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Macroplastic in soil and peat. A case study from the remote islands of Mausund and Froan landscape conservation area, Norway; implications for coastal cleanups and biodiversity

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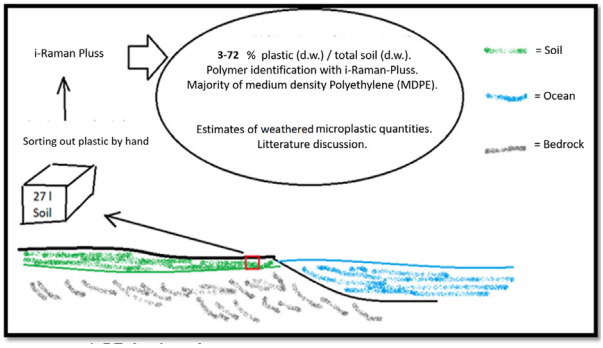
HIGHLIGHTS

- Large amounts of marine macroplastic pollution uncovered from vegetated soil.
- Macroplastic concentrations of 3 to 72 % (dw plastic/ dw soil samples).
- Use of hand held Raman Spectrometer for polymer detection; majority of MDPE.
- Estimates of future secondary microplastic concentrations, discussed compared to literature.
- Simple methodology for sampling and analysis of plastic induced soil.

GRAPHICAL ABSTRACT



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ABSTRACT

Marine plastic litter is ubiquitous and knowledge about its impact on coasts, open waters, the deep-sea, and the biota found in those habitats is increasing. However, studies of how it affects terrestrial environments such as islands are not as common. Over time, macroplastics in marine, as well as terrestrial environments, will fragment into microplastics. A toxic level of microplastic is defined by characteristics of the specific organisms and the habitat it affects, but also of the plastic itself. Plastic litter is being collected from wilderness areas through beach-cleanups by volunteers, schools and professionals. A question that needs to be addressed is whether macroplastic that is partially weathered and buried under vegetation should be taken out of the topsoil layer or left untouched to further degrade with the risk of negative impacts on soil organisms or removed from the topsoil layer. A quantification of the amount of plastic found within the topsoil layer is therefore of great interest. In this study, a survey was conducted in spring/autumn 2020 at Mausund and Froan landscape conservation area in Frøya municipality, Norway (N63°). Thirteen samples of vegetated soil from above the storm tide limit from eight remote and uninhabited islands were collected, quantified and analyzed, and the results showed high amounts of plastic. Potential future concentrations of microplastic in the samples if left untouched are estimated, based on a formula from existing literature.

1. Introduction

Micro- and macroplastics are ubiquitous. They are found in deep water sediments, in Arctic organisms at low trophic levels (Bergmann et al., 2017; Obbard et al., 2014; Knutsen et al., 2020), within indoor and

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outdoor air (Gasperi, 2018), tap water (WHO, 2019), animals throughout the food web (GESAMP, 2015; Hasnat, 2018) and in the terrestrial environment in general (Chae and An, 2018; Malizia and Monmany-Garzia, 2019; Accinelli et al., 2020). As most areas of our planet show traces of plastics, more research is encouraged (Puskic et al., 2020). Plastic is an important material in modern societies and we are not yet ready to move beyond the plastic age (Andrady and Neal, 2009). Worrying examples of plastic entering nature, causing potential risks for living organisms are being observed. It is important to quantify how much plastic is in nature and compare these results against known toxic levels in the literature. Limited numbers of studies on the concentration and effects of microplastics in terrestrial environments have been conducted so far (Chae and An, 2018; Qi et al., 2020). Lenz et al. (2016) calls for environmental realistic laboratory toxicity studies.

In this empirical study, microplastic items in nearshore soil and peat are counted, weighed, classified and the ratio between the amount of macroplastics and soil is calculated as percentage of total soil samples.

In addition, this article discusses how much microplastic the macroplastic found is likely to be fragmented into in terms of weight and number of particles if left to further degrade.

Macroplastics are defined in this paper as plastic particles greater than 5 mm in size; whereas microplastics are particles under 5 mm (GESAMP, 2015). Extreme hotspot concentrations of micro- and macroplastic in soil are normally characterized as sites in proximity to harbors, public areas, or dumpsites. In the context of this study, our research question is whether remote uninhabited islands in Norway show similar concentrations of plastics as hotspots areas.

This study was initiated when one of the authors of this article heard unusual sounds, while walking across remote islands along the Norwegian coast, in the area of Frøya and specifically Mausundvær and Froan landscape conservation area. It turned out to be plastic bottles and other forms of marine plastic litter washed off and buried underneath a layer of grass. The grass was turned upside down and the litter was revealed in surprisingly high quantities. The same trend was found in nearly all nearshore areas of the islands explored. In this study, eight Islands were randomly selected, and 13 soil samples in total were collected. Two of those were taken as reference samples, approximately 100 m from the shoreline, as they were expected to contain small concentrations of macroplastic.

The aim of this study is to (I) document how much macroplastic is found in the soil samples (II) document the types of plastic buried in the soil samples, and (III) estimate the quantity and weight of microplastics the macroplastic can be fragmented into if left to further degrade.

Experiences from low-cost sampling techniques, as a reliable methodology for research on plastics in soil are shared and discussed. Results are discussed in relation to existing literature on the toxicity of microplastic for the biota inhabiting soil and peat. Predictions of how much secondary microplastic the macroplastic will generate each year and how this will affect the biota are presented. We are also categorizing the types of macroplastics found.

Finally, the paper discusses macroplastic in relation to beach cleanup operations and other management implications, where it is today questionable how deep into the vegetation plastic should be removed or left to further degrade.

1.1. Theoretical background

In this chapter, we present theory from the literature on the effects of macroplastic on terrestrial vegetation, the rate of degradation from macro- to microplastic, and how soil organisms might be affected by both macroplastic, and secondary microplastic.

1.1.1. Weathering and chemical leakage of plastic polymers

Each plastic polymer has its specific decomposition rate. For instance studies of LEGO bricks, found acrylonitrile butadiene styrene (ABS) to be persistent in the marine environment for about 100–1300 years, with 3–40% breakdown by weight in an estimation of ±40 years (Turner et al., 2020). Loakeimidis et al. (2016) found polyethylene terephthalate (PET) bottles to radically change their FTIR-signature and lose functional groups after 15 years in the marine environment. On the other hand, Müller et al. (2001) estimated the lifetime of PET to be from 16 to 48 years based on kinetic models.

