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Microplastics and Nanoplastics

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# Monitoring moss reveals widespread deposition of airborne microplastics across the UK

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**Abstract**
Moss presents an excellent candidate for biomonitoring the atmospheric deposition of microplastics across wide spatial scales and to monitor trends over time due to its relative ease of sampling compared to alternative approaches such as conventional wet and dry deposition atmospheric sampling. Evaluation of representative sampling and processing procedures must be performed to ensure that quantification of microplastics in moss maintains integrity to the original sample. Using data from a sampling campaign of 52 locations across United Kingdom, we explore these key considerations and aspects of study design, to evaluate the potential use of moss as a bio-monitor for microplastic atmospheric deposition. A method for the isolation of microplastics from moss biomass using flow displacement and filtration is optimised for the extraction of microplastics approximately > 25 µm in size, appropriate for quantification by vibrational spectroscopy methods such as µ-FTIR. The approach is then applied to samples from six major genus of moss, common to the United Kingdom, across 52 natural or semi-natural landscapes. The survey design and analysis methodology are evaluated against quality assurance and control criteria, whilst the findings are critically discussed in light of relevant literature. This study represents the first survey of the extent of microplastic contamination of mosses across the United Kingdom, investigating correlations between location characteristics and microplastic polymer diversity and abundance. It shows near ubiquitous contamination of mosses with microplastics, irrespective of their location across the United Kingdom, and indicates that a diffuse atmospheric source may play a role in this widespread contamination of moss.

**Keywords** Microplastics, Atmospheric transport, Atmospheric deposition, Monitoring, Guidance, Vibrational spectroscopy, Baseline, Method development

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## Introduction

It is well established that mosses can be used as biomonitors to quantify deposition rates of atmospheric pollutants (ICPV, 2020). The thallus structures of pleurocarpous mosses such as *Hypnum cupressiforme* and *Pleurozium schreberi*, with high surface area to mass ratios, make them excellent at intercepting and accumulating particulate matter. In addition, these do not take up material from the substrate upon which they are growing, and so contribution of the substrate to moss concentrations of pollutants is generally limited. The International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICPV) conducts moss surveys across Europe every five years to quantify atmospheric deposition of trace metals, nitrogen, and persistent organic pollutants. The moss data have been shown to provide a complementary measure of elemental deposition from the atmosphere to terrestrial systems compared to conventional precipitation analysis, identifying atmospheric deposition as the main factor determining lead and cadmium content of mosses at the European scale [1, 2]. In 2015, a pilot study was conducted in Ireland to establish the potential of passive monitoring of moss to estimate atmospheric deposition of microplastics [3]. Microfibres were observed in all moss samples, indicating mosses are a viable candidate for such biomonitoring. This pilot study was limited to visual identification of microfibres, but highlighted the importance of quality assurance controls as well as the need for chemically specific analysis to confirm assignments of fibres as microplastics. Since this initial pilot study, several reports have been published using this passive biomonitoring approach to address specific research questions (e.g. Capozzi. [4], Jafarova. [5], Roblin. [3]. Mosses can also be collected from a 'cleaner' area (e.g. remote from urban influences) and transplanted into the area of study for a set duration. Known as active biomonitoring, this approach can be particularly effective in areas where mosses would usually be scarce, such as urban centres [6–8]. The evidence to-date suggests that microplastics can be detected in moss and that their use as a biomonitor for airborne microplastics is possible, if desired. Long-term monitoring requires a robust method with which a baseline can first be established, from which trends over time can then be investigated.

There are four aspects to consider when designing a monitoring scheme for any environmental contaminant: the sample collection, preparation, analysis and interpretation. Each of these aspects should be carefully considered when evaluating the potential for moss to act as a biomonitor for long term monitoring of airborne microplastics. Many different methods have been proposed capable of quantifying microplastics, each with their strengths and weaknesses. The choice of analytical method goes on to define suitable sample preparation and collection methods. Therefore, it is first essential to select an analytical instrument and from here, implement a monitoring design that will deliver robust data using this technique.

The analytical method selected for evaluation in this study is a common vibrational spectroscopy technique, Fourier Transform Infrared Microscopy (μ-FTIR). Selection of this analytical technique as the starting point for the design of the monitoring survey was based on several considerations:

- The method is chemically specific. Analysis of the returned spectra can be compared against libraries of known polymers and the type of microplastic can be identified. This is essential when considering possible sources.
- The method delivers particle size and shape information. This data is important from a mechanistic perspective, both to understand transport mechanisms of these plastics, but also from an (eco)toxicological perspective, where particle size and shape can influence their biological fate and effects [9].
- There is high uptake in the research community, meaning the instrument is quite widely available in research labs investigating microplastics e.g. across Europe. For example, the majority of participants in recent international interlaboratory studies evaluating the measurement and characterisation of microplastics, report using FTIR, e.g. Belz et al. [10]; De Frond et al. [11]; Isobe et al. [12]; and van Mourik et al. and [13].

The original ICP Vegetation Monitoring Manual describes in Annex 5 an example protocol for specific extraction and analysis, focusing on visual identification of microfibres [14]. The present study represents an opportunity to complement such protocols, extending the analytical range beyond just microplastic fibres, but to smaller fragments of plastic which are indistinguishable by the human eye under the microscope, but can be quantified through chemically specific techniques such as μ-FTIR.

Using μ-FTIR also presents an opportunity to increase the amount of moss that can be processed and analysed in a single sample. Most sample preparation methods are based around the principle of using some chemical or enzymatic digestion reaction to remove interfering material from the sample, whilst leaving the microplastics undegraded and so concentrated sufficiently for analysis. As the mass of interfering material is many orders of magnitude higher than the target microplastics and is never completely removed, such approaches often limit the sample unit size that can be analysed, typically to < 1 g of moss.

However, it can be argued that it is not always necessary to digest the entire moss biomass. It is not expected that particles greater than a micrometre in size can be accumulated in the moss tissue itself from atmospheric deposition. All spectroscopy-based techniques have a lower size limit of particle they can resolve. In the case of μ-FTIR, this is typically ~ 25 μm, larger than any microplastic that may be accumulated within the moss tissue itself arriving from the air. It is with this in mind, that we test a new method using flow displacement to extract and isolate particles from the moss external surfaces, followed by chemical digestion to clean up the samples and analyse microplastics using μ-FTIR. This allows for a larger mass of moss (and so more representative sample) to be analysed than conventional chemical digestion of entire moss biomass. Increasing the mass of moss that can be extracted and analysed in a single assessment is of benefit as it reduces the potential sampling error associated with collection of particles, particularly if the number of particles quantified in a sample are low, e.g. <50 [15].

In this way, the present study aims to provide insights into the following critical areas of study design when using moss as long-term biomonitors for airborne microplastics:

### Sampling design

- What sampling density is required across the UK?
- Can we increase the sample unit size using the flow displacement method to improve representativeness of the data generated per sample in any sampling design?

### Sample preparation

- Can we reduce contamination through control measures control and establish limits of detection using a blank assessment approach?
- Can we demonstrate repeatability of the method through quantifying recovery of representative microplastics using the proposed flow displacement method?

### Sample analysis and interpretation

- Can we use multiple lines of evidence from different analytical techniques to corroborate chemical identification of different polymers in moss samples?

On evaluating the proposed flow displacement method against these criteria, the results from a survey of moss from across the United Kingdom are discussed, focusing on the drivers of variation of microplastic concentrations in moss across the UK. Bringing together the critical evaluation of the method with the results from its application in this survey, we conclude with recommendations for further validation and support in the design of future monitoring studies that might employ moss as a biomonitor for microplastics at national or regional scales.

## Materials and methods

### Problem formulation: sampling design for a survey across the United Kingdom

This study aimed to investigate the level of airborne microplastic deposition across the UK in rural areas. The sampling strategy reflects this. Sites were selected to represent rural deposition, with minimal/no impact of local hotspots. Given the absence of data on which to base the sampling density specifically for microplastics, the survey aimed for a pragmatic sampling density of 1 moss sample per 5000 km$^2$. The overall strategy also included having a few sites located in closer proximity to one another, to allow observations of local variability in microplastic deposition. Sample sites were selected to cover the breadth of the UK, and included some very remote sites in addition to rural (but not 'remote') sites. The sites were chosen to capture a range of environmental variables such as rainfall and altitude.

