizzard (O'Halloran *et al.* 1988; Mateo *et al.* 2000). There also appears to be considerable potential for food web aided transfer of synthetic micro-particles, given that micro-particles can adsorb to plant material (D'Souza *et al.* 2020), along with coincidental ingestion by geese feeding in soil for buried vegetation such as tubers (Amat & Varo 2008). In turn, these micro-debris may also pass through the food chain when initially ingested by prey species (Mateos-Cárdenas *et al.* 2020).

Flocks of migratory and resident geese are a prominent feature of many wetland areas worldwide, but will readily exploit a mosaic of marine, freshwater and terrestrial habitats for feeding opportunities (*e.g.* Doyle *et al.* 2018; Mitchell & Hall 2018). Despite this, little consideration has been given to the potential ingestion of synthetic micro-particles by geese, with most of the few existing studies concerning Anatidae having focused on duck and shelduck (English *et al.* 2015; Gil-Delgado *et al.* 2017; Reynolds & Ryan 2018) or swan species (Coughlan *et al.* 2021a). To date, the ingestion of synthetic micro-particles by the "true geese" (Tribe Anserini, genera: *Anser* and *Branta*) has been restricted to a few selected species and sampling sites, as well a limited number of individuals (*e.g.* Holland *et al.* 2016; Coughlan *et al.* 2020). In particular, there is a scarcity of information concerning the ingestion of synthetic micro-particles by birds residing in inland wetland or terrestrial environments (Zhao *et al.* 2016; Reynolds & Ryan 2018; Coughlan *et al.* 2021b).

To date, most studies have relied on the examination of carcasses or regurgitated boluses for the detection of synthetic micro-particle ingestion by birds (Provencher *et al.* 2017, 2018). As such, the availability of assessable samples is often highly limited, with sample size frequently being restricted by temporal and spatial extents. Carcasses may also be biased, as mortality could be the result of debris-related morbidity for birds that have ingested greater amounts of synthetic debris. Contrastingly, non-invasive faecal sampling has the potential to provide more reliable estimates of ingestion frequency as well as toxicological effects (*e.g.* Martínez-Haro *et al.* 2011). Faecal samples only contain egested synthetic particles that are small enough to have passed through the entire gastrointestinal tract (Reynolds & Ryan 2018; Provencher *et al.* 2018; Coughlan *et al.* 2020, 2021a), so this can be complemented with an assessment of carcasses or regurgitated boluses for some species (*e.g.* geese and raptors).

In the present study, we aim to determine the occurrence and frequency of ingestion of synthetic micro-particles (including treated textile fibres) by various species of geese, by analysing faecal samples collected from across multiple sampling locations for the presence and abundance of these particles in the droppings. The species and sites selected for assessment were chosen largely on an opportunistic basis, whereby study populations coincided with contributors' access to sampling sites during routine geese monitoring, ringing or site maintenance activities. Given the proliferation of synthetic debris within natural environments during the Anthropocene, we expected that the ingestion of synthetic micro-particles by geese would be a widespread and reoccurring phenomenon across flocks of geese frequenting different areas. Further, given the susceptibility of coastal locations to the accumulation of synthetic debris, we hypothesised that geese at coastal sites would show higher levels of synthetic micro-particles ingestion than those occurring in inland areas. This analysis adds to the few previous studies on the ingestion of synthetic micro-particles by non-marine birds. Moreover, for the first time, ingestion of synthetic micro-particles by Greater White-fronted Geese *Anser albifrons*, Greylag Geese *A. anser* and Pink-footed Geese *A. brachyrhynchus* is investigated and reported.

Methods

Sample collection

Between May 2018 and October 2019 faecal samples were opportunistically collected from five goose species residing throughout Great Britain and Ireland across 24 different sampling sites (Fig. 1, Table 1). Samples were collected alongside other field and research activities, such as ringing. In all instances, fresh faecal samples were collected from monospecific roosting or loafing sites. Samples were collected with previously unused, clear polythene bags (*i.e.* freezer/sandwich bags). These were inverted, shaken and used like a glove to pick up the sample. For the present study, it was not possible to collect field controls to account for potential atmospheric deposition of micro-particles. Samples were collected at distances of at least one metre apart to ensure that they were produced by different individual birds (Coughlan *et al.* 2020, 2021a). Samples were refrigerated for up to five months prior to assessment.

A total of 809 faecal samples were collected from Greater White-fronted Geese (n = 1 sampling site), Greylag Geese (n = 6), Pink-footed Geese (n = 3), Canada Geese *Branta canadensis* (n = 9) and Barnacle Geese *B. leucopsis* (n = 6) throughout Britain and Ireland (Fig. 1, Table 1). Between 6–35 individual samples were collected on each

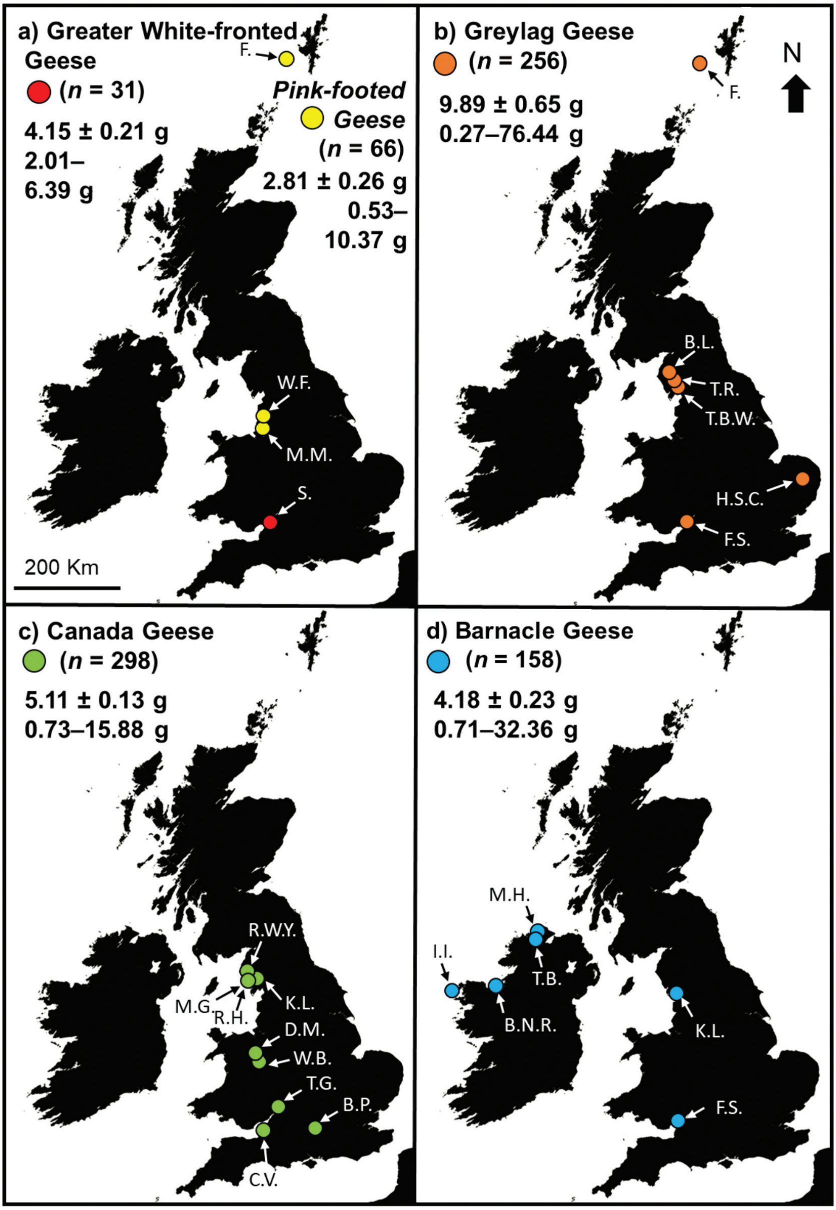

Figure 1. Sample site locations for Greater White-fronted Geese (*n* = 1), Greylag Geese (*n* = 6), Pink-footed Geese (*n* = 3), Canada Geese (*n* = 9) and Barnacle Geese (*n* = 6) throughout Britain and Ireland. Number of individuals sampled is shown (sample *n*). For specific location and sample details see Table 1. The arithmetic mean (± s.e.) of sample wet-weight mass is shown for each species, as is the range (minimum to maximum) in grams.