Degradation rate is dependent on, amongst other factors, polymer type, object thickness, environment, temperature, UV-radiation, physical abrasion, adhering biofilms and fungi. Estimating the total time of degradation from a mixture of plastics is therefore difficult if not impossible and estimated degradation rate in a marine environment cannot be directly compared to plastic buried in soil. Based on a literature review, Chamas et al. (2020) estimated the half-life of seven common polymers in buried soil (amongst other environments) to vary from 0.19 years for the polymers 'Others' (described as 'biodegradable plastic bags') to 4.6 years for low-density polyethylene (LDPE), 250 years for high-density polyethylene (HDPE) e.g. plastic bottles, to >2500 years for PET, PE and poly vinyl chloride (PVC) and to 5000 years for HDPE (pipes). The distinction between 'pipes' and 'bottles' relates to the thickness of the object rather than the polymer composition.

Macroplastic concentrating in beach sediments is found by Nakashima et al. (2012), to be a pathway for heavy metal contamination; however, the amounts measured in the study are not found to exceed US Environmental Protections Agency regulations in terms of annual leakages. Massos and Turner (2017) analyzed the elements Cd (cadmium), Pb (lead) and Br (bromine) in plastic pellets and plastic fragments, collected in SW England. The maximum concentrations of Cd, Pb and Br found were 3390 μg g^{-1}, 5330 μg g^{-1} and 13,300 μg g^{-1}, respectively.

In black food packaging, recycled from electronic and electrical waste, the following pollutants are found: brominated flame retardants (BFRs), Sb (antimony), Cd, Cr (chrome), Hg (mercury) and Pb (Turner, 2018). Colorants are associated with plastic containing metal substances (Groh et al., 2019). So-called pyroplastic is likely to be found in near-shore sediments. Pyroplastic is plastic deformed by heat, normally a result of low-temperature fire (Suyadi and Manullang, 2020; Menicagli et al., 2019).

1.1.2. Vegetation

When searching the terms '*macroplastic intitle:vegetation*' in Google scholar and '*macroplastic vegetation*' in webofscience.com and BASE-search.net, we found a total of nine studies (Suyadi and Manullang, 2020; Helcoski et al., 2020; Menicagli et al., 2019; Ding, 2021; Yao, 2019; Cozzolino et al., 2020; Ryan, 2020; Perez et al., 2018; Tramoy, 2019). Two of these studies are directly relevant to this case, as they investigate possible correlations between plastic abundance and vegetation health and development. Mangrove vegetation were found by Suyadi and Manullang (2020) to be negatively affected by plastic with statistically significant negative correlations ($p = 0.05$) between plastic abundance and mangrove tree density, tree height, mean tree diameter and density of seeding. Likewise, Menicagli et al. (2019) found that plastic chemical leachate negatively affected seeding and germination in sand dune vegetation.

1.1.3. Sediment and soil-dwelling organisms

Plastic is found in most wild animal species investigated (Machado et al., 2017; Rezania et al., 2018; Hasnat, 2018; GESAMP, 2015). Bivalves (*Ennucula tenuis* and *Abra nitida*) exposed to environmentally realistic concentrations of plastic (PE particles) experience a decrease in energy reserves and protein content. The severity of the effect increases with particle size (Bour et al., 2018). Bour et al. (2018, p. 655) also found a significant 'dose-dependent decrease in total energy', not dependent on particle size of the microplastic exposure. Wright et al. (2013) found the same trend with significant decreases in energy reserves in lugworms (*A. marina*) exposed to Unplasticized Polyvinyl Chloride or rigid Polyvinyl Chloride (uPVC). Bour et al. (2018) used concentrations

of 1, 10 and 25 mg/kg in their four-week exposure study, while Wright et al. (2013) used higher values of 1% and 5% (w/w). The same trends were found in exposure studies (20 μm polystyrene for 24 h) of Marine Copepod (*Calanus helgolandicus*) (Cole et al., 2015).

Microplastic pollution is proposed as a possible emerging contaminant with potential threats to terrestrial ecosystems by Machado et al. (2017); however, their study mainly focuses on soil-dwelling invertebrates, fungi and plant pollinators. Plastic is also part of what the Stockholm Resilience Centre qualify as 'novel entities' when describing the introduction of chemical pollution into the environment as one of the 9 planetary boundaries (Steffen et al., 2015). There is a lack of data so that it cannot be determined whether this boundary has yet been crossed (Steffen et al., 2015).

Soil invertebrates (*E. crypticus (*earthworm), *F. candida* (family of Isotomidae – six leg, *arthropods*) and *P. scaber* (common rough woodlouse) are found by Salonen et al. (2020) to be affected by exhibiting changes in energy reserves and feeding activity when exposed to concentrations corresponding to 0.062–28% (w/w) of polyester fiber (average of 760 μm ± 200 μm length of fibers). They did not find significant differences in mortality or reproduction of springtails, but they found a 34% decrease in feeding activity compared to the control sample for 1.5% (w/w) polyester short fiber exposure. *E. crypticus* responded with negatively altered reproduction for all concentrations of long fibers except 0.06% (w/w) making this a No Observed Effect Concentration (NOEC).

Earthworms *Lumbricus terrestris* were exposed to concentrations ranging from 7 to 60% of PE plastic mixed with plant litter (food for the *L. terrestris*) by Lwanga et al. (2016), which corresponds to a total of 1 to 15% (v/v) of the whole soil sample. At levels of 28 and 60% of microplastic concentrations (5 and 15% w/w); however, the mortality became 8 and 25% respectively and a significant weight loss was found when they were exposed to 28% microplastic-litter mix. In contrast, Prendergast-Miller et al. (2019) conducted an exposure study - using polyester microfiber - also with *L. terrestris*. They used 0.1 to 3% (w/w) exposure (for 35 days) and found no evidence of increased mortality, but a significant ($p < 0.001$) dose-dependent increase of the biomarker metallothionein (mt-2). Prendergast-Miller et al. (2019) also found that *L. terrestris* did not avoid microplastic particles, and that plastic present in the soil altered its burrowing behavior. This means that terrestrial plastic might alter key ecosystem services such as soil mixing provided by, amongst others, *L. terrestris*.

2. Methods

2.1. Sample collection

The samples were taken on the 3rd of March, 5th of June, 12th of August, 9th and 11th of September 2020. Coastal renovators, who are professional cleaners, had cleared large areas in the archipelago on the outer coast of central Norway. The 11 soil samples were taken from areas where a lot of marine litter has accumulated over time, but has been cleaned at the surface. The Islands and sampling sites within the archipelago were randomly selected, on the western side of these islands at sites with a minimum of 30 cm soil (Fig. 1 and Supplementary material, S1). The sites were vegetated and located just above the storm-tide level. We looked specifically at the amounts and types of plastic buried under the vegetation.