To avoid influence of local points sources attributable to particular land uses, careful consideration was taken as to the habitats sampled. These were semi-natural rural environments, with urban and arable land excluded and with all but two sampling points > 300 m from a road and > 100 m from a house, criteria aligned with the approach in the main ICPV moss survey, e.g. Frontasyeva and Harmens. [14].

### Sample collection

Moss samples were collected according to a standardised protocol [14], consistent with the 2020–2022 European Moss Survey, to which this sampling contributed [16]. Minor amendments were made to collect 2 L of moss rather than 1, and to collect moss in paper bags rather than plastic to ensure suitability for microplastic analysis. Each sampling site was located at least 300 m from main roads or populated areas and at least 100 m from any road or single house, to avoid the impact of local sources such as from tyre/road wear abrasion products and focus on longer-range transport. These criteria were based on previous studies that have shown for some roadside pollutants, particularly lead, elevated concentrations can be found within 200 m of a road [17]. In forests or plantations, samples were collected as far as possible in small open spaces and not from under a tree canopy, to avoid any influence of canopy drip.

A few additional samples were collected within conurbations as a contrast, including some from sub-urban country parks. For all but two samples (Manchester crematorium and Manchester-Withington) the criteria for road and house distance from the sampling site were met.

Due to the travel and site access restrictions due to the Covid-19 pandemic, many samples were collected from volunteers and site managers. The sampling protocol requested that each site collected a composite of ten moss samples from the location. This ensures representation of a wider spatial area in each sample, reducing the likelihood of very localised contamination influencing the results. Samples were collected into paper bags. Where practical feasibility does not allow for replicate samples from each location to be analysed, the moss monitoring manual also suggests samples may be pooled, in line with common practice for elemental analysis [14]. This was another driver of the decision to develop the flow displacement method as this would allow a greater and therefore more representative sample of moss to be analysed, reducing the sampling error that might be associated with only analysing a single sample at each location. This intends to mitigate to some extent the obscuring of individual variation within sites through sample pooling, which was necessary in order to maximise the geographical coverage of the survey.

Dead material and litter were removed from the samples in a ventilated laboratory, and only the last two to three years' growth segments were used for the analyses. Samples were dried at room temperature and stored in sealed paper bags until analysis.

The most frequently sampled moss species was *Pleurozium schreberi* (38%), followed by *Hylocomium splendens* (25%), *Pseudoscleropodium purum* (12%), *Hypnum cupressiforme* (8%) and *Rhytidiadelphus squarrosus* (4%), with other species accounting for a further 14% of samples.

### Sample preparation: flow displacement method to isolate and quantify microplastics > 25 µm in size from moss biomass

All reagents were prepared in reverse osmosis deionised (DI) water and were filtered using GF/C 1.2 µm glass fibre filters prior to use, to limit microplastic contamination from the reagents. Reagents were checked periodically for contamination. Fenton's reactions were performed with hydrogen peroxide (30%, ACS reagent grade, SLS, UK) and Iron (II) Sulphate•$7H_2O$ (SLS, UK). Acidification used 2% hydrochloric acid (HCl) and 5% sulphuric acid ($H_2SO4$). When stainless steel filters are used this refers to Porvair 47 mm diameter filter discs, used throughout the processing of samples with a 5 µm pore size. Two representative microplastics were used for spike recovery assessment from the extraction protocol, (PA, 60–93 µm, dry powder produced in house through cryo-milling and cascade filtration) and polystyrene (PS, 45 µm, liquid dispersion, Polysciences Europe GmbH, Germany).

Both flow displacement and conventional oxidation and density separation methods were employed during the study development phase, demonstrating the increase in mass of moss that could be analysed with flow displacement, from < 1 g to several grams of material (Supplementary Information 1). The conventional oxidation and density separation method was unable to digest some species of moss, and so deemed not fit-for-purpose. The following sections only describe the optimised flow displacement method for microplastic extraction from moss.

The flow displacement approach is based on a filtration rig system, through which 100 L of filtered water can be flushed over several grams of moss material, displacing microplastics from the moss structure and capturing these downstream on a stainless steel 5 µm pore diameter filter. The captured material is then further purified following a Fenton's reaction to reduce interfering organic material in the final analysis with µ-FTIR. An image of the flow displacement rig is provided in Fig. 1. Where possible, all components in contact with the sample, are made from stainless steel or glass. The hosing is made of silicone.

A sight glass chamber has been adapted to allow up to 10 g of moss to be flushed at a reasonably high flow rates of ~ 8 L per minute, using 5 µm filtered deionised water (Fig. 1). The moss is supported by a coarse 150 µm filter above the downstream stainless steel 5 µm filter onto which displaced microplastics are captured. A flow meter downstream of the filter rig allows an accurate volume of water flushed through the system to be established to allow for consistent extraction between samples, targeting 100 L volume for complete extraction.

Samples were delivered in paper bags for analysis. Transit, storage and handling of the samples offers an opportunity for microplastics to be shed into these bags. To test if this was the case after the bulk of a sample was removed from its paper bag, the remaining small pieces of moss and 'dust' left behind were shaken out and processed as a separate sample. Negligible numbers of MPs, below limits of detection were detected, indicating microplastics are trapped within the structure of the moss itself and not easily shed through transport, handling or storage. This supports the principle that the samples introduced to the sight glass in the filter rig have integrity to their original state when sampled.

### Sample analysis: quantification using µ-FTIR

After the extraction steps described above, samples were dispersed in 19.7 mL (+/- 1.98 mL) of 50% ethanol and

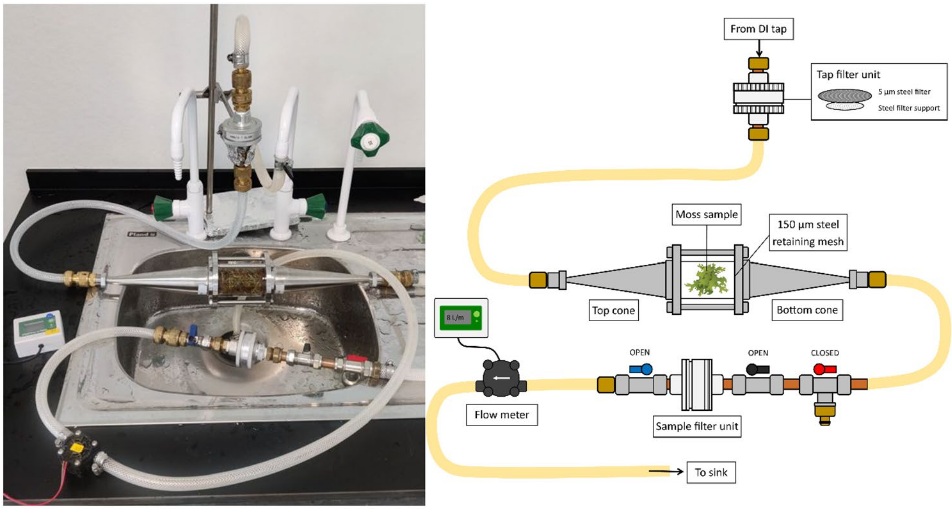


**Fig. 1** Image and schematic demonstration of the flow displacement rig used to extract microplastics from moss under forces of the water flowing through the moss

stored at room temperature before analysis. For spectroscopic µ-FTIR analysis, the samples were thoroughly mixed by vigorously shaking for 10 s, then a sub-sample immediately deposited onto a 25 mm diameter 3 µm pore size silver membrane filter (Sterlitech, Washington USA) using a glass pipette. Where possible, the entire sample was deposited, though only if this would not result in overloading of the deposition area with material, visible during the act of deposition. The volume of the sub-samples analysed were determined by weighing a whole sample before and after sub-sampling to 0.1 mg accuracy. On two occasions < 10% of the total sample could be deposited, and we reflect on adequate subsample sizes in relation to limits of detection in Sect. "Abundance of microplastics found in moss across the United Kingdom". In all other samples > 1 g of moss was represented in the final sample (mean = 5.17 g, stdev = 2.45 g). Particles quantified > LOD were then scaled to a concentration per gram of moss. All microplastics extracted from the moss and deposited from the subsample within the deposition area (about 11 × 11 mm) were identified and quantified with an imaging µ-FTIR spectrometer (PerkinElmer Spotlight 400), set to collect spectra in the range between 4000 and 700 $cm^{-1}$ wave numbers in reflectance mode. A background spectrum of the silver filter was collected and removed from resulting data. The pixel size selected was 25 µm, this therefore being the minimum particle size which could be resolved. Mapping was carried out at a resolution of 8 $cm^{-1}$, with two scans per pixel, and an interferometer speed of 2.2 cm/s.