Table 1. Sampling sites for each goose species included in the study. The percentage of samples that yielded at least one synthetic micro-particle (MPs) are shown (prevalence), as are total counts for detected micro-fibres and micro-fragments. GB = Great Britain; ROI = Republic of Ireland.

Site name	**Site code (coordinates)**	**Distance to coast (km)**	**Sample size (*n*)**	**Prevalence of MPs (%)**	**Geometric mean ± 95% CI of MPs per sample**	**Range of MPs per sample**	**Total no. micro-fibres**	**Total no. micro-fragments**
Greater White-fronted Geese								
WWT Slimbridge, GB	**S.** (51.73°N, –2.42°E)	28	31	41.9	0.49 ± 0.57	0–4	21	1
Greylag Geese								
Bassenthwaite Lake, GB	**B.L.** (54.64°N, –3.23°E)	24	32	28.1	0.29 ± 0.41	0–6	10	6
Foula Island, GB*	**F.** (60.13°N, –2.06°E)	0.5	103	44.7	0.58 ± 0.39	0–17	96	5
Frampton-on-Severn, GB	**F.S.** (51.76°N, –2.38°E)	32	18	66.7	1.16 ± 0.66	0–4	28	0
Horning Sailing Club, GB*	**H.S.C.** (52.71°N, 1.46°E)	22	43	100	4.82 ± 1.40	1–21	247	9
Thirlmere Reservoir, GB	**T.R.** (54.50°N, –3.05°E)	32	30	70.0	1.00 ± 0.46	0–6	36	3
Three Birks Wood, GB	**T.B.W.** (54.33°N, –2.95°E)	18	30	63.3	0.91 ± 0.52	0–6	29	9

Pink-footed Geese								
Foula Island, GB	**F.** (60.15°N, –2.06°E)	0.05	6	83.3	1.82 ± 1.94	0–6	15	0
Martin Mere, GB	**M.M.** (53.60°N, –2.88°E)	10	34	29.4	0.24 ± 0.18	0–2	11	0
Webster's Farm, GB	**W.F.** (53.68°N, –2.90°E)	10	26	50.0	0.75 ± 1.09	0–14	17	19
Canada Geese								
Beale Park, GB	**B.P.** (51.50°N, –1.11°E)	78	12	16.7	0.12 ± 0.22	0–1	2	0
Chew Valley, GB*	**C.V.** (51.34°N, –2.62°E)	28	64	64.1	1.12 ± 0.47	0–8	104	2
Doxey Marshes, GB	**D.M.** (52.81°N, –2.15°E)	91	16	18.8	0.20 ± 0.35	0–2	4	1
Killington Lake, GB	**K.L.** (54.30°N, –2.63°E)	24	28	32.1	0.32 ± 0.28	0–2	10	3
Miller Ground, Windermere, GB	**M.G.** (54.38°N, –2.92°E)	24	30	36.7	0.37 ± 0.29	0–3	15	1
Rayrigg Hall, Windermere, GB	**R.H.** (54.37°N, –2.92°E)	24	30	26.7	0.22 ± 0.19	0–2	6	3
Royal Windermere Yacht Club, GB*	**R.W.Y.** (54.37°N, –2.92°E)	21	30	20.0	0.21 ± 0.36	0–5	9	2
Twyning Green, GB*	**T.G.** (52.03°N, –2.13°E)	72	58	39.7	0.43 ± 0.24	0–4	32	4
Wolseley Bridge, GB	**W.B.** (52.78°N, –1.97°E)	88	30	20.0	0.16 ± 0.18	0–2	4	3

Table 1 (*continued*).

Site name	Site code (coordinates)	Distance to coast (km)	Sample size (n)	Prevalence of MPs (%)	Geometric mean ± 95% CI of MPs per sample	Range of MPs per sample	Total no. micro-fibres	Total no. micro-fragments
Barnacle Geese								
Frampton-on-Severn, GB	**F.S.** (51.76°N, –2.38°E)	32	31	51.6	0.74 ± 0.56	0–7	35	0
Killington Lake, GB	**K.L.** (54.30°N, –2.63°E)	16	22	22.7	0.23 ± 0.27	0–2	7	0
Ballygilgan Nature Reserve, ROI*	**B.N.R.** (54.34°N, –8.55°E)	0.02	48	45.8	0.66 ± 0.49	0–8	51	1
Inishkea Islands, ROI	**I.I.** (54.12°N, –10.21°E)	0.1	20	80.0	1.35 ± 0.80	0–6	35	1
Malin Head, ROI	**M.H.** (55.38°N, –7.37°E)	0.1	19	47.4	0.89 ± 1.02	0–7	30	0
Trawbreaga Bay, ROI	**T.B.** (55.29°N, –7.32°E)	0.01	18	44.4	0.51 ± 0.44	0–3	12	1

Note: * = sites sampled on multiple occasion across seasons during the study period of May 2018 to October 2019: Ballygilgan Nature Reserve (autumn 2018, spring 2019), Chew Valley (summer 2018, winter 2019), Foula Island (spring 2018, winter, spring and autumn 2019, Horning Sailing Club (summer 2018, autumn 2018), and Twyning Green (spring 2019, summer 2019).

sampling occasion. Samples were collected from five sites on multiple occasions across different seasons (Table 1). The linear distance from sampling sites to the nearest coastline was determined using Google Maps. In turn, these measured distances were grouped as: ≤ 1.0 km, 5.0–10.0 km, 10.1–20.0 km, 20.1–30.0 km, 30.1–35.0 km, and > 70.0 km. Samples were not collected at between 1.01–4.99 km. Meteorological seasons of spring, summer, autumn and winter were also considered: March–May, June–August, September–November, and December–February, respectively.

Digestion, separation and microscopy

In the laboratory, following the protocol outlined by Coughlan *et al.* (2020), each sample was transferred into an individual beaker and weighed on an analytical balance (0.01 g: Mettler Toledo AB104). The mass of each sample was recorded. Samples were then digested in solutions of iron(II) sulfate heptahydrate ($FeH_{14}O_{11}S$: 0.05M) and 30% hydrogen peroxide (H_2O_2) at 60°C (at a ratio of 2:1 for H_2O_2 to $FeH_{14}O_{11}S$), until total digestion had occurred (Masura *et al.* 2015). The digestion process was used to eliminate labile organic matter such as plant and animal residues. Chemically treated textile fibres, including dyed cotton and wool fibres, can be resistant to complete digestion. An application ratio of approximately 20 ml per 10 g of faecal sample was employed.

Once digestion was complete, a saturated solution of NaCl (*i.e.* 360 g l^{-1}) was used to isolate micro-particles from denser undigested mineral components by flotation. The resulting supernatant was carefully decanted and vacuum filtered onto filter pads (Whatman 41: 47 mm diameter, 20 μm pore). All filter pads were placed in clean glass Petri dishes and dried at room temperature within these glass lid dishes. Once dry, samples were examined under a stereomicroscope (Olympus SZX16). All synthetic particles were visually identified, using the criteria outlined by Zhao *et al.* (2016), and measured with a line-gauge ruler. Recovered particles were classified into shape-type categories, size range and colour tone (Provencher *et al.* 2017; Bessa *et al.* 2019). Fibres can be considered as thread-like strands of uniform thickness, while micro-fragments (or shards) are non-thread-like structures usually with irregular dimensions. For simplification, colour tones were subsequently regrouped as three colour tones (either as light/clear, mid or dark tone: Zhao *et al.* 2016). Identification of colour is a recommended protocol to support classification and can assist with the determination of synthetic micro-particle sources. This study focused on the detection of synthetic micro-particles ≥ 0.5 mm in size (*i.e.* micro-fibres and micro-fragments), as the analysis of smaller synthetic particles is considered problematic given uncertainties around airborne contamination by ultra-small particles (Torre *et al.* 2016). Despite following the criteria outlined in Zhao *et al.* (2016), treated textile micro-fibres such as dyed cotton could not be definitively isolated from purely synthetic micro-fibres. Accordingly, all anthropogenic micro-fibres detected were combined for analysis.