Most of the samples were collected down to the bedrock, i.e. 27–33 cm depth. We sampled 27 l of soil at each of the 13 locations, including the vegetated topsoil layer. Each sample was dug out and cut with knives. The sites are shown on a map in Fig. 1, and the coordinates are provided in the Supplementary material, S1.

All the equipment was rinsed a minimum of three times with distilled water, and finally with ethanol. The soil samples were excavated using small shovels and knives.

It was not possible to extract traditional core samples due to the presence of fishing and aquaculture ropes as well as other macroplastics. All the samples were therefore taken as one mixed sample of the topsoil-layer down to 33 cm. For a number of sites, this meant digging to the bedrock. This methodology for research on plastics in soil is low-cost and because large volumes (27 l) are analyzed, sources of error that affect the results are limited.

2.2. Sample preparation

The samples were preserved in polypropylene (PP) boxes. Each box has the capacity to hold 27 l. Sampling was standardized by filling each box completely with soil and plastic.

For most of the samples, macroplastic was separated from the sample the day after collection. Some samples were stored in a freezer at −24 °C for two weeks prior to sorting and weighing.

2.3. Classification

Macroplastics were weighed in grams (weight uncertainty ±2 g) per 27 l and the ratio between macroplastics and soil was calculated as a percentage. The types of plastic present in the soil samples were also recorded.

In addition, an estimation of microplastic amounts resulting from the decomposition of the microplastic found was calculated. The uncertainty in number of grams, is not visualized further into the extrapolation. This decision was taken due to the high uncertainty related to this calculation, and the fact that the level of uncertainty does not change the overall trend.

After the soil and macroplastics were weighed, the plastics were sorted by product category. The categories were inspired by Haarr et al. (2020) but adjusted to our data. The categories were 'commercial products' divided into 'Commercial ropes', and 'Not ropes'; "Private ('on the fly') and Household items", 'Pyroplastic' (Ehlers and Ellrich, 2020) and finally 'Other items' (Haarr et al., 2020). It is possible that some of the ropes are non-commercial; however, Haarr et al. (2020) argue that as the great majority are used commercially, it is the most logical way of classifying ropes. The great majority of 'other' items was impossible to classify due to their degree of decomposition. Some sources in the literature give the size of the macroplastic found. Based on experience with sample collection, sorting, and analysis, we concluded that these estimates were not relevant, due to the instability of the plastic litter in nature. As an example, a bucket could be counted as one piece of macroplastic of 35 cm size, or, if it is breaking apart while sampling, should it be counted as e.g. 150 pieces? The size of the plastic items is therefore not reported in this article. A selection from each sample/site was further analyzed to identify the type of plastic (polymer) with a Raman Spectrometer (Figs. 2 and 3). The randomly selected pieces gave a picture of which polymers were found in each sample/site (Fig. 5).

2.3.1. Proportion of plastic vs. soil

Each of the 11 samples, with soil and plastic, and the two reference samples, which were blind tests with only soil (number 8 and 13) were weighed and turned upside down on a clean table. One of the samples, before sorting are visualized in Fig. 4. Before handling the sample in the laboratory, sorting out and examining visible plastics, three samples were taken out of their glass jars; weighed, dried at 60 degrees for 48 h, then weighed again.

The macroplastic was also dried in a drying cabinet at a maximum of 50 degrees for 5 days and nights. The weight of the soil and macroplastic before and after drying was used to calculate wet weight vs. dry weight and the results are given in gram and percent of macroplastic within 27 l of soil and plastic (Table 1).

2.3.2. Plastic product type and color

From each sample, the macroplastic items were sorted by product type. As previously mentioned, the categories were 1) Commercial ropes, 2) Commercial, not ropes, 3) Private & Household, 4) Pyroplastic

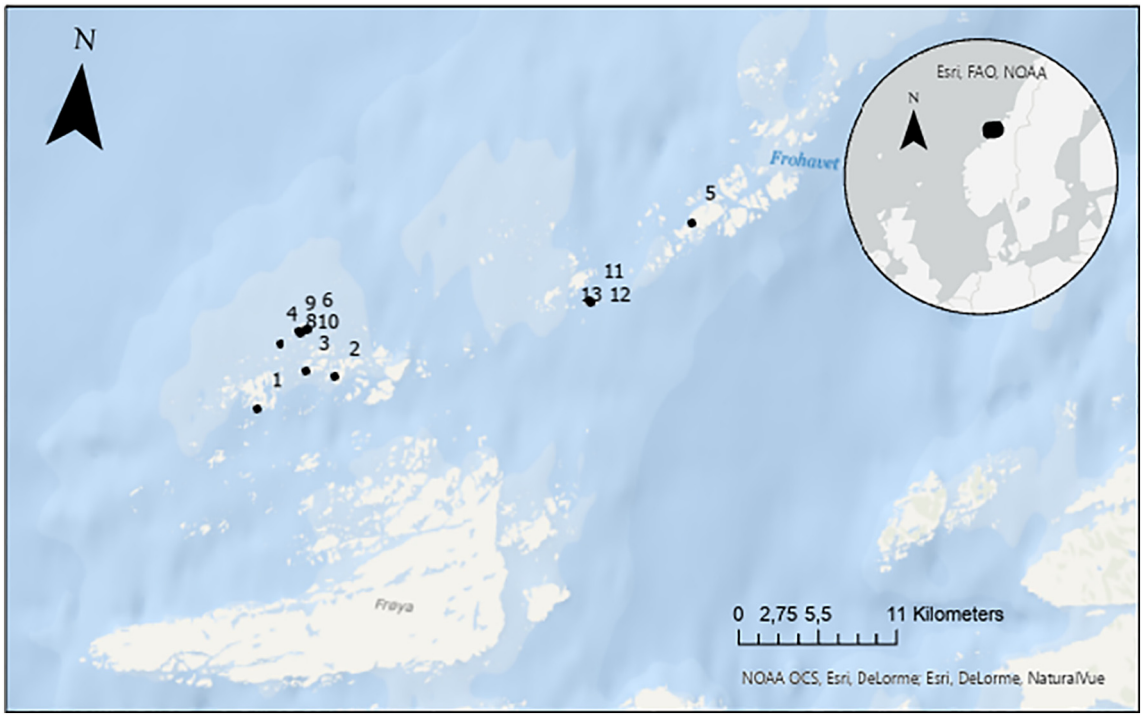

Fig. 1. Map of the sampling area and sampling sites in Central Norway. Layout: Jakob B. Cyvin, 2021.

and 5) Other items (Fig. 2). The color of each product was also determined and these results are presented in the Supplementary material, S2. The basis for this is that different inorganic pollutants give different colors, and there are indications of color-dependent ingestion of macroplastic by birds (Groh et al., 2019; Holland et al., 2016; Turner, 2018).