Automated spectral matching of the raw data was performed using the Purency Microplastics Finder software [18]. This software uses machine learning algorithms to automate the data analysis of microplastics measurements. The automated particle finding and analysis prevents operator bias, which can occur with manual methods. The output generates particle counts by polymer type and provides information on the two-dimensional aspects of each particle. A total of 21 common polymers were searched for in the library: polypropylene (PP) polyethylene (PE), polyvinylchloride (PVC), polyurethane (PU), polyethylene terephthalate (PET), polystyrene (PS), acrylonitrile butadiene styrene (ABS), polyamide (PA), polycarbonate (PC), poly(methyl methacrylate) (PMMA), polyoxymethylene (POM), cellulose acetate (CA), ethylene-vinyl-acetate copolymer (EVAc), ethylene vinyl alcohol (EVOH), polyacrylonitrile (PAN), polybutylene terephthalate (PBT), polyether ether ketone (PEEK), polyphenylsulfone (PPSU), polysulfone (PSU), silicone and polylactic acid (PLA).

### Corroboration of a sub-set of particles using Laser Direct Infra-Red Imaging

Corroboration of polymer identification was performed on a subset of particles analysed with Laser Direct Infrared spectroscopy (Agilent 8700 LDIR Imaging System, USA). The LDIR uses a quantum cascade laser that can be rapidly tuned through different wavelength ranges for microscopic and spectroscopic analysis of particles. Once a particle has been located, a high-resolution image was captured and then a full infrared spectrum in the range of 975 cm – 1 to 1800 cm – 1 obtained. These spectra are compared with the Microplastics Starter 1 and 2 libraries (Clarity analysis software v1.4.1, Agilent Technologies, USA). To pinpoint the exact same particle in the µ-FTIR image and LDIR scan for corroboration, it was necessary to perform this assessment on larger particles, that could clearly be seen and navigated to in the high-resolution visible image for spectra collection in the LDIR. A total of

11 particles from 5 independent samples were identified as suitable for this corroboration test.

### Quality assurance and control – recording and reporting

To ensure transparent reporting and meet current best practices in quality assurance and control (QA/QC) for the collection, preparation and analysis of microplastics samples, we report a review of critical QA/QC criteria, scoring our methodology according to the principles first outlined in Koelmans et al. [19] then further refined specifically for air and atmospheric deposition in Wright et al. [20]. Reviewing the proposed methodology, we suggest the approach would score 16 out of a possible total of 20. Justification for this score and a breakdown against criteria is provided in Supplementary Information 1 – Table S1. A summary of the quality assurance and control measures taken across the whole workflow is represented in Supplementary Information 1 - Figure S6.

### Search terms to review the available literature on microplastics in moss

The Web of Science Core Collection (WoS) was searched using the search term:

> *(microplastics OR microplastic particles OR plastic pollution OR microdebris OR synthetic polymers) AND (moss OR bryophytes OR bryophyta OR mosses OR non-vascular plants) AND (monitoring OR detection OR measurement OR analysis OR assessment OR quantification)*

A total of 40 results were returned from this search, for which abstracts were screened for relevance. Of these, 10 articles were considered relevant, documenting the use of either moss or lichens as passive biomonitors for airborne microplastics. These articles were compared with an existing list of literature generated through unstructured searches. Two additional articles were identified which were not picked up by the WoS search terms, meaning a total of 12 relevant articles were reviewed, using moss or lichen as a biomonitor for microplastics.

### Data treatment and statistics

The main dependent variables in the analysis were the total microplastic concentration (expressed as MP/g) and the polymer diversity detected (integer score of the sum of unique polymers of the 21 searched for in the library detected in a sample > LOD). Total concentration and polymer diversity were log-transformed prior to running constrained ordinations. Redundancy Analysis (RDA, “vegan” and “ggfortify” packages) was performed on the full dataset, to evaluate whether any of the following variables were significant in explaining the variation in the abundance and polymer diversity of microplastics in moss: latitude, average total precipitation from nearest monitoring station (all monitoring stations within 91 km of the sample point, period covered 2021–2022), elevation, tree canopy distance and urban index. The urban index refers to the mean percentage urban coverage across all 1 km squares, within a 5–10 km radius of the sample location. Land cover class and the growth types of moss are also recorded to further distinguish the samples. The data for these additional explanatory variables are reported in Supplementary Information 2 – Table S2. Statistics were performed in RStudio, version 4.3.2.

To investigate whether there was redundancy in the sampling design, i.e. could fewer samples have been collected and the same conclusion reached, a semi-variogram was constructed and Kriging analysis was performed. It is important to note that the semi-variogram is flawed when the number of observations is not large enough. Typically, there should be at least 30 or 40 observations in the sample. In this case there were 52 locations across the United Kingdom.

Three variogram models were tested for best fit: circular, exponential and spherical models. All geostatistics were performed in R, version 4.4.0, ‘gstat’ and ‘nlme’ packages. To test which was the best fitting model, the fitting errors (or residuals) were compared. The sum of squared error (SSErr) was calculated for each of the models. The smaller this number, the better the fit (0 indicates a perfect fit). A model that did not specify a covariance structure (“null model”) was also run, to investigate whether adding the autocorrelation structures (i.e. accounting for distances between sampling locations) improved the model fit. The fit statistics of the null model and the models with the different covariance structures were examined and the likelihoods of these models compared.

## Results and discussion

### Optimisation and confirmation of the monitoring method

In this section we critically discuss the optimisation of the method and its strengths and weaknesses in the context applying the method for monitoring atmospheric deposition of microplastics in rural areas. The workflow consists of sample collection, preparation and analysis. Critical areas for development were:

- Can we increase the mass of moss prepared for analysis to ensure representative samples?
- Can we demonstrate low contamination during the workflow and establish limits of detection?
- Can we demonstrate repeatability of the method through positive controls and recovery assessment?
- Can we use multiple lines of evidence to corroborate polymer identification in the final analysis?

These questions are addressed in the following sections.

### *The flow displacement method increases the mass of moss that can be prepared for analysis*

Commonly, sample preparation for microplastic analysis involves some chemical digestion step, in which interfering material is removed through chemical degradation, whilst leaving the microplastic particles intact for measurement and quantification. Initial trials of direct digestion of moss material found that a conventional Fenton's reaction comprising of incubation of 1 g of moss material at 50ºC in 20 mL 30% H2O2 and 5 mL of 0.05 M Fe(II) for 24 h did not successfully digest the moss tissue for some species (Figure S1, Supplementary Information), preventing deposition.

Therefore, the flow displacement method was developed, to concentrate on quantification of the fraction of microplastic particles that would not be integrated into the moss biomass itself. Overall, the sample unit size per location was greatly increased using the flow displacement method (Fig. 1), with a median mass of moss represented in samples being 5.4 g (mean = 5.17 +/- 2.45 g).

It should be noted that the starting mass of moss was not standardised as there were concerns that differences in the volume of moss across samples and species might lead to different packing densities in the extraction chamber if a fixed mass of moss was introduced. This was a cause of concern as the recovery may appreciably decrease in a more densely packed column, for example. Whilst the starting mass of moss was not fixed, there was very little correlation between the mass of moss represented in the sample and the concentration of microplastics reported ($R^2 = 0.08$). However, we appreciate that the use of variable amounts of moss may introduce a supplementary source of variability that we are not able to quantify in the design. In future, comparing for example, replicates of moss from the same location with a fixed mass would allow this to be assessed.

Whilst the mass of moss that can be analysed using the flow displacement method is greatly increased, there is still room for future improvement on this method, given the high volume of water required. In the period since these samples were extracted and the method developed and optimised, other approaches following similar principles have been published, which may represent an opportunity to reduce the water use in future studies. For example, Wenzel et al. [21] exfoliate microplastics from the moss with the additional use of glass beads, reducing the water requirements to displace the microplastics from the moss structure. Such a system could be tested using the same recovery and blank assessment in the future to assess whether data would be comparable to the current approach. It may also be that the water could be recirculated in future assessments, to reduce the volume required per sample.