To curtail potential contamination of the samples, glassware rather than plastic apparatus was used throughout. Glassware was acid washed prior to use and covered with fresh aluminium foil during the entire extraction procedure. All apparatus was also inspected through a stereomicroscope for the presence of micro-particles prior to sample processing. In addition, immediately before processing the first sample of each batch, all glassware was double rinsed with distilled water and a procedural control sample was processed using this distilled water. This damp filter pad was then placed in a Petri dish and used as a laboratory contamination control (*n* = 46; see Coughlan *et al.* 2020, 2021a). Analysts wore 100% white cotton lab coats, non-fibrous cotton-based under-clothing and nitrile gloves to reduce the potential for human contamination. A lint roller was used to remove any hair, dust and fluff from the external surfaces of clothes and worksurfaces immediately prior to handling the samples.

Statistical analyses

Given that so few were detected (*n* = 5 pieces), larger synthetic particles of > 5 mm in length were not included in the analysis. Geometric means are used to better account for a skewed data distribution and variability of faecal sample mass. The abundance of synthetic micro-particles detected per sample was compared among species, seasons (spring, summer, autumn, winter), and categories of linear distance from the coast, all as fixed factors. Analyses were undertaken for the total number of synthetic micro-particles, and also for each particle type separately (*i.e.* micro-fibres and micro-fragments). Generalized Linear Mixed Models (GLMM) with a negative binomial error distribution and loglink function in the *glmmTMB* package (Brooks *et al.* 2017) were used to account for the many samples with zero values and overdispersion. Sample mass (*i.e.* the weight of the faecal sample) was used as a continuous variable due to the variability of sample masses, while sampling location was considered as a random factor. Additionally, a quasi-Poisson regression was used to assess differences among sampling locations, while linear regression was used to assess the relationship between the number of synthetic micro-particles detected and sample mass. All statistical analyses were performed using R version 4.3.3 (R Core Team 2024).

Results

Potential contamination from the polyethene field collection bags appeared negligible, as only 0.32% of samples yielded micro-particles with transparent colour tones (*e.g.* clear, white-blue, yellow). In turn, potential laboratory contamination was also negligible, with only 22 synthetic micro-fibres being detected by control filter pads; *i.e.* a rate of 0.03 per processed faecal sample. Therefore, no adjustments were made to the results.

At least one synthetic micro-particle was detected in 46.5% of the faecal samples assessed (*n* = 809 samples), with micro-particles being recovered from each species and every location. Among species, the proportion of faecal samples that contained at least one synthetic micro-particle ranged from 36.6%–58.6%, for: Canada Geese (36.6%), Greater White-fronted Geese (41.9%), Pink-footed Geese (42.4%), Barnacle Geese (48.1%) and Greylag Geese (58.6%). Sample mass ranged from 0.27–76.44 g with an arithmetic mean (± s.e.) of

6.22 ± 0.24 g. Sample masses for individual species are given in Fig. 1. In total, 940 synthetic micro-particles were recovered (micro-particles per sample: geometric mean ± 95% CI = 0.66 ± 0.14; range = 0–21), which consisted of 866 micro-fibres (0.61 ± 0.13; 0–21) and 74 micro-fragments (0.05 ± 0.04; 0–14) (Table 1). In addition, five fibres of > 5 mm in length were also detected. Four fibres were recovered from Canada Geese (Chew Valley, n = 3; Miller Ground, n = 1), while one fibre was detected in a Pink-footed Goose sample (Webster's Farm).

The majority of the synthetic micro-fibres recovered had dark colour tones (96.4%; *e.g.* navy-blue, black, dark red), with very few micro-fibres showing mid (3.1%; *e.g.* blue, green, red) or light colour tones (0.5%; *e.g.* clear, white-blue, yellow). Although most synthetic micro-fragments also had dark colour tones (60.8%), a greater proportion of micro-fragments showed mid (18.9%) and light colour tones (20.3%) than observed for micro-fibres.

Mixed models indicated that season and distance both had significant partial effects on the total abundance of synthetic micro-particles (levels "winter" and "> 70 km", both $P < 0.05$; Table 2), with fewer micro-particles being recovered during winter months and at distances of > 70 km from the coast (Fig. 2A,B). For the sub-category of micro-fibres, season and distance again displayed significant partial effects on the total abundance of synthetic micro-particles (levels "winter" at $P < 0.01$, with "5.0–10.0 km" and "> 70 km" both at $P < 0.05$; Table 2), with fewer micro-fibres being detected for these sample categories. The abundance of synthetic micro-particles did not significantly differ among species (Fig. 3A, Table 2), nor was a difference detected among geese for the sub-categories of synthetic micro-fibres and micro-fragments (Figs. 3B,C, Table 3). Sample mass had a significant effect on the abundance of synthetic micro-particles ($P < 0.01$; Table 2) and micro-fibres ($P < 0.05$), but not on micro-fragments (Table 3). A significantly greater number of synthetic micro-particles were detected at Horning Sailing Club compared to all other locations (GLM: $\chi^2_{21} = 679.65$, $P < 0.001$, with all *post hoc* pairwise comparisons of $P < 0.05$; Fig. 4). Larger faecal samples tended to contain slightly greater numbers of synthetic micro-particles compared to smaller samples ($R^2 = 0.25$, $P < 0.001$; Fig. 5).

Discussion

Although the quantities of synthetic debris ingested by geese tended to be low, the present study demonstrates that synthetic micro-particle ingestion is likely a frequent and widespread phenomenon in flocks of different goose species throughout Great Britain and Ireland. At least one micro-particle was recovered from 36.6–58.6% of samples obtained from the species considered, which is broadly similar to amounts reported for Anatidae elsewhere: 4.3–53.8% (Canada: English *et al.* 2015), 0.0–50.0% (Canada: Holland *et al.* 2016), and 43.8–60.0% (Spain: Gil-Delgado *et al.* 2017). Other studies have however reported both higher and lower instances of synthetic debris ingestion, at rates of 79.0% (Ireland: Coughlan *et al.* 2020), 81.8–91.7% (Great Britain: Coughlan *et al.* 2021a) and 0.0–

Table 2. Effects of species, season, distance from the coast, and sample mass on the total abundance of synthetic micro-particles recovered per sample, from negative binomial mixed models. GWG = Greater White-fronted Geese, GG = Greylag Geese, PG = Pink-footed Geese, CG = Canada Geese and BG = Barnacle Geese.

Variables	Level of effect	*n*	β	s.e.	χ^2	*P*
Species	GWG	31	0.43	0.72	0.004	1.91
	GG	256	0.19	0.28	0.43	1.02
	PG	66	0.85	0.59	2.07	0.30
	CG	298	–0.03	0.40	0.01	1.87
	BG	158	–	–	–	–
Season	Spring	499	–0.21	0.24	0.78	0.75
	Summer	177	0.19	0.25	0.57	0.90
	Winter	70	–0.82	0.31	7.05	**< 0.05**
	Autumn	63	–	–	–	–
Distance (km)	≤ 1.0	214	–	–	–	–
	5.0–10.0	60	–1.37	0.76	3.20	0.15
	10.1–20.0	80	–0.88	0.52	2.88	0.18
	20.1–30.0	260	–0.60	0.46	1.63	0.40
	30.1–35.0	79	–0.34	0.50	0.48	0.98
	> 70.0	116	–1.38	0.58	5.69	**< 0.05**
Sample mass (g)		809	0.02	0.01	8.80	**< 0.01**
Location	Random contribution (variance): 0.2882					

Note: the species "Barnacle Goose", season "autumn" and distance "≤ 1.0 km" are not included in the table because the levels for these factors were aliased, so effectively had estimates of zero. Sampling location was included as a random factor. The sample sizes (*n*), regression coefficients (β) and their standard errors (s.e.), and the main effects (χ^2 and associated *P* value) are given for each variable included in the model. Significant values are highlighted in bold.