2.3.3. Raman spectrometer

A total of 113 macroplastic items (17% weight) were analyzed with i-Raman Plus 532H Portable Raman Spectrometer with a laser operating at 785,1 nm. The libraries used in these analyses were: *Raman Polymers & Polymer Additives Library* with 3412 spectra and *Raman Dyes, Pigments & Stain Library* with 1364 Spectra. Raman Spectrometers have a weak signal for materials that are dark in color, thin walled plastics and no signal for black materials. Blends with different concentrations of paraffin and polyethylene give different properties to these plastic items (Chen and Wolcott, 2014). Plastic items of known polymer composition were analyzed with the Raman Spectrometer before the plastic items from this study for quality control. Quality indices of at least 80% match

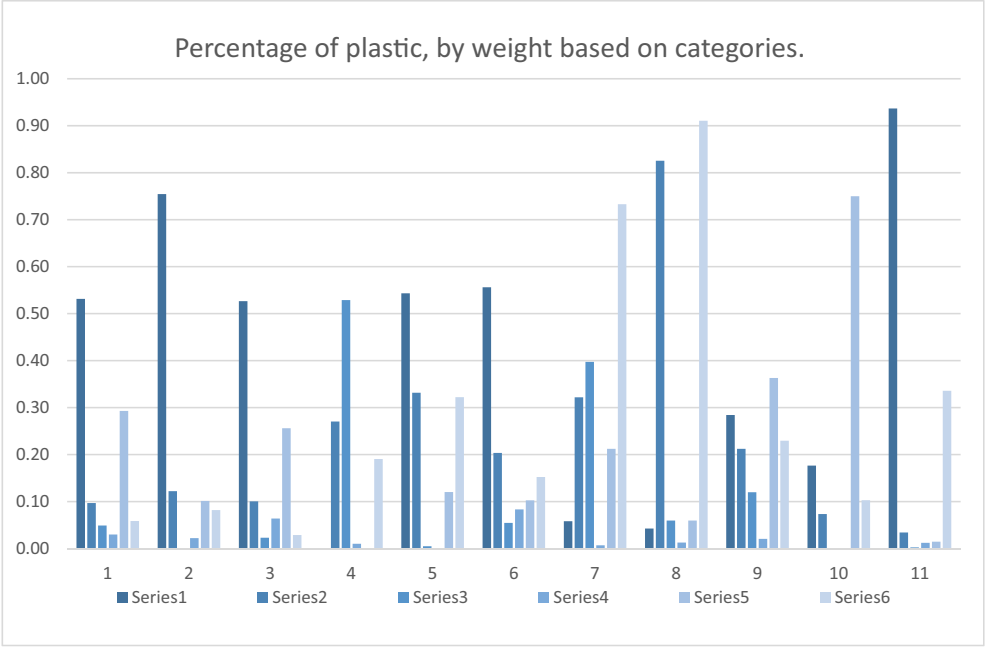

Fig. 2. Proportions of macroplastics found for all sites except control sites (8 and 13) for the following categories 'Commercial, ropes'; 'Commercial, not ropes'; 'Private and Household items', 'Pyroplastic' and 'Other' items. Classification inspired by Haarr et al. (2020).

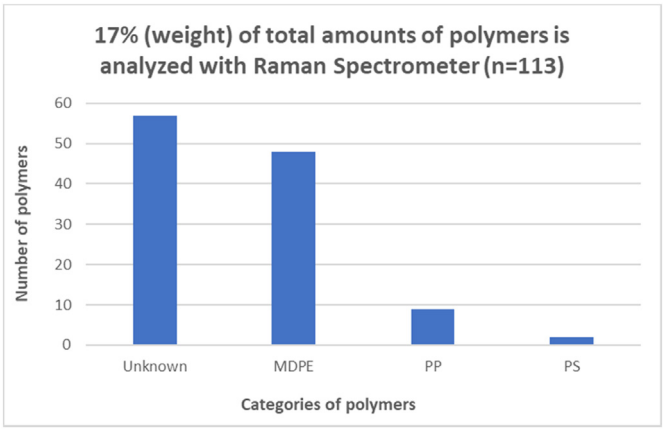

Fig. 3. Polymers (plastic samples) analyzed with a Raman Spectrometer. The categories are 1) unknown, 2) medium density polyethylene (MDPE), 3) polypropylene (PP) and 4) polystyrene (PS).

with the library were selected as approved matches. This value is vital to distinguish between 'approved' or 'disapproved' scanning. The plastic items analyzed were randomly selected from each of the each of the soil samples one to twelve (except number 8), i.e. 11 samples. The amount of material scanned (weight) is visualized in Fig. 2.

In addition to the analysis using a Raman Spectrometer, the plastic was also examined visually; results are described in Section 3.3.

2.3.4. Estimates of future secondary microplastic levels

In the result section, we are presenting estimates of weight and future projections of the number of secondary microplastic particles, due to further weathering of the macroplastic currently found in the soil samples.

The equation used for estimating number of future microplastic particles is as follows:

$$\left(\frac{m}{v}\right) * d = \textit{estimated number of MP}\frac{\textit{particles}}{kg}\ \textit{with density}\frac{0,93g}{cm^3}.$$

When m = (grams of macroplastic in the sample/kg of total sample), v = volume of one microplastic particle with the diameter of 100 μm which equals $5.24 * 10^{-7}cm^3$, and d = 1.07 (density = 0.93 g/cm^3).

It is important to mention that some of the fragments are likely to be washed out of the soil, and it is unclear whether all macroplastic that is degrading, will go through the micro- and nanoplastic stages or if some of the mass will undergo the change back to the basic elements of carbon, hydrogen and oxygen (Chamas et al., 2020). The projection of future mass of the microplastic is based on basic extrapolation, with 500 years of half-life as a reference (Chamas et al., 2020). These estimates are rough and need validation.

3. Results and discussion

The main results from this study comprise of a quantification of macroplastics in the soil samples and a characterization of the type, color and weight of plastic items in each soil sample.

In addition an estimate of the future number of microplastic particles produced through the weathering of the macroplastic currently found is provided, based on a formula from the literature. The plastic litter found is classified into broad categories (see Section 2.3.2) and its polymer composition is presented.

3.1. Macroplastic quantification and estimation of future microplastic content in soil samples

The percentage of different types of plastic based on weight is presented in Fig. 2. The results show that the majority is made up of commercial ropes, with a high proportion of 'other' items, where it was not possible to identify the original object. An example of these objects is a high number of plastic films, and fragmented pieces of hard plastic.

Pyroplastic was found in all the samples analyzed. The sources of the pyroplastic found are not known: Sources, composition, chemicals and properties should be further investigated.