### *Low contamination is observed during sample preparation and limits of detection can be established*

Both recovery assessment and blank assessment are important to understand when evaluating a new method. Full procedural blanks ($n = 3$) were run during the method development that included the flushing step through the rig to ascertain whether the rig system itself or the reagents used in sample preparation shed microplastics into the sample. Very low contamination arises from the action of flow displacement of 100 L pre-filtered DI water through the rig, or from the subsequent Fenton's reaction on the captured displaced material. A low baseline of microplastic particles were detected in the blanks, at low incidences of only a few particles of some polymer types per sample (Supplementary Information - Figure S5). This ensures excellent limits of detection (LOD) per gram of moss. The poorest limits of detection were for polyamide (PA), acrylonitrile butadiene styrene (ABS), polypropylene (PP), and polyethylene (PE). However, even these were still sensitive to concentrations greater than 0.9 MP/g at their poorest LOD (Supplementary Information, Figure S5).

### *Good repeatability in recovery is achieved with the flow displacement method*

Full details of the development and optimisation of the flow displacement method can be found in the Supplementary Information, Sect. "Introduction". Briefly, the selection of the high-volume flow displacement method arose from an iterative process of development. Conventional chemical digestion of the whole moss tissue identified the opportunity for a flow displacement approach to increase the sample mass that could be prepared. Gravity-fed flow displacement was first tested, decanting increasing volumes of water over moss suspended above a filter. Recovery of two spiked representative materials were tested: 45 µm polystyrene (PS) spheres (Polysciences Europe GmbH, Gemany) and cryo-milled polyamide (PA, 60–93 µm), developed in house. Recovery plateaued after gravity flushing with between 20 and 30 L of water for both materials, with the cumulative total recovery after 30 L displacement of only ~ 35% for the smaller PS particles, and ~ 25% for the larger PA (Supplementary Information - Figure S2).

Subsequent trials with the optimised high flow rate flow displacement rig (Fig. 1) with 100 L of water passed through the rig found higher recovery of the PS particles spiked to 5 g of moss (97%, s.d. 46%, $n = 3$, Supplementary Information - Figure S4). This demonstrates good recovery of small particles close to the lower size limit of detection of the μ-FTIR from the external surfaces of the moss.

#### *How confident are we in the polymer assignments?*

To assign a polymer identity to the detected microplastic particles, numerous software solutions and algorithmic tools are available to researchers. A full review of the strengths and weaknesses of each is not the purpose of this study. However, it is beneficial to consider some qualitative assessment of the assigned polymers across analytical techniques, to corroborate and/or challenge the findings of the analysis. This is particularly important when establishing a baseline for the prevalence of microplastics in moss across large geographic areas. Understanding the polymer identities of different microplastics, may, in time, contribute to a picture of possible sources of microplastics to air and any changing trends in these emissions across time and space.

To achieve the highest level of evidence and unequivocally identify microplastics in a sample, positive results from a combination of multiple and justified orthogonal techniques would be necessary [22]. Using the maps generated by the μ-FTIR, we are able to identify what might be considered "presumptive plastic containing particles" according to the classification system proposed in Thomas et al. [22]. Imaging vibrational spectroscopy, combined with microscopy as used in the present study, provides some opportunity to increase the confidence in the identification of these particles. Characteristics consistent with plastic material from the visible image, combined with the chemical assignment from the FTIR would further corroborate identification. However, full orthogonal assessment between the microscope images and FTIR map was not possible for the full range of particles identified in this study. This is due to image quality and resolution issues at the small scale of particles identified as plastic in these samples (typically < 100 μm) preventing correlative analysis on individual particles and diagnosis of other characteristic visible traits of microplastics in these images. Some large particles and fibres can be identified and support the identification of plastics but this was only possible on a handful of samples and so we do not overstate this evaluation. Developments in the software and imaging capabilities of μ-FTIR instruments would vastly improve our capacity to perform such orthogonal assessments, but were not possible in the present study.

However, it was still desirable to demonstrate some supporting evidence of correct identification of microplastic polymers in the present study. To this end, a small corroboration exercise was performed across infra-red techniques, with 11 particles from 5 samples analysed with LDIR to see if the polymer identity of plastic particles could be confirmed across analytical instruments. This is not a full validation of the polymer identification, which might require analysis by an orthogonal technique, i.e. one which does not rely on the same principles of measurement, in this case infra-red analysis.

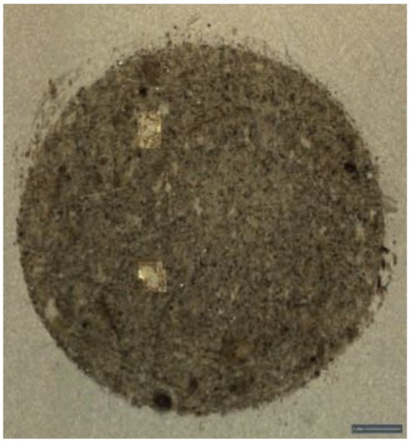
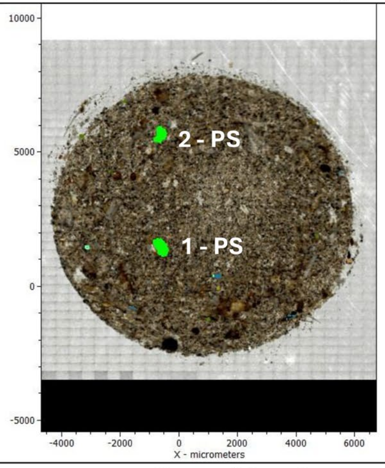
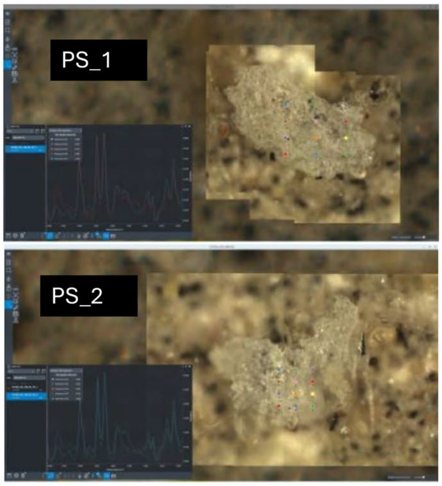
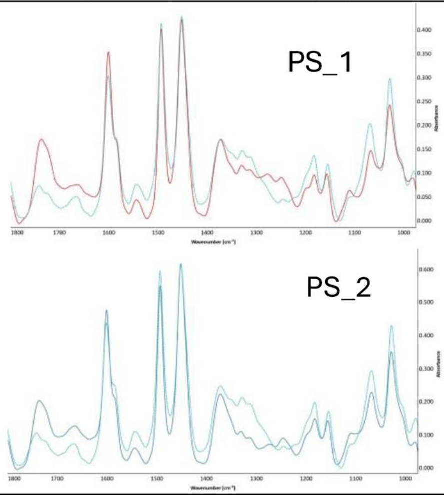
Only larger particles could be visualised and navigated to with certainty for corroboration of their identity in the LDIR. This constrained the selection of the final 5 samples for which this could be done with confidence, and the 11 particles analysed in this demonstration. Of these 11 particles, 4 polymer types were detected, PU, EVAc, PMMA, and PS and their identity confirmed across both μ-FTIR and LDIR. An example of two PS particles identified at the sampling location of Cors Goch is presented in Table 1. It should be noted that whilst this provides some evidence of corroboration of polymer identification of plastics across two infra-red techniques, it is not possible to conclude that this strong corroboration would hold true for smaller particles towards the lower limit of detection of particle sizes. This was beyond the scope of the current assessment, as the approach required selecting particles large enough to confidently return to across the μ-FTIR and LDIR analysis. Development of the capability for such instrument platforms as those used in the present study to locate specific co-ordinates and return to them across multiple instruments, would enable a more systematic correlative assessment across techniques to address this issue. However, in this small corroboration exercise we go beyond standard practice of using a single technique or single hyphenated technique for analysis, and show good corroboration of polymer identification for larger plastics on a subset of particles from samples representing 10% of locations monitored.