17.0% (South Africa: Reynolds & Ryan 2018), which indicates that substantial variation may occur between species and sampling locations. Sample size could also be a cause of variability between studies, with differences in the ingestion of synthetic micro-particles potentially influenced by inter-specific foraging habits, habitat choice,

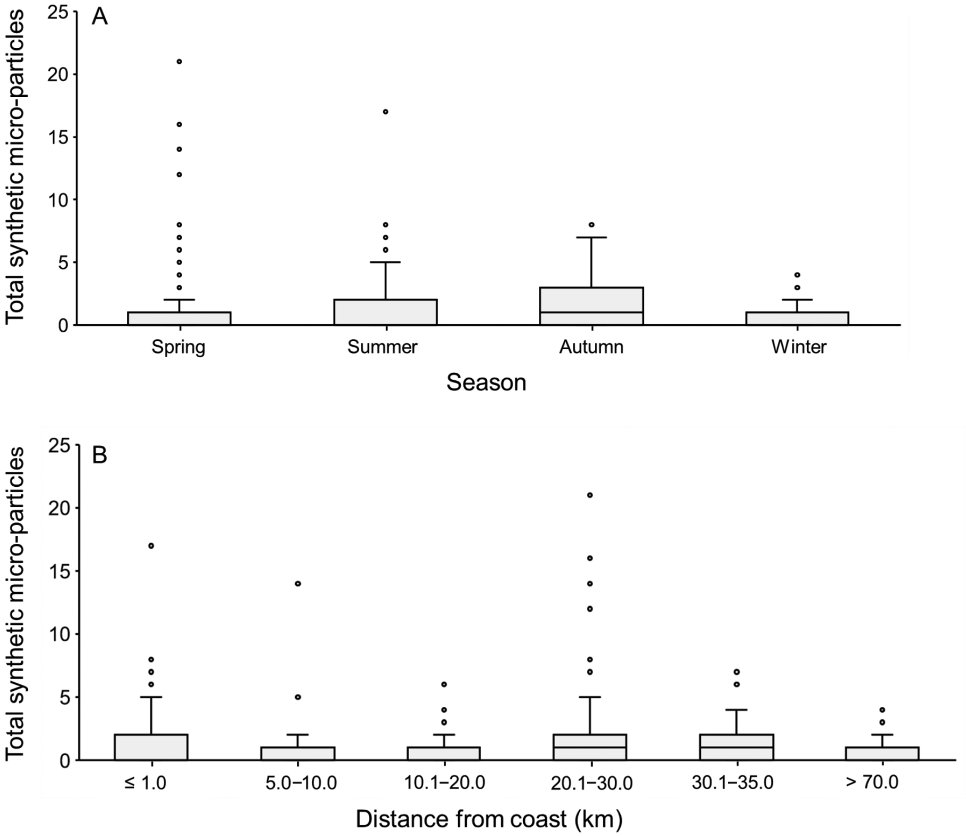

Figure 2. Median values for synthetic micro-particles recovered from a total of 809 faecal samples for geese throughout Britain and Ireland in relation to: (A) season, and (B) distance between sampling locations and the coastline. Interquartile ranges (IQR), maximum and minimum IQR values, and outliers are shown. Generalized Linear Mixed Models indicated that both season and distance have significant partial effects, at the "winter" and "> 70.0 km" levels (both $P < 0.05$; Table 2). Note: zero-inflated data yielded numerous median values of zero.

and the quantity of biomass ingested and egested daily, as well as the extent of synthetic debris pollution among locations. The number of species known to ingest synthetic micro-particles is however increasing with, we believe, this being the first record of it occurring in Greater White-fronted Geese, Greylag Geese and Pink-footed Geese.

Widespread and reoccurring ingestion of synthetic micro-particles by goose species

It appears ingestion of synthetic micro-particles can occur in remote coastal locations, as well as in inland rural areas and locations adjacent to large urban centres. However, it appears that distance from the coast correlates with the quantity of synthetic

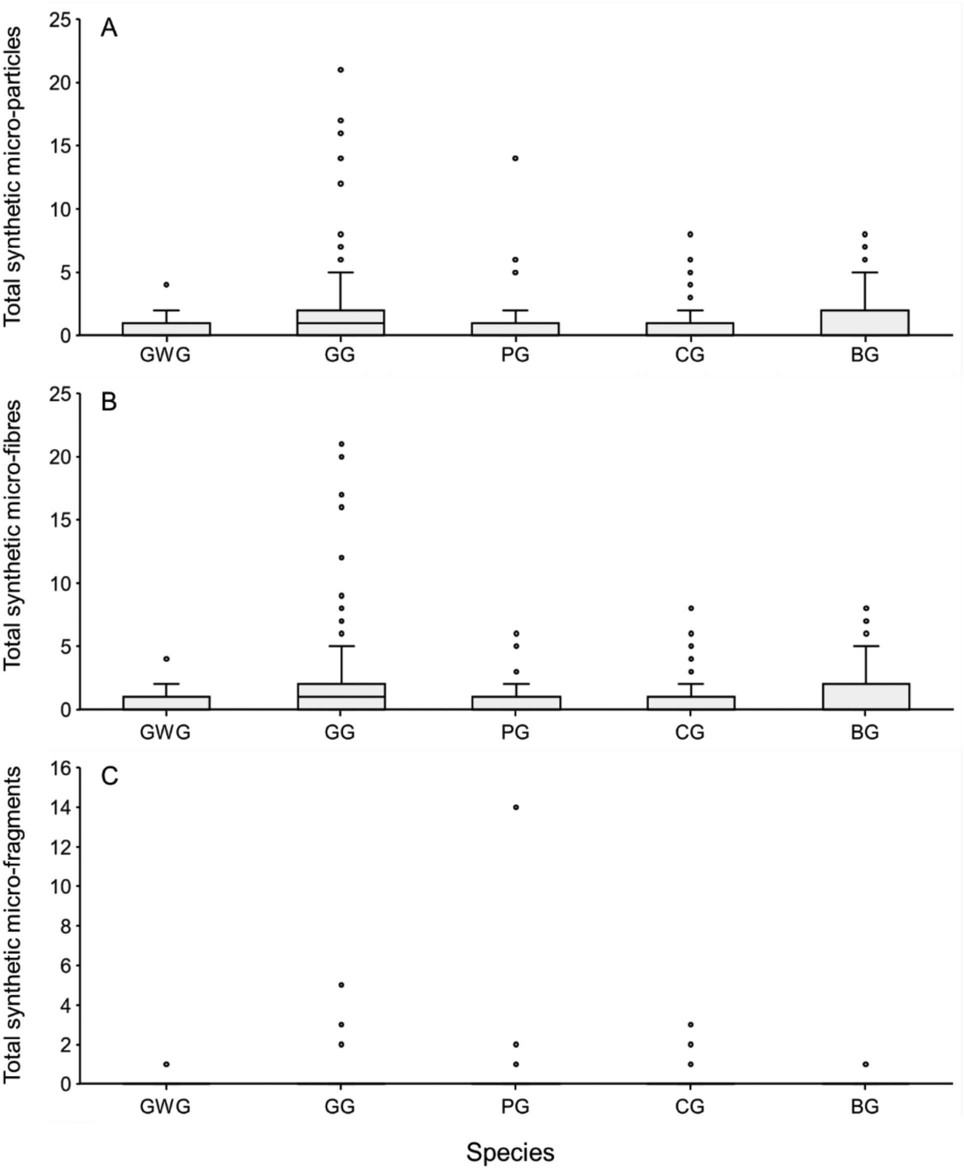

Figure 3. Median values for synthetic micro-particles recovered from a total of 809 faecal samples for Greater White-fronted Geese (GWG), Greylag Geese (GG), Pink-footed Geese (PG), Canada Geese (CG) and Barnacle Geese (BG) throughout Britain and Ireland. (A) = all synthetic micro-particles, (B) = shape-type sub-categories of micro-fibres and (C) = micro-fragments (C). Interquartile ranges (IQR), maximum and minimum IQR values, and outliers are provided. A significant effect was not detected for species (*i.e.* all n.s.). Note: zero-inflated data yielded numerous median values of zero.

Table 3. Effects of species, season, distance from the coast, and sample mass on the total abundance on micro-particle subcategories of synthetic micro-fibres and micro-fragments, from negative binomial mixed models.