Percentages of macroplastic within the soil samples are presented in Table 1. Estimates of future microplastic concentrations per kg of dry soil are also presented in Table 1 as number of particles. The decision to communicate mass and number of particles is based on existing literature; as both number of particles/(weight/volume) for sediment

Fig. 4. Sample number 3 before sorting out macroplastic.
Photo: Jakob B. Cyvin.

Table 1
Results of the analysis of soil samples. Total weight (soil and plastic) g/27 l, % of plastic in each sample and estimated number of microplastic particles after degradation. The uncertainty associated with the weighing process is ±2 g.

Sample ID	Total dry weight in grams (soil and plastic)/27 l	% of plastic in samples dw plastic/dw total weight sample	Estimated number of MP particles/kg with density 0,93 g/cm^3. Spheres of 100 μm in diameter. Medium density PE	Estimated number of MP particles/kg/year with 'half-life land' (buried) of 500 years. Spheres of 100 μm in diameter. High density PE. Based on Chamas et al. (2020)
1	13,200	28.19%	575,789,069	1,205,438
2	8800	37.05%	756,640,452	1,829,434
3	10,600	29.66%	605,785,762	1,323,690
4	12,000	72.67%	1,484,006,547	2,868,746
5	22,500	11.87%	242,471,698	511,427
6	10,500	22.92%	468,040,623	1,924,990
7	10,700	6.71%	137,073,050	325,296
9	11,000	15.92%	325,139,179	651,411
10	7000	12.97%	264,990,108	683,736
11	12,300	3.60%	73,552,294	86,746
12	13,700	25.99%	530,757,965	1,060,998

(e.g. Claessens et al., 2011; Knutsen et al., 2020; Brown et al., 2011), and mass/(volume/weight) are presented in the literature for exposure studies (Lee et al., 2013; Bour et al., 2018; Cole et al., 2015; Salonen et al., 2020).

Sample 1,2,3,4,5,6,7,9,10, 11 and 12 show a wide range of variation in the proportion of plastic, but all soil samples except one (ID: 11) were highly infiltrated with plastic (Table 1). After sorting the soil for 13 samples (including two reference samples at the top of the islands which are not presented in Table 1), and a total of 351 l of soil, only 4 earthworms (*Lumbricus terrestris*) were found. Without control samples from the same elevation, it is difficult to determine how many soil organisms 'should have been there'. However, it seems surprising to find so few in the topsoil layer. Further research is needed to investigate whether this is a trend in plastic-ridden topsoil or an isolated case.

Microplastic concentrations in the soil is so far not estimated, but based on Chamas et al. (2020), and an estimate of linearity in time-dependent weathering from macro to microplastic, it is predicted that the macroplastic found will correspond to between 7.35×10^5 and 1.4×10^9 microplastic particles (estimates based on 100 μm spheres) per kg dry soils each year when estimating a half-life of 500 years (Table 1). Within each sample of 27 l of soil, this corresponds to 1.5–35% microplastic of the weight in 35 years, with 3.5% in sample 4 already in 50 years. Existing microplastic concentrations in the samples are not included in this estimate.

Nakashima et al. (2012) and Massos and Turner (2017) found microplastic and plastic fragments to leak chemicals and heavy metals. In relation to our findings of up to 70% plastic in the soil, further research is needed to determine whether these soils are also getting contaminated by similar chemicals.

3.2. Macroplastic analysis with Raman Spectrometer

The different polymers detected with the Raman Spectrometer are presented in Fig. 3. Supplementary materials (S3) shows a selection with six spectra, from the scanning of samples 3a, 2a2, 3h, 5e, 5l, 7a. These are 6 of 113 analyzed samples.

The vast majority of our 113 objects analyzed with a Raman Spectrometer, were found to be made up of medium density polyethylene (MDPE) and unknow plastics. Polypropylene (PP) and polystyrene (PS) were also recorded. It is not surprising that PE dominates, as PE is the most widely used plastic in the world (Andrady, 2015).

Some plastic fragments showed paraffin on one side and polyethylene (PE) on the other side. For fragments such as these, the result was published as Medium Density Polyethylene (MDPE), after visual examination. It was not appropriate to assess whether there were significant differences between the 11 locations where the samples were taken.

One possible explanation for the result *unknown* being dominant is that the plastic items analyzed were weathered and depolymerized. The plastic samples analyzed had possibly previously been at sea and buried in soil for many years. Chamas et al. (2020) explain the degradation at the surface of the plastic fragments with mass loss and depolymerization. Plastic products will, after being carried by ocean currents, washed against rocks, and buried in terrestrial environments for a long time, being exposed to UV radiation and temperature differences, quickly become brittle and there will be changes in the polymer surface with visible cracks, cavities and surface degradation (Chamas et al., 2020). These processes affect the time it takes for fragmentation and degradation. A library of degraded plastics is one way to increase the reliability of the spectroscopy analysis.

3.3. Visual examination of macroplastic

Macroplastics were found in 11 of the 13 soil samples. As abovementioned, the plastic was sorted out from all sites except control sites (8 and 13) for the categories described in Section 2.3.

Fig. 4 (Sample 3) shows the plastic fragments before separation from the soil. In sample 3, ropes and single fibers degraded from ropes were the main findings. In sample 10, a lot of thin-walled plastic and ropes were found. Fig. 5 shows the amount of macroplastic from sample 10 and the randomly selected fragments from the same sample which was then analyzed with a Raman Spectrometer.

Multiple rope fragments and thin-walled plastic items were isolated from the 11 soil samples after visual inspection. The results from the Raman Spectrometer analysis of the rope fragments appeared as 'unknown'. The supplier states that i-Raman plus has a weak signal for thin-walled plastic sheets and no signal for black materials. This is not to say that it is not plastic. All fragments extracted from the sample were visually identified as plastic by three different scientists. The results were 'unknown' on 56 of the 113 samples. The high number of 'unknown' results is explained by Chamas et al. (2020) by the degree of weathering which makes the plastic material difficult to analyze. The change in plastic structure gives weak or no Raman signal. The microplastic items found in this study (Tables 1 and 2) are expected to further fragment into high numbers of microplastic particles (Chamas et al., 2020), which will with high probability surpass concentrations of microplastic known to cause damage to the local biota (Salonen et al., 2020; Lwanga et al., 2016; Prendergast-Miller et al., 2019). Macroplastic itself is found to cause changes in the morphology of the vegetation (Suyadi and Manullang, 2020; Menicagli et al., 2019) and we were interested to know if this is the case also for the vegetation that is covering the western islands of Norway. Samples 1–4 and samples 6 and 12 have particularly high concentrations of plastic (Table 1). The low numbers of invertebrates found during sorting is also worth mentioning. The results of the polymer composition seem incongruous (Fig. 3), due to very high levels of medium density PE compared to e.g. sea bottom sediments. However, it is natural that plastic types with lower polymer numbers should be the ones washing up on beaches as they will have a density lower than water and be floating at the surface. Our results show that the western side of the islands on the coast of mid-Norway is highly polluted down to at least 30 cm below the surface. Already after 50 years, the levels of microplastic within the soil, created by the weathering of the macroplastic present, will reach values higher than 1–3% of the soil by weight (Table 2) at multiple sites investigated. When comparing these levels to toxicology studies presented in the introductory chapter, we conclude that these are likely to negatively affect the local biota (Wright et al., 2013; Bour et al., 2018; Cole et al., 2015; Salonen et al., 2020; Prendergast-Miller et al. (2019). The biota is likely to be affected through altered soil properties from the presence of macroplastics as physical obstacles, and from secondary microplastics, due to their toxicity, leaching of heavy metals