### Results of the survey of moss across the United Kingdom

#### *Abundance of microplastics found in moss across the United Kingdom*

Moss samples were analysed from 52 sites across the United Kingdom (Fig. 2). Sampling sites covered a range of land cover class, species and a good distribution from across the United Kingdom, representing more urbanised as well as more rural locations. The site selection and sampling protocol was designed to limit the influence of local sources of contamination, to establish a baseline of microplastics transported distances through the air and deposited into moss. On just three occasions were microplastics not quantified above the limits of detection (< LOD): near Thetford (Norfolk), Wivenhoe Woods (Essex) and Warkworth (Northumberland). This demonstrates quite ubiquitous contamination of mosses with microplastics, irrespective of their location across the United Kingdom. It is an indication that a diffuse atmospheric source may play a role in this widespread contamination of moss.

**Table 1** Example confirming polymer identity across µ-FTIR and LDIR analysis

| ID | Visible image. High resolution areas identified for particle confirmation | Visible image from µ-FTIR and particle overlay from Purency analysis |
|---|---|---|
| LOC-24B-R2 |  |  |
| | High resolution target in the visible image. Map of point analyses by LDIR | LDIR spectra collected for the particle compared to the library spectra |
| |  |  |

When detected, the mean total concentration of microplastics ≥ 25 µm in size in moss across the UK was 4.52 MP/g (SD 4.11), ranging across three orders of magnitude between 0.33 and 24.92 MP/g. This ubiquity, but relatively low abundance, highlights the importance of having a method which can quantify microplastics in an adequate mass of sample.

Small sample masses of moss might lead to false negative results, if insufficient material was analysed to ensure that the particles identified are above limits of detection. For the three locations reported as < LOD, replicate samples from the same location would be needed to be taken and analysed. In Wivenhoe Woods, the < LOD result may be due to insufficient material being possible to deposit and so poorer limits of detection, as < 1 g of moss was represented in the final analysis. However, for Thetford and Warkworth 6.7 and 5.7 g of moss were represented in the final analysis respectively, indicating these really do represent lower contamination sites, still being < LOD, even given the considerable mass of moss that could be extracted and analysed. In this study we were able to process and analyse up to 10 g of moss per sample. Limits of detection for different polymers were typically between 1 and 3.3 particles per moss sample, with the exception of ABS and PA which had detection limits of 6.6 and 8.7 particles per sample. Once normalised to the mass of moss extracted and analysed, these limits of detection ranged from 0.08 to 0.9 microplastic particles per gram of moss (Supplementary Information – Table S2).

Of the three locations that could be considered truly urban (locations 71, 73 and 84 in Sutton Park, Liverpool and Manchester respectively), there was no clear pattern of these being the most contaminated sites, representing the 5th, 17th and 32nd most contaminated sites

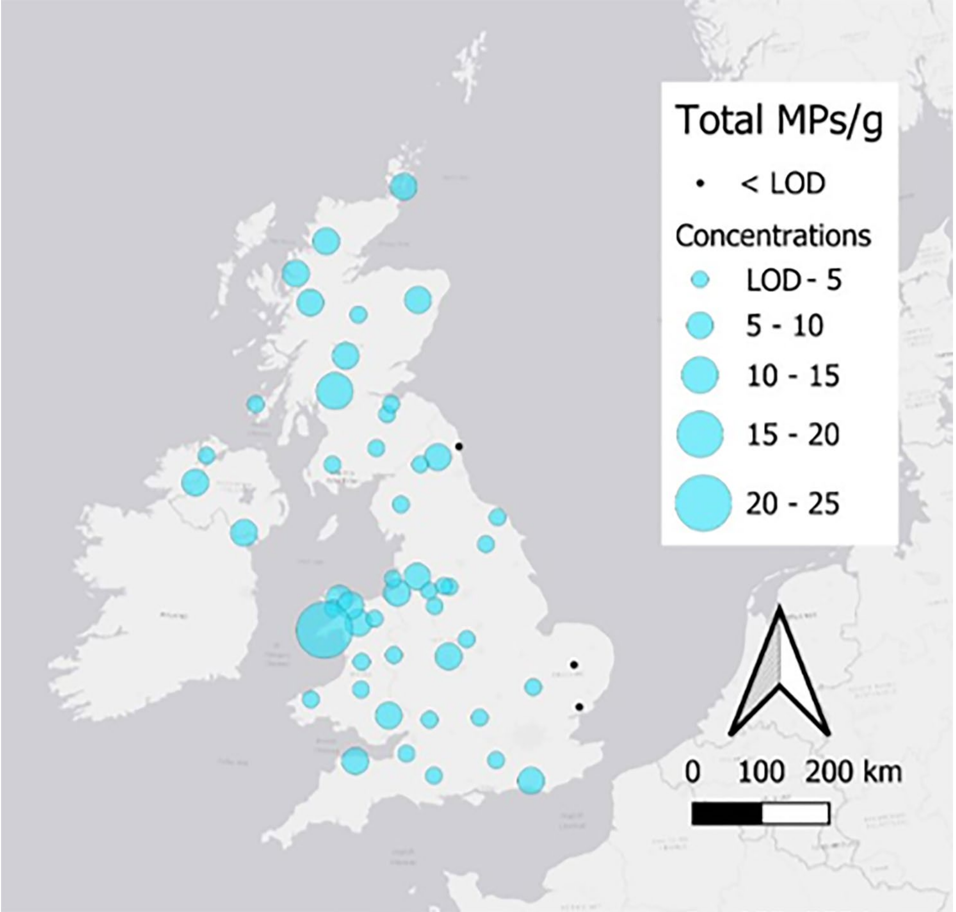


**Fig. 2** Abundance of microplastics in moss at the sampled locations, reported as the total microplastic concentration per gram of dry moss material. Sites where insufficient plastic material was detected above the limits of detection are denoted as < LOD. Data points are scaled by size, assigned as fixed interval categories between < LOD to 25 MP/g moss for visualisation purposes only

respectively of the 52 sampled locations. Meanwhile, some of the highest concentrations per gram moss were found in locations including Ward Hill in Scotland and in rural northwest Wales (Fig. 2).

### *Characteristics of microplastics found in moss across the United Kingdom*

A diverse range of plastic polymers were detected, with 11 of the 21 polymers searched for in the library detected above limits of detection. To interpret the polymer diversity, first we must be sure that we have collected sufficient microplastic particles to be representative.

A number of proposals have been reported for the minimum number of particles that must be detected to quantify characteristics of the microplastic population with a given level of confidence [15]. For example, if 96 microplastic particles are quantified and chemically identified, it has been estimated that this information would be associated with a 10% sampling error. Increasing the number of particles analysed reduces the uncertainty, with 386 particles required for a 5% sampling error [23]. Others have suggested that to quantify continuous distributions like particle size, 500 particles should be measured as a guide [24].

In the current assessment, we correct for the blanks and only report microplastics above the limits of detection. In this way, the following assessment does not consider the raw data of all microplastic particles detected in the samples. Rather, it considers the number of microplastic particles of each polymer, positively identified per gram of moss, that were above the limits of detection. The sum of each polymer type detected (per gram moss, across all locations), was equivalent to 236 particles. The final distribution of polymer types across all moss surveyed is calculated as a proportion of this total. Therefore, it might be expected that we have a sampling error associated with the reported polymer diversity of somewhere between 5 and 10%.

The prevalence of different synthetic polymers in moss across the UK can be understood in two ways. First the absolute proportional contribution each polymer makes up to the total number of microplastics detected across all moss (Fig. 3A). Another way to understand prevalence of different types of microplastics is to consider the frequency of detection of these polymers across the moss samples (Fig. 3B).

Microplastics with the highest overall abundance in moss were polyurethane (PU), cellulose acetate (CA) and ethyl-vinyl-acetate copolymer (EVAc), representing respectively 37.54, 20 and 13.17% of all microplastics detected (Fig. 3A). PU has very wide-ranging applications, from its use in as a laminate waterproof in compound fabrics, to its application as a coating and binder, from flexible foams and paints used in construction, to insulation in home furnishings and appliances. Cellulose acetate fibres are used in cigarette filters, one of the most commonly littered items, for example, as found on European beaches [25]. EVAc is a co-polymer in which vinyl acetate is blended with polyethylene to confer particular properties, such as improving adhesiveness in polyethylene films, and thus has spectral similarities with pure polyethylene. Other common uses include in adhesives, sealants and coatings.