Variables	Level of effect	Micro-fibres				Micro-fragments			
		β	s.e.	χ^2	P	β	s.e.	χ^2	P
Species	GWG	0.03	0.77	0.002	1.93	0.22	1.49	0.02	1.77
	GG	0.15	0.29	0.27	1.21	1.23	0.78	2.51	0.23
	PFG	0.85	0.77	2.18	0.28	–15.81	78,001.18	4.010^{-6}	2.00
	CG	–0.15	0.42	0.13	1.43	0.70	0.95	0.53	0.93
Season	Spring	–0.21	0.24	0.81	0.74	–	–	–	–
	Summer	0.11	0.25	0.22	1.28	–	–	–	–
	Winter	–0.97	0.31	9.89	**< 0.01**	–	–	–	–
Distance (m)	5.0–10.0	–1.80	0.79	4.59	**< 0.05**	18.81	7,802.18	4.0×10^{-6}	2.00
	10.1–20.0	–1.02	0.56	3.30	0.14	0.10	0.74	1.80	0.36
	20.1–30.0	–0.63	0.49	1.66	0.40	0.38	0.78	0.23	1.26
	30.1–35.0	–0.32	0.54	0.30	1.10	–0.58	0.90	0.41	1.26
	> 70.0	–1.49	0.62	5.79	**< 0.05**	0.61	0.96	0.40	1.05
Sample mass (g)		0.02	0.01	8.63	**< 0.01**	0.05	0.04	1.83	0.35
Location	Random contribution (variance):	0.3352				1.80×10^{-13}			

Note: the species "Barnacle Goose", season "autumn" and distance "≤ 1.0 km" are not included in the table because these levels of the respective factors were aliased. See Table 2 for further explanation. It was not possible to calculate season values for micro-fragments because detection levels were highly skewed towards samples taken in spring and summer. Significant χ^2 values are highlighted in bold.

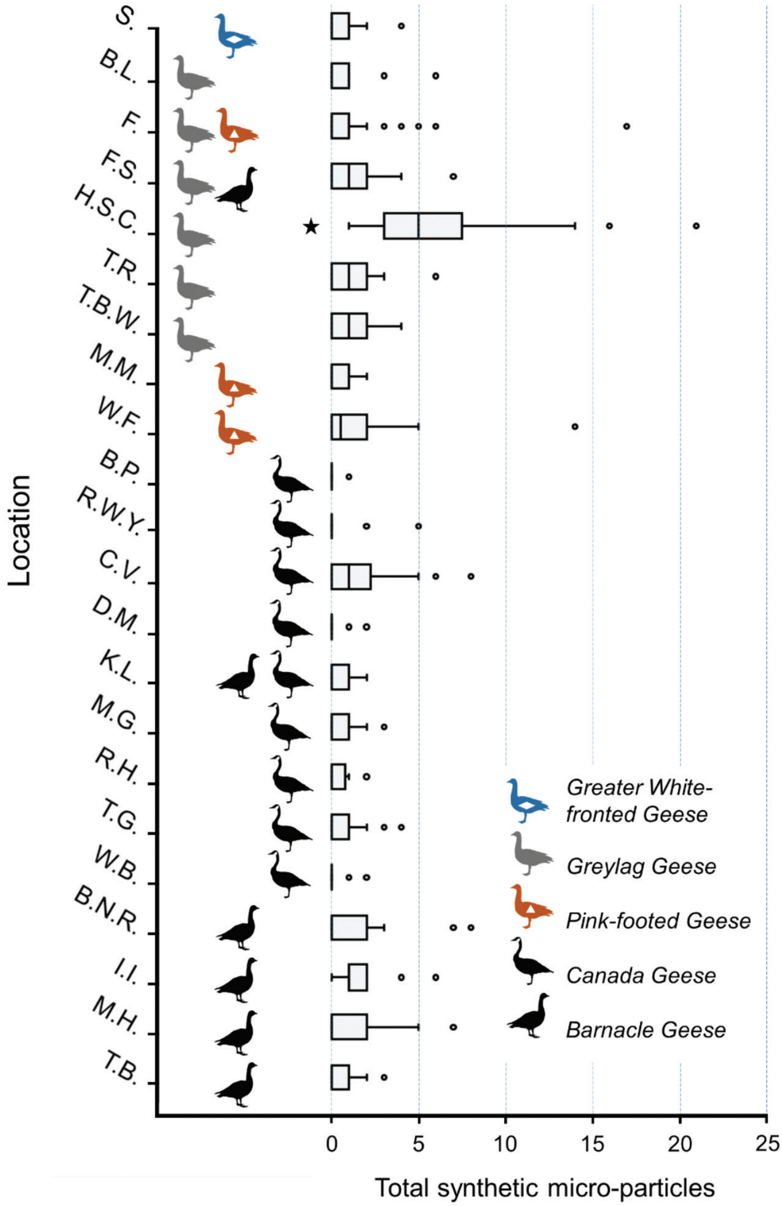

Figure 4. Median values for synthetic micro-particles recovered from a total of 809 faecal samples for geese at locations throughout Britain and Ireland. Interquartile ranges (IQR), maximum and minimum IQR values, and outliers are shown. The star symbol denotes a statistical difference among H.S.C. and all other locations ($P < 0.05$). All other counts were statistically similar (*i.e.* all n.s.). Note: zero-inflated data yielded numerous median values of zero.

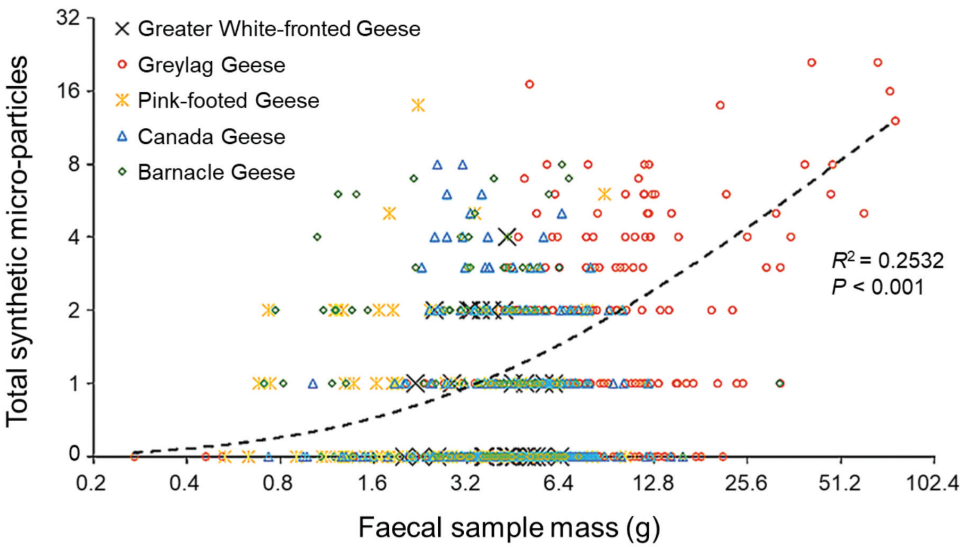

Figure 5. Log-log relationship for the total number of synthetic micro-particles detected per faecal sample relative to the mass of each sample for the assessed geese. The coefficient of determination (R^2) for linear regression is shown. The y-axis log-scale commences at the zero value for ease of interpretation.

micro-particles ingested by geese, with fewer micro-particles being ingested by geese residing at the furthest inland points (> 70 km). Nevertheless, geese species appear to be universally prone to ingesting synthetic micro-particles irrespective of the location. Ingestion of synthetic debris has previously been documented for various seabirds residing in coastal locations of Ireland (Acampora *et al.* 2016). Yet records of synthetic debris ingestion remain scarce for birds inhabiting coastal locations in Britain, perhaps reflecting there being fewer studies in this area (see for example Harris & Wanless 1994; Coughlan *et al.* 2021a). Nevertheless, the detection of synthetic micro-particles in geese dwelling at coastal sites in Britain is in-line with international reports for seabirds and waterbirds. In general, there is a paucity of information available concerning the fate of synthetic micro-particles in inland terrestrial and wetland environments (Zhao *et al.* 2016; Wong *et al.* 2020). In recent years, various studies have indicated that synthetic debris can be ingested by bird species residing in terrestrial (Zhao *et al.* 2016; Coughlan *et al.* 2021b), and freshwater habitats (Gil-Delgado *et al.* 2017; Winkler *et al.* 2020), often as a result of food chain transfer for predatory and omnivorous birds (*e.g.* D'Souza *et al.* 2020). The present study amplifies these previous insights by demonstrating that the ingestion of synthetic micro-particles by waterbirds is prevalent in non-marine environments. Further, our study demonstrates that obligate herbivores such as geese can regularly ingest synthetic micro-particles.