Fig. 5. The totality of macroplastic items found in sample number 10 (to the left) and the pieces that were randomly selected for analysis with a Raman Spectrometer (to the right). Photo: Hilde Ervik.

and even the creation of future plastic induced rocks such as plastiglomerates (De-La-Torre et al., 2021) or plastic exposed to heat called pyroplastic (Ehlers and Ellrich, 2020). The samples were taken in areas with waste visible at the surface, but not specifically within spots visually found to be *hotspots*. We can therefore not say that these results are an overrepresentation of reality and can only wonder how representative these levels of pollution are for the West coast of Norway as a whole.

4. Concluding remarks and directions for further research

On the western side of the remote islands of Mausund and Froan landscape conservation area, in Frøya municipality Trøndelag county, Norway, we found concentrations of microplastic ranging from 3 to 72% (dw/dw) in soil samples from vegetated areas above the tide limit. The majority of the samples investigated should, based on its amount of plastic be characterized in the same category as hot spots. Ropes made up most of the plastic items found. MDPE-plastic dominated the composition of polymers. The number of future microplastics is dependent on the polymer thickness and on the surface area of the plastic when sedimented. UV-degraded plastic coming from the sea will have started the weathering process and its half-life time will therefore be lower (Table 1). More research is needed to determine the current polymer composition of existing macro vs. microplastic and possible correlations between plastic concentrations and vegetation density, health, and biodiversity. The prediction that 'there will be more plastic than fish in the world's oceans by 2050' is a highly cited (e.g. Naidoo and Glassom, 2019; Jovanović, 2017; McNeish et al., 2018) example of a similar extrapolation based on estimates with high levels of uncertainty (Jambeck et al., 2015; Jennings et al., 2008; World Economic Forum, 2016), but with an important message as long as it is used correctly.

The literature presented in this paper leads to the idea that there is a high probability for valid correlations between plastic abundance and the health of the terrestrial biota within the remote geographical sites of Mausund, Norway. Due to the small amount of research found through the literature review, it is difficult to advise whether sediments like the ones presented in this paper should be cleaned or left for further degradation. To resolve this dilemma, more research is needed about the possible causal correlation between soil health, the health of biota and macro and microplastic concentrations, and the effects of disruption during beach-cleanups. Are there any *thresholds* where cleaning should be conducted or not conducted given the concentration of plastic within the soil?

Another point to consider is that over a timespan of thousands of years, there is a high probability that islands off the coast of Norway will experience fire, especially due to human factors (Bleken et al., 1997). Pyroplastic (Ehlers and Ellrich, 2020) and plastiglomerates can be created during fires (De-La-Torre et al., 2021), with possible leaching of chemicals into the soil. The concentrations found in this study would probably create layers of plastiglomerates, transforming the soil properties fundamentally. It would be interesting to find out whether the total plastic concentrations found in this study are representative for the area and whether this affects the soil biodiversity. EDNA is a possible tool for investigating whether there is a correlation between macroplastic concentration and biodiversity. The finding of multiple pieces of pyroplastic in all samples is of great interest, and its source, fate and impact should be further investigated. We are asking the question of whether these samples are an exception or the rule, within the plastic-soil layer of the western island of Mausund landscape conservation area.

The method used for digging soil samples, sorting, weighing and drying is simple and robust for sampling terrestrial soil, useful for universities, citizen scientists, schools and researchers with limited resources who want to investigate the relations between soil and plastic.

Table 2
Projected microplastic concentrations. Percentages of microplastic (d.w/d.w) and estimates are based on the weathering rates provided by Chamas et al. (2020). Estimates based on half-life durations of 50, 100, 200, 300 and 500 years. Uncertainty from weighing process: ±2 g.

Sample ID	Gram of macroplastic (±2 g)/27 l of soil (one sample)	% microplastic in 50 years	% microplastic in 100 years	% microplastic in 200 years	% microplastic in 300 years	% microplastic in 500 years
1	981	1.47%	2.95%	5.89%	8.84%	14.73%
2	870	2.24%	4.47%	8.94%	13.41%	22.36%
3	1520	1.62%	3.23%	6.47%	9.70%	16.17%
4	1038	3.51%	7.01%	14.02%	21.03%	35.05%
5	219	0.63%	1.25%	2.50%	3.75%	6.25%
6	682	1.25%	2.51%	5.01%	7.52%	12.53%
7	173	0.40%	0.80%	1.59%	2.39%	3.98%
9	235	0.80%	1.59%	3.18%	4.78%	7.96%
10	376	0.84%	1.67%	3.34%	5.01%	8.36%
11	40	0.11%	0.21%	0.42%	0.64%	1.06%
12	410	1.30%	2.59%	5.19%	7.78%	12.96%

Other factors not considered here, such as number of biological taxa, water infiltration or microplastic concentration can easily be incorporated in future studies.

We are recommending more research in this field, so as to properly advise beach cleanup volunteers and professionals on the proper course of action when it comes to macroplastic removal from terrestrial environments. We also raise the question of bushfires, and the implications for soil quality when plastic is present.

CRediT authorship contribution statement

Jakob Bonnevie Cyvin: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Hilde Ervik:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Anne Aasen Kveberg:** Investigation, Methodology, Writing – review & editing. **Christina Hellevik:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.147547.

References

Accinelli, C., Abbas, H.K., Bruno, V., Nissen, L., Vicari, A., Bellaloui, N., ... Shier, T.W., 2020. Persistence in soil of microplastic films from ultra-thin compostable plastic bags and implications on soil Aspergillus flavus population. Waste Manag. 15 (113), 312–318. https://doi.org/10.1016/j.wasman.2020.06.011.