Polyvinyl chloride (PVC) and polyethylene terephthalate (PET) were also quite abundant, representing respectively 8.77 and 4.56% of the total microplastic numbers detected across moss samples. PVC is the world's third most widely produced polymer, with many uses across construction and consumer products, as well in food packaging and as a coating in textiles. PET plastics are used in both textiles and in packaging, for example, in plastic PET drink bottles. Other plastics which are also known to have high production volumes such as polypropylene (PP) and polystyrene (PS) were less abundant overall, representing only a few percent of the total number of microplastic particles detected above limits of detection. Polyethylene (PE), a major plastic used for packaging materials, items that might be commonly littered, is perhaps unexpectedly absent in the data, being below limits of detection in all samples. However, EVAc, a polymer associated in blends with PE is widely detected, which may account in some part for this apparent low detection of pure PE signal in the moss, with these two spectra closely resembling one another.

When considering the frequency of detection of particular plastics across the moss surveyed, a similar picture emerges for the four most common polymers. PU, CA, PVC and EVAc are still the most frequently observed plastics, being detected in between 60 and 87% of all locations across the UK. However, a more nuanced narrative emerges for some of the less abundant plastics, such as PS and PET. Whilst the overall concentration of these in moss across the UK was perhaps lower than other polymers, their frequency of detection was still quite high, being found in 19 and 33% of mosses respectively. Therefore, whilst PET contributed only 4.56% of the total numbers of microplastic detected across locations, it was present in detectable concentrations in around one third of all locations across the UK.

The current monitoring survey was not designed to establish the sources of microplastics detected. It must also be reiterated that the assessment is not of all possible microplastics, but rather those operationally constrained by the sample preparation and measurement technique, of particles ≥ 25 μm in size. The ICP Vegetation Monitoring Manual provides guidance on principles for analysing

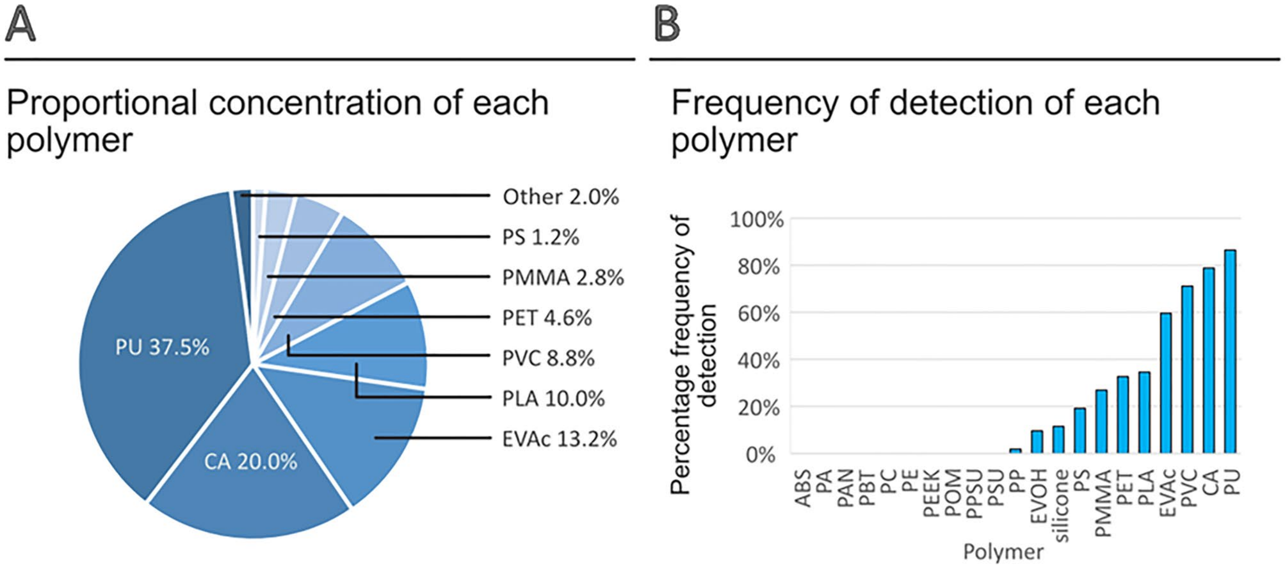


**Fig. 3** Polymer diversity in moss sampled across the UK. Pannel A represents the proportional abundance of each polymer across all microplastics detected, whilst Pannel B represents the frequency of moss samples in which each polymer was detected as a proportion of the total number of moss locations ($n = 52$)

microplastic fibres in moss [14]. These guidelines represent a basis from which standard methods could be agreed for the analysis of this particular sub-set of the microplastic continuum. The work presented in the present study, represents a complementary assessment that extends the analytical window beyond just quantification of microplastic fibres, to smaller plastic particles that cannot be distinguished following visual identifiable features under the microscope. There was no clear pattern of the diversity of plastics found across the UK, although there was a weak relationship between increasing total abundance of microplastics and an increase in the diversity of microplastics detected ($R^2$ = 0.18, slope = 0.2; Figure S8).

### Critical discussion of the survey design and future recommendations

To establish a program for monitoring microplastics in moss, suitable for long-term observations of spatial and temporal trends, it is important to ensure that variables in the sampling design do not overly influence the results. These include the types of moss collected or other landscape features that describe the sampling locations, which could plausibly influence the sources of microplastics in the air, or their deposition into moss. It is also important to make the survey design as efficient as possible to ensure that it is cost effective in the long term. Principle component analysis and kriging analysis are used in the following section to explore these questions.

#### *The survey design successfully limited the influence of local factors on the total abundance of microplastic in moss*

Principal component analysis (PCA) can help us understand the relationship between the set of variables that might influence total microplastic concentrations in moss from the sampling campaign, and whether different moss species can be compared. Redundancy analysis (RDA) is then useful in reducing the number of variables, identifying where variables may be driving the differences in microplastic abundance seen between sample locations.

Redundancy analysis finds the constrained axes explains only 27% of variation in total microplastic abundance, with only latitude being significant in the model ($p = 0.018$). Urban Index (10 km) is also close to significance in the model at alpha 0.05 ($p = 0.08$). It can be seen from Fig. 4 that there is no clustering of any particular