Repeated sampling of five selected locations, namely Ballygilgan Nature Reserve

Chew Valley, Foula Island, Horning Sailing Club and Twyning Green (Table 1), revealed that ingestion of synthetic micro-particles by geese is a reoccurring phenomenon. Although Coughlan *et al.* (2020) previously documented repeated micro-debris ingestion for Barnacle Geese at a single location over a four-year period, the present study indicates that repeated ingestion in multiple seasons occurs across species and sites. While informative, a truly reliable assessment of any change in debris ingestion frequencies would require sampling events consisting of > 14,000 birds (*e.g.* ± 5% detection rate with a sampling power of 80%; Lavers & Bond 2016), which is simply not feasible for the vast majority of study systems. Further, movement ecology also needs to be considered to identify locations where synthetic debris is likely to be ingested and subsequently deposited on a daily (*e.g.* Martín-Vélez *et al.* 2021) or seasonal timescale (*e.g.* Doyle *et al.* 2021). Nevertheless, repeated multi-year assessments should be pursued to better elucidate temporal patterns of synthetic micro-particle ingestion by geese and other Anatidae over longer time periods.

Interestingly, very few debris particles > 5 mm in length were detected (n = 5), despite it being likely that geese would encounter synthetic debris > 5 mm in size, given their abundance in European environments (*e.g.* Vriend *et al.* 2023). However, synthetic micro-particles can be produced through the fragmentation of larger particles due to biotic and abiotic effects (*e.g.* Mateos-Cárdenas *et al.* 2020), including within digestive tracts of birds (Provencher *et al.* 2018), especially granivorous waterfowl with strong gizzards (Mayhew & Houston 1993) that are potentially capable of mechanically disintegrating larger synthetic debris items over time (Reynolds & Ryan 2018). Therefore, the ingestion of debris > 5 mm in size may result in the presence of synthetic micro-particles of ≤ 5 mm in faecal samples.

Origin and fate of recovered synthetic micro-particles

The exact origin of the recovered synthetic micro-particles is unknown, but their ingestion by geese is likely a result of environmental contamination. The presence of synthetic micro-particles in natural environments is often due to the breakdown of larger synthetic debris items (Law & Thompson 2014) and has previously been linked to the availability of historical or current sources of synthetic debris at study sites (*e.g.* Gil-Delgado *et al.* 2017; Reynolds & Ryan 2018). Notably, synthetic micro-fibres can be dispersed in high quantities locally *via* shedding from synthetic clothing (Napper & Thompson 2016; De Falco *et al.* 2019). Whilst spatial and temporal variation for the distribution and abundance of synthetic debris seems to regularly occur, these debris are generally considered to be a widespread contaminant of freshwater and terrestrial environments worldwide (*e.g.* Stanton *et al.* 2020; Wong *et al.* 2020). The present study would have benefited from inclusion of field controls to account for potential atmospheric deposition of micro-particles (*e.g.* Allen *et al.* 2020); however, the methodology focused on collection of fresh samples which likely reduced risk of atmospheric contamination. Ingestion of synthetic micro-particles may also occur when geese forage on agricultural lands, especially farmland where plastic sheets have been deployed for crop protection or lands treated with biosolid sludges derived from wastewater treatment plants, which can harbour extremely high abundances of micro-particles (> 15,000 synthetic particles kg^{-1}; Mahon *et al.* 2017).

Although a detailed assessment of each sampling location was not possible, coastal areas were especially prone to the presence of synthetic debris, which generally appear to have been washed in from the sea along low lying shorelines by tidal forces (*e.g.* domestic waste and fishing gear; Coughlan *et al.* 2020, 2021a). On Foula and the Inishkea Islands, for example, this synthetic debris can be blown further inshore during storm conditions and can be found in geese foraging areas. Our data indicate ingestion rates appear to be similar among coastal and inland locations situated < 35 km from the coast. Although inland locations can be susceptible to both urban and agricultural sources of synthetic micro-particles. The present study does not account for urbanisation, human population densities, land use or differences in agricultural practices among regions, and these landscape level variables could influence the prevalence of synthetic micro-particles among sampling sites. Future studies should attempt to sample geese more widely across Great Britian and Ireland, with greater inclusion of inland areas and consideration of landscape level effects.

The fate of synthetic micro-debris following their excretion by geese will also need to be considered to elucidate their complete impact on the environment. Due to poor digestive performance, Anatidae faeces can contain undigested food items that will attract other organisms to forage on these faeces, including other Anatidae such as swans (*i.e.* coprophagy, *e.g.* Shimada 2012). Differences in the duration of retention within bird gastrointestinal tracts will need to be considered to reveal possible durations of exposure to leached chemical compounds, as well as likely vectoring of synthetic debris and associated chemical contaminants among environs. For example, as a long-distance migrant, Ireland's wintering Barnacle Geese population originates exclusively from remote areas of north-east Greenland, while British populations tend to arrive from both Greenland and Svalbard (Wernham *et al.* 2002). As hypothesised before by Coughlan *et al.* (2020), with short gut retention times of 1.9–3.1 h (Prop & Vulink 1992), Barnacle Geese could potentially vector synthetic particles and other contaminants amongst remote areas of Greenland, Iceland and Ireland. Further, several Anatidae have demonstrated longer gut retention times of up to 96 h, including Greylag Geese (García-Álvarez *et al.* 2015), which increases their capacity to act as biovectors considerably. On a local scale, geese typically move several kilometres during the day between favoured feeding and roosting sites (Giroux & Patterson 1995), ranging from 1–20 km depending on the time of year (Doyle *et al.* 2023). Accordingly, the micro-particles recorded were not necessarily ingested in the habitats where faeces were collected. Biovectoring of synthetic debris ingested in agricultural fields to wetlands where the geese roost is a process that may be worth investigating, in the same way that geese input nutrients into wetlands (Dessborn *et al.* 2016).

Considerations for future research

Further in-depth assessments are required to ascertain the overall impact of synthetic micro-particles on individual Anatidae, as well as potential long-term population effects. In particular, the extent of absorption and subsequent impacts of chemical contaminants requires investigation, especially in relation to bird health and developmental life stages (*i.e.* embryotic and neonate stages; Tanaka *et al.* 2020). Greater quantification of the amounts and types of synthetic debris available across different environments is also required to elucidate the level of contamination risk, as well as the rates of ingestion and retention by waterbird species (English *et al.* 2015; Holland *et al.* 2016; Reynolds & Ryan 2018). Although visual identification is considered reliable (Zhao *et al.* 2016; Reynolds & Ryan 2018; Stanton *et al.* 2019), there remains a risk that some non-synthetic fibres may be misidentified as synthetic fibres. Yet the release of non-synthetic micro-fibres into environments also represents a harmful environmental contaminant and their detection within faecal samples would also be of concern (*e.g.* chemically treated textiles; Stone *et al.* 2020).

Naturally originating textile micro-fibres, such as treated cotton and wool fibres modified for textile applications inclusive of impregnation with dyes, colour stabilisers, flame retardants, water and stain repellents (*e.g.* Liu *et al.* 2022), have emerged as a concerning environmental pollutant (Stanton *et al.* 2019; Stone *et al.* 2020). Although an abundance of studies shows detrimental environment, ecological and physiological effects linked to the proliferation of pure synthetic micro-particles across terrestrial and aquatic ecosystems, the ecotoxicological impact of treated natural fibres remains poorly explored – particularly in relation to persistence, toxicity, and chemical load (Stanton *et al.* 2024). Treated textile micro-fibres and pure synthetic fibres could not be definitively isolated from one another by the present study, yet detection of any anthropogenic material is concerning for environmental health and conservation. Future research seeking to distinguish between synthetic and natural micro-fibres should also consider the use of analytical chemistry techniques, such as Raman and Fourier Transform Infrared Spectroscopy (FTIR), for identification of polymers ingested by wildlife (Zhao *et al.* 2016; Stanton *et al.* 2019).

Conclusion

The present study demonstrates that ingestion of low quantities of synthetic micro-particles is a frequent and widespread process within flocks of geese inhabiting locations across Great Britain and Ireland. Further research is however required to provide a better understanding of the types, sources and fates of synthetic micro-particles in goose habitats, as well as their possible impact on the birds' physiological and developmental processes.