Andrady, A.L., 2015. Plastic and Environmental Sustainability. John Wiley & Sins, Inc, Hoboken, New Jersey (doi: 978-1-118-31260-5).

Andrady, A.L., Neal, M.A., 2009. Epplications and societal benefits of plastics. Philos. Trans. R. Soc. B 364. https://doi.org/10.1098/rstb.2008.0304.

Bergmann, M., Wirzberger, V., Krumpen, T., Lorenz, C., Primpke, S., Tekman, M.B., 2017. Microplastics in Arctic deep-sea sediments from the HAUSGARTEN observatory. Environ. Sci. Technol. 51 (19), 11000–11010. https://doi.org/10.1021/acs.est.7b03331.

Bleken, E., Mysterud, I., Mysterud, I., 1997. Skogbrann og miljøforvaltning - en utredning om skogbrann som økologisk faktor. [Forest fire and environmental management - an investigation about forest fire as ecological factor.]. Direkotrat for fire and and eksplosion defence, department of Biology, University of Oslo, directorate for civil contingency, directorate for nature management, Skogbrann forsikringsselskap.

Bour, A., Haarr, A., Keiter, S., Hylland, K., 2018. Environmentally relevant microplastic exposure affects sediment-dwelling bivalves. Environ. Pollut. 236, ss. 652–660. https://doi.org/10.1016/j.envpol.2018.02.006.

Brown, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Environ. Sci. Technol. 45 (21), 9175–9179. https://doi.org/10.1021/es201811s.

Chae, Y., An, Y-J., 2018. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: a review. Environ. Pollut. 240, ss. 387–395. https://doi.org/10.1016/j.envpol.2018.05.008.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., ... Suh, S., 2020. Degradation rates of plastics in the environment. ACS Sustain. Chem. Eng. 8 (9), 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635.

Chen, F., Wolcott, M.P., 2014. Miscibility studies of paraffin/polyethylene blends as form-stable phase change materials. Eur. Polym. J., pp. ss. 44–52.

Claessens, M., De Meester, S., Van Landuyt, L., De Clerck, K., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62 (10), 2199–2204. https://doi.org/10.1016/j.marpolbul.2011.06.030.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., & Galloway, T. S. (2015). The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod Calanus helgolandicus. Environ. Sci. Technol., 49(2), ss. 1130–1137. doi: https://doi.org/10.1021/es504525u.

Cozzolino, L.N., Nicastro, K.R., Zardi, G., Los Santos, C.B., 2020. Species-specific plastic accumulation in the sediment and canopy of coastal vegetated habitats. Sci. Total Environ. s, 138018. https://doi.org/10.1016/j.scitotenv.2020.138018.

De-la-Torre, G.E., Dioses-Salinas, D.C., Pizarro-Ortega, C.I., Santillán, L., 2021. New plastic formations in the Anthropocene. Sci. Total Environ., 142216 https://doi.org/10.1016/j.scitotenv.2020.142216.

Ding, L.W., 2021. The occurrence of microplastic in Mu Us Sand Land soils in northwest China: different soil types, vegetation cover and restoration years. J. Hazard. Mater. s, 123982. https://doi.org/10.1016/j.jhazmat.2020.123982.

Ehlers, S.M., Ellrich, J.A., 2020. First record of 'plasticrusts' and 'pyroplastic' from the Mediterranean Sea. Mar. Pollut. Bull. 151, 110845. https://doi.org/10.1016/j.marpolbul.2019.110845.

Gasperi, J.W., et al., 2018. Microplastics in air: are we breathing it in? Curr. Opin. Environ. Sci. Health, ss. 1–5 https://doi.org/10.1016/j.coesh.2017.10.002.

GESAMP, 2015. Sources, fate and effects of microplastics in the marine environment: a global assessment. In: Kershaw, P.J. (Ed.), (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 90, p. 96.

Groh, K.J., Backhaus, T., Carney-Almroth, B., Geueke, B., Inostroza, P.A., Lennquist, A., ... Muncke, J., 2019. Sci. Total Environ. 651 (2), 3253–3268. https://doi.org/10.1016/j.scitotenv.2018.10.015.

Hasnat, M. A. (2018). A review paper on the hazardous effect of plastic debris on marine biodiversity with some possible remedies. Asian J. Med. Biol. Res., 4, ss. 233–241. doi: https://doi.org/10.3329/ajmbr.v4i3.38461.

Haarr, M.L., Pantalos, M., Hartviksen, M.K., Gressetvold, M., 2020. Citizen science data indicate a reduction in beach litter in the Lofoten archipelago in the Norwegian Sea. Mar. Pollut. Bull. 153, 111000. https://doi.org/10.1016/j.marpolbul.2020.111000.

Helcoski, R.Y., Yonkos, L.T., Sanchez, A., Baldwin, A.H., 2020. Wetland soil microplastics are negatively related to vegetation cover and stem density. Environ. Pollut. s, 113391. https://doi.org/10.1016/j.envpol.2019.113391.

Holland, E.R., Mallory, M.L., Shutler, D., 2016. Plastics and other anthropogenic debris in freshwater birds from Canada. Sci. Total Environ. 571, 251–258. https://doi.org/10.1016/j.scitotenv.2016.07.158.

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 (6223), 768–771. https://doi.org/10.1126/science.1260352.

Jennings, S., Mélin, F., Blanchard, J.L., Forster, R.M., Dulvy, N.K., Wilson, R.W., 2008. Global-scale predictions of community and ecosystem properties from simple ecological theory. Proc. Royal Soc. B: Bio. Sci. 275 (1641), 1375–1383. https://doi.org/10.1098/rspb.2008.0192.

Jovanović, B., 2017. Ingestion of microplastics by fish and its potential consequences from a physical perspective. Integr. Environ. Assess. Manag. 13, 510–515. https://doi.org/10.1002/ieam.1913.

Knutsen, H., Cyvin, J.B., Totland, C., Lilleeng, Ø., Wade, E.J., Castro, V., ... Arp, H.H., 2020. Microplastic accumulation by tube-dwelling, suspension feeding polychaetes from the sediment surface: a case study from the Norwegian Continental Shelf. Mar. Environ. Res. 161, 105073. https://doi.org/10.1016/j.marenvres.2020.105073.

Lee, K.-W., Shim, W.J., Kwon, O.Y., Kang, J.-H., 2013. Size-dependent effects of micro polystyrene particles in the marine copepod *Tigriopus japonicus*. Environ. Sci. Technol. 47 (19), 11278–11283. https://doi.org/10.1021/es401932b.

Lenz, R., Enders, K., Nielsen, T.G., 2016. Microplastic exposure studies should be environmentally realistic. Proc. Natl. Acad. Sci. 113 (29), ss. 4121–4122. https://doi.org/10.1073/pnas.1606615113 (Jul).