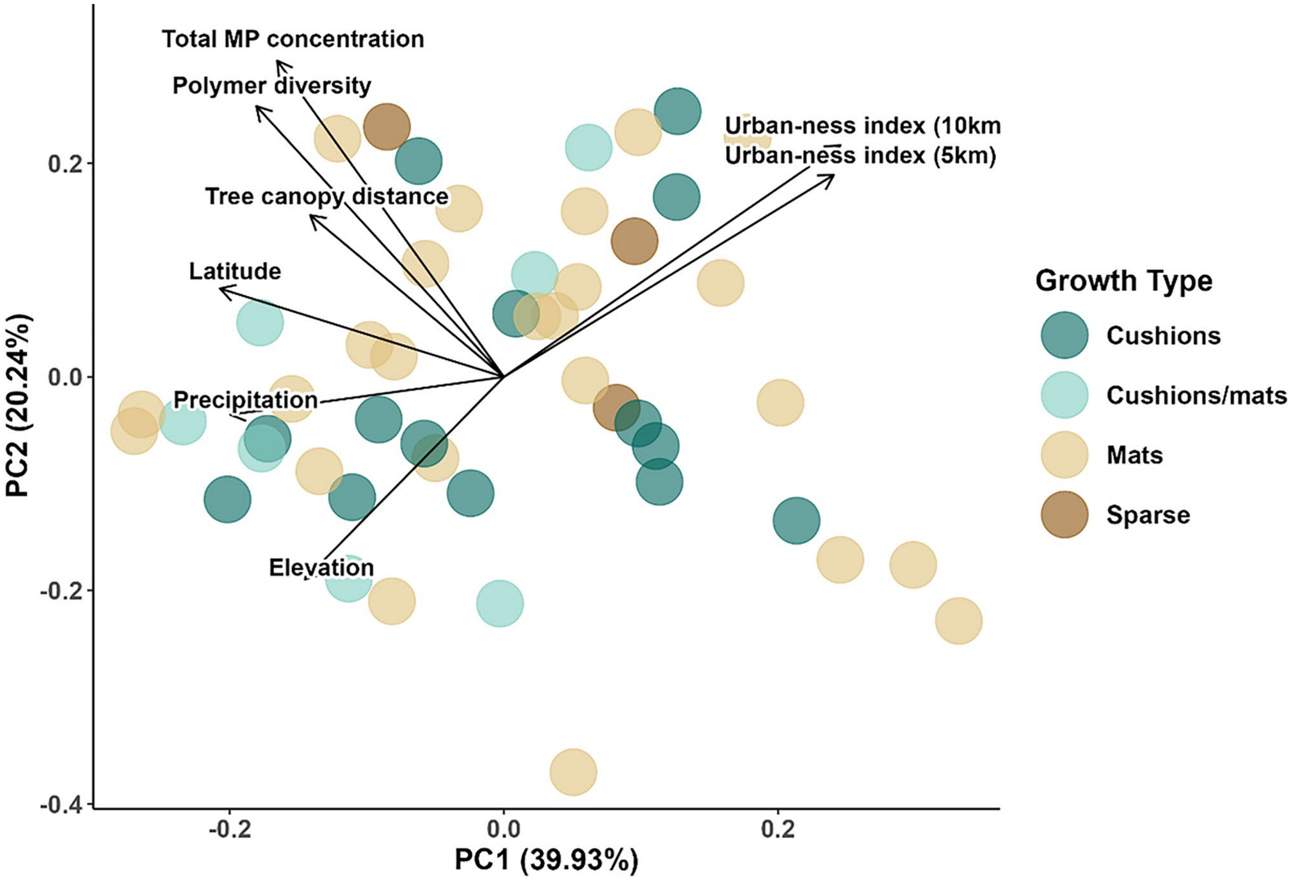


**Fig. 4** Principal components analysis (PCA) with vector fitting of the different geographical and environmental factors with different growth types highlighted in the points shows no clustering of any particular species with these factors

species of moss or growth type in the plot, and so no correlation between the species type and other geographic or environmental variables which could also drive distribution of microplastics across the UK. This indicates that the sampling design was successful in limiting the influence of local factors that might determine the prevalence of microplastics in moss.

In addition to the PCA results, we can use statistical analysis of variance to test whether it is appropriate to compare the data generated for the range of moss species collected. Ideally, only a single species of moss would have been collected, but practically this was not possible across all sites. The challenge of sampling just a single species of moss when surveying a large area is well recognised and was the focus of a study by Cowden and Aherne [26], who found concentrations of metals Al, V, Cr, Fe, Ni, and Pb correlated well between *Hylocomium splendens* and *Pleurozium schreberi*. These were also the two most commonly collected species in the present survey.

The variability in reported concentrations for these two species was consistent (Levene's test, F(1,30) = 0.73, $p$ = 0.399) and the species were found not to be significantly different (ANOVA, F(30,1) = 0.008, $p$ = 0.93). This makes sense, as the physiological structure of the two moss species are very similar. They have a high surface to mass ratio, and both species produce branching, feathery fronds which often form mats on the ground, with newer growth growing on top of older, dying and dead material. These features might enable the two species to trap microplastics particles within the superstructure of the moss tissue in a similar way. Indeed, whilst it has been demonstrated that species selection is important when comparing biomonitoring data for microplastics in mosses compared to lichens, these differences were largely attributed to structural characteristics and habitat differences between moss and lichen [5], which are of less concern between the mosses sampled in the present survey. To confirm this with confidence, a dedicated survey in which comparisons between moss species collected in the same sites would be required.

### *The survey was efficient, with little redundancy in the sampling design*

The sampling density used in the survey was informed by our understanding of other contaminants. The recommended sampling density of moss for heavy metals is 1.5 moss samples per 1000 km$^2$, to reflect a statistically valid density to investigate trends [14]. When analysing for microplastics, no statistical validation has been performed to date. However, in contrast to metals where steep gradients in deposition are found around industrial areas, microplastic deposition is thought to be less heterogenous, particularly across rural areas [5]. This informed the design of a lower sampling density of 1 per 5000 km$^2$ in the present survey. We can use statistics to understand the success of this sampling design.

Kriging analysis, a method of spatial interpolation is used to depict the spatial autocorrelation of the measured sample points as a semi-variogram. For randomly distributed data, there is little spatial autocorrelation, so the range estimated by the semi-variogram analysis is usually very small, and the sill (value that the semi-variogram model attains at the range) is reached quickly. This pattern was observed in the data from the current survey, indicating little spatial autocorrelation (Supplementary Information – Figure S9). The sampling design was therefore effective at avoiding redundancy in the data.

Avoiding redundancy in sampling design is beneficial for the aims of the current assessment, to establish a baseline understanding of the atmospheric deposition of microplastics in rural sites across the UK, free from the influence of local sources.

However, if the purpose of future surveys is to understand predictor variables and the environmental fate processes which lead to this widespread distribution of microplastics across rural sites in the UK, a different survey design may be preferable. For example, distances between sampling points can be manipulated to test hypotheses concerning local point sources or specific variables driving environmental fate processes.

### *Plausibility of the results*

It is important to consider the plausibility of the results in the light of other available evidence. Broadly, the current survey finds widespread contamination of moss across the UK, in locations that should be free from the influence of specific local sources such as roads and dwellings.

It is challenging to contextualise these concentrations against existing literature. There is no equivalent published data for other regions suitable for direct comparison, i.e. equivalent assessment of moss, using μ-FTIR and of microplastics in the same size region ≥ 25 μm in diameter.

A total of 13 relevant articles could be found in the Web of Science Core Collection following the search terms described and after screening papers for relevance. Of these, none used μ-FTIR spectroscopy to quantify microplastics and their polymer composition, meaning no direct comparison is possible of like-for-like studies. Most studies used optical microscopy ($n$ = 9), using a list of visual clues to identify probable microplastics, with some studies confirming polymer identity on a subset of particles ($n$ = 4). These studies reported microplastic concentrations in moss in a similar range as those found across the UK in the present survey, typically in the low tens of particles per gram. None reported higher concentrations than 100 microplastic particles per gram of moss or lichen material, with the exception of the one study which also used vibrational spectroscopy. In this instance Raman microscopy rather than infra-red was used, reporting particles down to a size of 0.6 µm [27], much lower than the lower limit of 25 µm pixel size resolution of the µ-FTIR used to analyse the present UK survey. This likely explains the much higher abundance reported of microplastics in the Raman microscopy study, of 128,863 MP/g, ~ 90% of which were < 15 µm in diameter, with a modal size range between 1 and 2 µm. A summary of some of the pertinent findings from the existing literature on microplastics in moss is presented in Table 2.

It is also useful to consider studies designed to provide mechanistic insight into the transport of microplastics in air. This allows critical assessment of the broader suggestion from the literature that microplastics are indeed transported some distance in the air, and may be subject to local, regional or even longer-range transport.

Investigations into microplastics in moss and lichens generally report a correlation along gradients of urbanisation of increasing microplastic and microfibre concentrations along the gradient from rural to urban centres [4, 6, 7, 28, 30–33]. Indeed, Jafarova et al. [30] conclude that the correlation between distance to urban centres, tissue content of other pollutants such as chromium and nickel and prevalence of microplastics suggest local and regional scale factors within a range of 10–100 km driving microplastic contamination, rather than long-range sources. Similarly, Wright et al. [34] estimate the distance travelled of non-fibrous and fibrous microplastics > 100 µm, measured by an atmospheric deposition sampler at an height of ~ 50 m above ground level in London, as being between 12 and 60 km. It is therefore plausible that microplastics detected in moss in the rural survey of the United Kingdom are indeed those transported truly via atmospheric deposition, rather than any direct local sources.

### *What about smaller microplastics?*

No study to date quantifying microplastics in air provides a full description of the whole microplastic continuum (5 mm to 1 µm), nor across all relevant polymers (e.g. Table 1). This is not a unique challenge for the study of microplastics in air, but is common to research across all environments. Whilst no single technique is quantitative of microplastics across their entire diversity [35], there are promising analytical techniques under development that can allow for microplastics, even smaller than those quantified in the present study to be evaluated. These include Raman microscopy, or mass spectrometry techniques such as gas chromatography-mass spectrometry [21, 27]. In the current study, we present a rationale for the use of a commonly employed vibrational spectrometry technique, µ-FTIR. Using its lower limit of detection to inform a sample processing design, this allows for increased material to be extracted and thus benefit from increased representativeness of each sample analysed. By necessity, this method limits its application to smaller microplastics, allowing for quantification of microplastic particles ≥ 25 µm.