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References

Acampora, H., Lyashevska, O., Van Franeker, J.A. & O'Connor, I. 2016. The use of beached bird surveys for marine plastic litter monitoring in Ireland. *Marine Environmental Research* 120: e87–e91.

Allen, S., Allen, D., Moss, K., Le Roux, G., Phoenix, V.R. & Sonke, J.E. 2020. Examination of the ocean as a source for atmospheric microplastics. *PLoS ONE* 15(5): e0232746.

Amat, J.A. & Varo, N. 2008. Grit ingestion and size-related consumption of tubers by Greylag Geese. *Waterbirds* 31: 133–137.

Baulch, S. & Perry, C. 2014. Evaluating the impacts of marine debris on cetaceans. *Marine Pollution Bulletin* 80: 210–221.

Bessa, F., Frias, J., Kögel, T., Lusher, A., Andrade, J., Antunes, J., Sobral, P., Pagter, E., Nash, R., O'Connor, I., Pedrotti, M.L., Keros, E., León, V.M., Tirelli, V., Suaria, G., Lopes, C., Raimundo, J., Caetano, M., Gago, J., Viñas, L., Carretero, O., Magnusson, K., Granberg, M., Dris, R., Fischer, M., Scholz-Böttcher, B.M., Lorenzo, S.M., Grueiro, G., Fernández-González, V., Palzzo, L., Camedda, A., de Lucia, G.A., Avio, C.G., Gorbi, S., Pittura, L., Regoli, F. & Gerdts, G. 2019. Harmonized protocol for monitoring microplastics in biota. JPI-Oceans BASEMAN Project Report No. 10.13140/RG.2.2.28588.72321/1. JPI-Oceans BASEMAN Project, Brussels, Belgium.

Brooks, M.E., Kristensen, K., van Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Maechler, M. & Bolker, B.M. 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *The R Journal* 9: 378–400.

Coughlan, N.E., Doyle, S., Baker-Arney, C., Griffith, R.M., Lyne, L., Williams, H., Kelly, T.C., McMahon, B.J., Dick, J.T.A. & Cunningham, E.M. 2020. Ingestion of anthropogenic debris by migratory barnacle geese *Branta leucopsis* on a remote north-eastern Atlantic island. *Marine Pollution Bulletin* 160: 111588.

Coughlan, N.E., Baker-Arney, C., Brides, K., Dick, J.T.A., Griffith, R.G., Holmes, C., Johnston, R., Kelly T.C., Lyne, L. & Cunningham, E.M. 2021a. First record of synthetic micro-fibre ingestion by Mute Swans *Cygnus olor* and Whooper Swans *C. cygnus*. *Wildfowl* 71: 72–82.

Coughlan, N.E., Cunningham, E.M., Griffith, R.M., Baker-Arney, C., Lyne, L., Dick, J.T.A. & Kelly, T.C. 2021b. Ingestion of synthetic micro-fibres by the Eurasian Magpie *Pica pica*. *Irish Birds* 43: 23–28.

Cunningham, E.M., Kiriakoulakis, K., Dick, J.T.A., Kregting, L., Schuchert P. & Sigwart J.D. 2020. Driven by speculation, not by impact – the effects of plastic on fish species. *Journal of Fish Biology* 96: 1294–1297.

De Falco, F., Di Pace, E., Cocca, M. & Avella, M. 2019. The contribution of washing processes of synthetic clothes to microplastic pollution. *Scientific Reports* 9: 1–11.

de Souza Machado, A.A., Kloas, W., Zarfl, C., Hempel, S. & Rillig, M.C. 2018. Microplastics as an emerging threat to terrestrial ecosystems. *Global Change Biology* 24: 1405–1416.

D'Souza, J.M., Windsor, F.M., Santillo, D. & Ormerod, S.J. 2020. Food web transfer of plastics to an apex riverine predator. *Global Change Biology* 26: 3846–3857.

Dessborn L., Hessel R. & Elmberg J. 2016. Geese as vectors of nitrogen and phosphorus to freshwater systems. *Inland Waters* 6: 111–122.

Doyle, S., Walsh, A., McMahon, B. J. & Tierney, T.D. 2018. Barnacle Geese *Branta leucopsis* in Ireland: results of the 2018 census. *Irish Birds* 11: 23–28.

Doyle, S., Cabot, D., Griffin, L., Kane, A., Colhoun, K., Bearhop, S. & McMahon, B.J. 2021. Spring and autumn movements of an Arctic bird in relation to temperature and primary production. *Journal of Avian Biology*: e02830.

Doyle, S., Cabot, D., Griffin, L., Kane, A., Colhoun, K., Redmond, C., Walsh, A. & McMahon, B. 2023. Home range of a long-distance migrant, the Greenland Barnacle Goose *Branta leucopsis*, throughout the annual cycle. *Bird Study* 70: 37–46.

English, M.D., Robertson, G.J., Avery-Gomm, S., Pirie-Hay, D., Roul, S., Ryan, P.C., Wilhelm, S.I. & Mallory, M.L. 2015. Plastic and metal ingestion in three species of coastal waterfowl wintering in Atlantic Canada. *Marine Pollution Bulletin* 98: 349–353.

Gall, S.C. & Thompson, R.C. 2015. The impact of debris on marine life. *Marine Pollution Bulletin* 92: 170–179.

García-Álvarez, A., van Leeuwen, C.H., Luque, C.J., Hussner, A., Vélez-Martín, A., Pérez-Vázquez, A., Green, A.J. & Castellanos, E.M. 2015. Internal transport of alien and native plants by geese and ducks: an experimental study. *Freshwater Biology* 60: 1316–1329.

Gil-Delgado, J.A., Guijarro, D., Gosálvez, R.U., López-Iborra, G.M., Ponz, A. & Velasco, A. 2017. Presence of plastic particles in waterbirds faeces collected in Spanish lakes. *Environmental Pollution* 220: 732–736.

Giroux, J.-F. & Patterson, I.J. 1995. Daily movements and habitat use by radio-tagged Pink-footed Geese *Anser brachyrhynchus* wintering in northeast Scotland. *Wildfowl* 46: 31–44.

Harris, M.P. & Wanless, S. 1994. Ingested elastic and other artifacts found in puffins in Britain over a 24-year period. *Marine Pollution Bulletin* 28: 54–55.

Holland, E.R., Mallory, M.L. & Shutler, D. 2016. Plastics and other anthropogenic debris in freshwater birds from Canada. *Science of the Total Environment* 571: 251–258.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R. & Law, K.L. 2015. Plastic waste inputs from land into the ocean. *Science* 347: 768–771.

Kooi, M., Besseling, E., Kroeze, C., van Wezel, A.P. & Koelmans, A.A. 2018. Modeling the Fate and transport of plastic debris in freshwaters: review and guidance. *In* M. Wagner & S. Lambert (eds.), *Freshwater Microplastics*, pp. 125–152. The Handbook of Environmental Chemistry, Vol 58. Springer, Cham, Switzerland.

Kurniawan, S.B. & Imron, M.F., 2019. The effect of tidal fluctuation on the accumulation of plastic debris in the Wonorejo River Estuary, Surabaya, Indonesia. *Environmental Technology & Innovation* 15: 100420.

Lavers, J.L. & Bond, A.L. 2016. Ingested plastic as a route for trace metals in Laysan albatross

(*Phoebastria immutabilis*) and Bonin petrel (*Pterodroma hypoleuca*) from Midway Atoll. *Marine Pollution Bulletin* 110: 493–500.

Lavers, J.L., Bond, A.L. & Hutton, I. 2014. Plastic ingestion by flesh-footed shearwaters (*Puffinus carneipes*): implications for fledgling body condition and the accumulation of plastic-derived chemicals. *Environmental Pollution* 187: 124–129.

Law, K.L. & Thompson, R.C. 2014 Microplastics in the seas. *Science* 345: 144–145.

Liu, Y., Ding, D., Lu, Y., Chen, Y., Liao, Y., Zhang, G. & Zhang, F. 2022. Efficient and durable cotton fabric surface modification via flame retardant treatment. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 648: 129005.

Mahon, A.M., O'Connell, B., Healy, M.G., O'Connor, I., Officer, R., Nash, R. & Morrison, L. 2017. Microplastics in sewage sludge: effects of treatment. *Environmental Science and Technology* 51: 810–818.