Loakeimidis, C., Fotopoulou, K., Karapanagioti, H.K., Geraga, M., Zeri, C., Papathanassiou, E., ... Papatheodorou, G., 2016. The degradation potential of PET bottles in the marine environment: an ATR-FTIR based approach. Nat. Sci. Rep. 6:23501. https://doi.org/10.1038/srep23501.

Lwanga, E.H., Gertsen, H., Gooren, H., Peters, P., Salanki, T., van der Ploeg, M., ... Geissen, V., 2016. Microplastics in the terrestrial ecosystem: implications for lumbricus. Environ. Sci. Technol. 50, 2685–2691. https://doi.org/10.1021/acs.est.5b05478.

Machado, A. d, Kloas, W., Zarfl, C., Hempel, S., Rilling, M.C., 2017. Microplastics as an emerging threat to terrestrial ecosystems. Glob. Chang. Biol. 24, s, 14051416. https://doi.org/10.1111/gcb.14020.

Malizia, A., Monmany-Garzia, A. Carolina, 2019. Terrestrial ecologists should stop ignoring plastic pollution in the Anthropocene time. Sci. Total Environ., ss. 1025–1029 https://doi.org/10.1016/j.scitotenv.2019.03.044.

Massos, A., Turner, A., 2017. Cadmium, lead and bromine in beached microplastic. Environ. Pollut., ss. 139–145 https://doi.org/10.1016/j.envpol.2017.04.034.

Menicagli, V. B., Balestri, E. & Lardicci, C. (2019). Exposure of coastal dune vegetation to plastic bag leachates: a neglected impact of plastic litter. Sci. Total Environ., ss. 737–748. doi:https://doi.org/10.1016/j.scitotenv.2019.05.245.

McNeish, R.E., Kim, L.H., Barrett, H.A., et al., 2018. Microplastic in riverine fish is connected to species traits. Sci. Rep. 8, 11639. https://doi.org/10.1038/s41598-018-29980-9.

Müller, R.-J., Kleeberg, I., Deckwer, W.-D., 2001. Biodegradation of polyesters containing aromatic constituents. J. Biotechnol., ss. 87–95 https://doi.org/10.1016/S0168-1656(00)00407-7.

Naidoo, T., Glassom, D., 2019. Decreased growth and survival in small juvenile fish, after chronic exposure to environmentally relevant concentrations of microplastic. Mar. Pollut. Bull. 145, 254–259. https://doi.org/10.1016/j.marpolbul.2019.02.037.

Nakashima, E.I., Kako, S., Takahashi, S., Isobe, A., Itai, T., 2012. Quantification of toxic metals derived from macroplastic litter on Ookushi Beach, Japan. Environ. Sci. Technol. 18, ss. 10099–10105. https://doi.org/10.1021/es301362g.

Obbard, R.W., Sadri, S., Wond, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future 2 (6), 315–320. https://doi.org/10.1002/2014EF000240.

Organization, W. H, 2019. Microplastic in Drinking-water (doi:978-92-4-151619-8).

Perez, L., Soares-Gomes, S.-G., Bernardes, M.C., 2018. A case study on the influence of beach kiosks on marine litter accumulating in Camboinhas beach, Southeast Brazil. J. Coast. Conserv. 22, 1085–1092. https://doi.org/10.1007/s11852-018-0615-z.

Prendergast-Miller, M.T., Katsiamides, A., Abbass, M., Sturzenbaum, S.R., Thorpe, K.L., Hodson, M.E., 2019. Polyester-derived microfibre impacts on the soil-dwelling earthworm Lumbricus terrestris. Environ. Pollut. 251, 453–459. https://doi.org/10.1016/j.envpol.2019.05.037.

Puskic, P.S., Lavers, J.L., Bond, A.L., 2020. A critical review of harm associated with plastic ingestion on vertebrates. Sci. Total Environ. 747, 14066. https://doi.org/10.1016/j.scitotenv.2020.140666.

Qi, R., Jones, D.L., Li, Z., Liu, Q., Yan, C., 2020. Behavior of microplastics and plastic film residues in the soil environment: a critical review. Sci. Total Environ. 10 (703), 134722. https://doi.org/10.1016/j.scitotenv.2019.134722.

Rezania, S., Park, J., Md Din, Mat Taib, S., Talaiekhozani, A., Kumar Yadav, K., Kamyab, H., 2018. Microplastics pollution in different aquatic environments and biota: a review of recent studies. Mar. Pollut. Bull. 133, 191–208. https://doi.org/10.1016/j.marpolbul.2018.05.022.

Ryan, P.G., 2020. The transport and fate of marine plastics in South Africa and adjacent oceans. S. Afr. J. Sci. (5/6), s. 7677 https://doi.org/10.17159/sajs.2020/7677.

Salonen, S., Dolar, A., Kokalj, A.J., Skalar, T., Dolcet, L.P., Hurley, R., van Gestel, C.A., 2020. Exploring the impacts of plastics in soil – The effects of polyester textile fibers on soil invertebrates. Sci. Total Environ. 700, 134451. https://doi.org/10.1016/j.scitotenv.2019.134451.

Steffen, et al., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223), 1259855. https://doi.org/10.1126/science.1259855.

Suyadi, Manullang, C.Y., 2020. Distribution of plastic debris pollution and it is implications on mangrove vegetation. Mar. Pollut. Bull., 111642 https://doi.org/10.1016/j.marpolbul.2020.111642 (s.).

Tramoy, R.C., 2019. Plastic debris dataset on the Seine river banks: plastic pellets, unidentified plastic fragments and plastic sticks are the top 3 items in a historical accumulation of plastics. Data Brief https://doi.org/10.1016/j.dib.2019.01.045.

Turner, A., 2018. Black plastics: linear and circular economies, hazardous additives and marine pollution. Environ. Int., ss. 308–318 https://doi.org/10.1016/j.envint.2018.04.036.

Turner, A., Arnold, R., Williams, T., 2020. Weathering and persistence of plastic in the marine environment: lessons from LEGO. Environ. Pollut., 114299 https://doi.org/10.1016/j.envpol.2020.114299 (s).

World Economic Forum, The Ellen MacArthur Foundation & Company, M, 2016. The New Plastics Economy: Rethinking the Future of Plastics.

Wright, S.L., Thompson, R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, ss. 483–492. https://doi.org/10.1016/j.envpol.2013.02.031.

Yao, W.D., et al., 2019. Micro- and macroplastic accumulation in a newly formed Spartina alterniflora colonized estuarine saltmarsh in southeast China. Mar. Pollut. Bull. s, 110636. https://doi.org/10.1016/j.marpolbul.2019.110636.