There is no guidance for what region of the microplastic continuum is most important from a policy perspective, with environmental quality standards absent. From a research perspective, the most relevant region of the microplastic continuum will be driven by the purpose of the assessment. For example, if the purpose is to understand the emissions and fate of textile fibres, an analytical method which can detect the most common textile polymers and relevant sizes would be sufficient. On the other hand, if the purpose is to investigate the inhalable or respirable fraction of microplastics, another approach may suit best, which can target these smallest microplastics, in the PM10 and PM2.5 region. Whether a method is fit for purpose can only be judged in the context of the purpose of the assessment.

This presents a challenge to the research and regulatory communities. How do we prioritise and select the most appropriate measure and analysis of microplastics to meet a particular regulatory goal? One solution might be to focus the research effort to build a comprehensive description of microplastics along their whole continuum in different environments. These descriptions of the distributions of size, shape and polymer could then be used to allow for extrapolation from data that quantifies microplastics only within a narrow range, to an estimate of the whole population of "all" microplastics in a sample [36]. This could allow data to be extrapolated beyond the analytical limits of a single technique, and thus compared across techniques. This would also begin to allow datasets generated for one objective, to be repurposed to address future research questions.

One such approach has been proposed as a way in which to resolve the non-alignment of exposure and hazard data in the environmental risk assessment of microplastics [37]. Indeed, continuous distributions for microplastics found in different aquatic environments have been estimated [24], and a similar approach may be informative for airborne microplastics. The ultimate aim for such an approach would be allow for robust extrapolations to be made from data generated for example by µ-FTIR analysis to the expected concentrations of plastics beyond the analytical regions of this technique, e.g. to those microplastics < 25 µm in size. Such mathematical predictions of the continuous distribution of microplastics in different environments have been restricted to date to commonly reported lower size limits for analysis of microplastics, typically > 10 µm. Given the importance

**Table 2** Summary of publicly available studies reporting microplastics in moss or lichen

| Location | Species surveyed | Microplastic concentrations | Size range reported | Analytical method | Synthetic nature verified? | Reference |
|---|---|---|---|---|---|---|
| Ontario, Canada | Moss (*Pleurozium schreberi*) | Mean 7.9 MP/g | 0.03–4.51 mm<br>Median 0.56 mm | Optical microscopy | No | Bertrim and Aherne. [6] |
| Naples, Italy | Moss (*Hypnum cupressiforme*)<br>Lichen (*Pseudevernia furfuracea*) | Raman suggests 20% of microfibres found are plastic, therefore estimated mean between 17.4 and 20.4 plastic microfibres / g | 1.08–1.5 mm mean length<br>0.2–10.1 mm range lengths | Optical microscopy + Raman | Verification on a subset of ~ 100 particles | Capozzi et al. [7] |
| Luján, Argentina | Lichen (*Ramalina celastri*) | Baseline 16.54 MP/g<br>Rural 53.67 MP/g | Fibres ~ 1.5 mm in length | Optical microscopy | No | Gollo et al. [28] |
| Siena, Italy | Moss (*Pseudoscleropodium purum*). Lichen (*Evernia prunastri*) | 1 MP/g in control (rural moss) | Visual limit of detection reported ~ 50 µm<br>Fibre lengths ranged 114–4530 µm | Optical microscopy | Verification of plastic in ~ 20% of fibres found | Grifoni et al. [29] |
| Purchased moss Origin: New Zealand | Sphagnum moss | 128,863 MP/g. Note, 89% of all particles were < 15 µm | 0.8 to 65.4 µm in size.<br>Modal size range was 1–2 µm | Raman microscopy | Yes | Hagelskjær et al. [27] |
| Tuscany, Italy | Pleurocarpous moss | 4.8 MP/g | > 50 µm | Optical microscopy + µ-FTIR | µ-FTIR verification of a subset of particles | Jafarova et al. [30] |
| Italy | Lichen (*Evernia prunastri*). Moss (*Pseudoscleropodium purum*) | 14.5 MP/g mean across all moss | > 50 µm | Optical microscopy | No | Jafarova et al. [5] |
| Shiraz, Iran | Moss (*Grimmia critina*) | 0.22–1.55 MP/g | No information reported | Optical microscopy | No | Khodabakhshloo et al. [31] |
| Ireland | Moss (*Hylocomium splendens*) | 24 microfibres /g. Qualitative conclusion ~ 25% are plastic from visible properties | Mean length 1.02 mm. Range: 0.83–1.20 mm | Optical microscopy | No | Roblin and Aherne. [3] |
| Altipiani di Arcinazzo, Italy | Lichens (*Cladonia* and *Xanthoria* species) | 36 MP/g | 15 mm (+/- 0.2) average fibre length. Range 0.1–5 mm | Optical microscopy + ATR-FTIR | ATR-FTIR verification of subset of particles | Taurozzi et al. [32] |
| Milan, Italy | Lichen (*Evernia prunastri*) | 20 MP/g in rural control site | 127–615 µm, with a mean length of 354 µm | Optical microscopy | No | Jafarova et al. [33] |
| Campania, Italy | Moss (*Hypnum cupressiforme*) | 71 +/- 13 MP/g across all sites | Mode size class was 0.6–0.8 mm<br>Mean length of fibres between ~ 1.15–1.7 mm | Optical microscopy + FTIR | FTIR verification of 30 particles | Capozzi et al. [4] |

of the < 10 μm fraction of particulate matter for human inhalation exposure, there is still a need for new data to be generated in this size region, to complete the description of microplastics down to 1 μm. Note, that as smaller microplastics are expected to be more abundant, a corresponding reduction in required sample volume or starting mass of moss may be justified when targeting analysis of smaller particles than those under examination in the current study. Further studies to identify minimum representative sample required for accurate determination of smaller microplastics would be needed. There is also concern that plastic particles in the sub-micrometre or even nanometre range may experience distinct environmental fate, biodistribution and toxicities which are poorly understood. Significant developments in analytical chemistry are required to characterise environmental plastics in this region to fill these gaps in our understanding of the plastic pollution continuum.

## Conclusions and recommendations

Overall, the survey designed aimed to allow for longer range transport of microplastics in air to be quantified, likely due to regional factors, at a scale of 10–100 km range, rather than those from hyper local point sources such as roads and dwellings. Microplastics were found in 49 out of 52 of the sites sampled, indicating widespread deposition of microplastics to moss, and with a wide range of polymers detected. The results are plausible, given what is known mechanistically about microplastics transport in air. The sampling design also meets the purpose of the assessment, with no redundancy identified in the sampling locations.

There are of course still questions remaining that the current survey does not answer, and indeed, were not the purpose of the original design. Source apportionment remains to be investigated. The evidence for microplastic transport in air to date would suggest that it is likely that regional and local atmospheric transport (tens to hundreds of kilometres) is responsible for the changing contamination of microplastics across the United Kingdom observed in the current study. Mechanistic insights into the medium to long range transport of microplastics in air are still required. The survey also provides a snapshot in time, as a baseline which can be built upon, rather than any insight into temporal trends. To address these research questions, specific survey designs such as transects away from suspected point sources, or temporal studies at different scales are needed that can build on the survey established here. If it is required that smaller microplastics should also be monitored, continued developments in analytical chemistry and spectroscopy are needed to complete our understanding of the plastic pollution continuum in these smaller size ranges.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43591-026-00191-8.

Supplementary Material 1 - Supporting Information

Supplementary Material 2 - Summary Data

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**Author contributions**

Richard K. Cross: Writing – Original draft, Conceptualization, Methodology, Visualization, Formal analysis, Supervision, Writing – review & editing. Ruairidh Cox: Investigation, Methodology. Sarah L. Roberts: Visualization, Formal analysis, Writing - Original Draft. Alexnadra Howard: Investigation, Methodology, Writing - Original Draft. Katrina Sharps: Formal analysis, Writing - Original Draft. Felicity Hayes: Conceptualization, Supervision, Writing – review & editing.

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**Data availability**

Summary data from the survey and detailed results from the analysis are provided within the manuscript and in the supplementary information files.

## Declarations

**Ethical approval**

Not applicable.

**Competing interests**

The authors declare no competing interests.

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