Martínez-Haro, M., Green, A.J. & Mateo, R. 2011. Identifying sources of Pb exposure in waterbirds and effects on porphyrin metabolism using noninvasive fecal sampling. *Environmental Science & Technology* 45: 6153–6159.

Martín-Vélez, V., van Leeuwen, C.H., Sánchez, M.I., Hortas, F., Shamoun-Baranes, J., Thaxter, C.B., Lens, L., Camphuysen, C.J. & Green, A.J. 2021. Spatial patterns of weed dispersal by wintering gulls within and beyond an agricultural landscape. *Journal of Ecology* 109: 1947–1958.

Masura, J., Baker, J., Foster, G. & Arthur, C. 2015. *Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for Quantifying Synthetic Particles in Waters and Sediments*. NOAA Technical Memorandum, NOS-OR&R-48. U.S. Department of Commerce, Silver Spring, Maryland, USA.

Mateo, R., Guitart, R. & Green, A.J. 2000. Determinants of lead shot, rice and grit ingestion in ducks and coots. *Journal of Wildlife Management* 64: 939–947.

Mateo, R., Green, A.J., Lefranc, L., Baos, R. & Figuerola, J. 2007. Lead poisoning in wild birds from Southern Spain: a comparative study of wetland areas and species affected, and trends over time. *Ecotoxicology and Environmental Safety* 66: 119–126.

Mateos-Cárdenas, A., O'Halloran, J., van Pelt, F.N.A.M. & Jansen M.A.K. 2020. Rapid fragmentation of microplastics by the freshwater amphipod *Gammarus duebeni* (Lillj.). *Scientific Reports* 10: 12799.

Mayhew, P. & Houston, D. 1993. Food throughput time in European wigeon *Anas penelope* and other grazing waterfowl. *Wildfowl* 44: 174–177.

Mitchell, C. & Hall, C. 2018. Greenland Barnacle Geese *Branta leucopsis* in Britain and Ireland: results of the international census, spring 2018. Wildfowl & Wetlands Trust, Slimbridge, UK.

Napper, I.E. & Thompson, R.C. 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. *Marine Pollution Bulletin* 112: 39–45.

O'Connell, M.O., Smiddy, P. & O'Halloran, J. 2009. Lead poisoning in mute swans (*Cygnus olor*) in Ireland: recent changes. *Biology & Environment Proceedings of the Royal Irish Academy* 109B: 53–60.

O'Halloran, J., Myers, A.A. & Duggan, P.F. 1988. Lead poisoning in swans and sources of contamination in Ireland. *Journal of Zoology* 216: 211–223.

O'Hanlon, N.J., James, N.A., Masden, E.A. & Bond, A.L. 2017. Seabirds and marine plastic debris in the northeastern Atlantic: a synthesis and recommendations for monitoring and research. *Environmental Pollution* 231: 1291–1301.

Pierce, K.E., Harris, R.J., Larned, L.S. & Pokras, M.A. 2004. Obstruction and starvation associated with plastic ingestion in a northern gannet *Morus bassanus* and a greater shearwater *Puffinus gravis*. *Marine Ornithology* 32: 187–189.

Plastics Europe. 2024. *Plastics – the Fast Facts 2024*. Plastics Europe AISBL Rue Belliard 40, Brussels, Belgium.

Prop, J. & Vulink, T. 1992. Digestion by barnacle geese in the annual cycle: the interplay between retention time and food quality. *Functional Ecology* 6: 180–189.

Provencher, J., Bond, A., Aver-Gomm, S., Borrelle, S., Bravo Rebolledo, E., Hammer, S., Kuhn, S., Lavers, J., Mallory, M., Trevail, A. & van Franeker, J. 2017. Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. *Analytical Methods* 9: 1454–1469.

Provencher, J.F., Vermaire, J.C., Avery-Gomm, S., Braune, B.M. & Mallory, M.L. 2018. Garbage in guano? Microplastic debris found in faecal precursors of seabirds known to ingest plastics. *Science of the Total Environment* 644: 1477–1484.

R Core Team 2024. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Reynolds, C. & Ryan, P.G. 2018. Micro-plastic ingestion by waterbirds from contaminated wetlands in South Africa. *Marine Pollution Bulletin* 126: 330–333.

Rossi, L.C., Scherera, A.L. & Petrya, M.V. 2019. First record of debris ingestion by the shorebird American Oystercatcher (*Haematopus palliatus*) on the southern coast of Brazil. *Marine Pollution Bulletin* 138: 235–240.

Shimada, T. 2012. Ducks foraging on swan faeces. *Wildfowl* 62: 224–227.

Stanton, T., Johnson, M., Nathanail, P., MacNaughtan, W. & Gomes, R.L. 2019. Freshwater and airborne textile fibre populations are dominated by 'natural', not microplastic, fibres. *Science of the Total Environment* 666: 377–389.

Stanton, T., Johnson, M., Nathanail, P., MacNaughtan, W. & Gomes, R.L. 2020. Freshwater microplastic concentrations vary through both space and time. *Environmental Pollution* 263: 114481.

Stanton, T. James, A., Prendergast-Miller, M.T., Peirson-Smith, A., KeChi-Okafor, C., Gallidabino, M.D., Namdeo, A. & Sheridan, K.J. 2024. Natural fibers: why are they still the missing thread in the textile fiber pollution story? *Environmental Science and Technology* 58: 12763–12766.

Stone, C, Windsor, F.M., Munday, M. & Durance, I. 2020. Natural or synthetic – how global trends in textile usage threaten freshwater environments. *Science of the Total Environment* 718: 134689.

Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M. & Watanuki, Y. 2013. Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine debris. *Marine Pollution Bulletin* 69: 219–222.

Tanaka, K., Watanuki, Y., Takada, H., Ishizuka, M., Yamashita, R., Kazama, M., Hiki, N., Kashiwada, F., Mizukawa, K., Mizukawa, H., Hyrenbach, D., Hester, M., Ikenaka, Y. & Nakayama, S.M.M. 2020. In vivo accumulation of plastic-derived chemicals into seabird tissues. *Current Biology* 30: 723–728.

Torre, M., Digka, N., Anastasopoulou, A., Tsangaris, C. & Mytilineou, C. 2016. Anthropogenic microfibres pollution in marine biota. A new and simple methodology to minimize airborne contamination. *Marine Pollution Bulletin* 113: 55–61.

Vriend, P., Schoor, M., Rus, M., Oswald, S.B. & Collas, F.P.L. 2023. Macroplastic concentrations in the water column of the river Rhine increase with higher discharge. *Science of the Total Environment* 900: 165716.

Wernham, C., Toms, M., Marchant, J., Clark, J., Siriwardina, G. & Baillie, S. 2002. *The Migration Atlas: Movement of Birds of Britain and Ireland*. T. & A.D. Poyser, London, UK.

Windsor, F.M., Tilley, R.M., Tyler, C.R. & Ormerod, S.J. 2019. Microplastic ingestion by riverine macroinvertebrates. *Science of the Total Environment* 646: 68–74.

Winkler, A., Nessi, A., Antonioli, D., Laus, M., Santo, N., Parolini, M. & Tremolada, P. 2020. Occurrence of microplastics in pellets from the common kingfisher (*Alcedo atthis*) along the Ticino River, North Italy. *Environmental Science and Pollution Research* 27: 41731–41739.

Wong, J.K.H., Lee, K.K., Tang, K.H.D. & Yap, P.-S. 2020. Microplastics in the freshwater and terrestrial environments: prevalence, fates, impacts and sustainable solutions. *Science of the Total Environment* 719: 137512.

Wood, K.A., Brown, M.J., Cromie, R.L., Hilton, G.M., Mackenzie, C., Newth, J.L., Pain, D.J., Perrins, C.M. & Rees, E.C. 2019. Regulation of lead fishing weights results in mute swan population recovery. *Biological Conservation* 230: 67–74.

Zhao, S., Zhu, L. & Li, D. 2016. Microscopic anthropogenic litter in terrestrial birds from Shanghai, China: not only plastics but also natural fibers. *Science of the Total Environment* 550: 1110–1115.

Photograph: Barnacle Geese at Inishkea, Republic of Ireland, by Susan Doyle.