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Microplastic pollution on hiking and running trails in Australian protected environments

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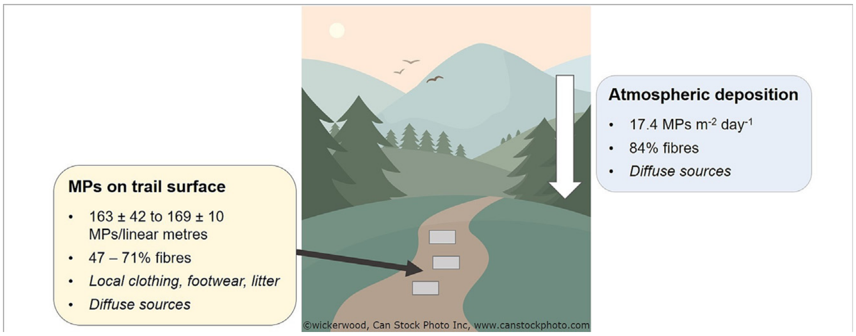
HIGHLIGHTS

- MP quantities and characteristics were assessed in two protected areas in Australia.
- MPs deposited from the atmosphere averaged 17.4 m^{-2} day^{-1}.
- Recreational trail surfaces showed 162.5 ± 41.6 and 168.7 ± 18.5 MPs/linear metre.
- MPs were mainly polyurethane, polyethylene terephthalate, polystyrene and polyamide.
- MPs were sourced to clothing, footwear, food packaging and diffuse sources.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastics (MPs) are ubiquitous worldwide, present even in remote areas of the natural environment. Hiking and trail running are a source of MPs on recreational trails in protected environments, which are characterised by high biodiversity and natural, ecological or cultural significance. Our understanding of the risks of microplastic pollution is impeded however by a lack of information on MPs present in the soil environment in such areas. This study characterised the quantity and physicochemical characteristics of MPs in two conservation areas in south-eastern Australia: 1) the adjacent Duval Nature Reserve and Dumaresq Dam Reserve, and 2) the Washpool and Gibraltar Range National Parks. We measured atmospheric deposition over a six-month period in the Reserves, and baseline amounts of MPs on recreational trails in the Reserves and National Parks. Atmospheric deposition averaged 17.4 MPs m^{-2} day^{-1} and was dominated by fibres, comprising 84 % of MPs. Microplastics detected on trail surfaces ranged from 162.5 ± 41.6 MPs/linear metre to 168.7 ± 18.5 MPs/linear metre and exhibited a very wide range of physical and chemical characteristics. The majority of MPs on the trail surfaces comprised polyurethane, polyethylene terephthalate and polystyrene, and 47–71 % were fibres. Microplastics were attributed to clothing, footwear, litter, and diffuse sources. Minimising and preventing MP pollution, however, is complex given there are multiple direct and diffuse sources, and several factors influencing increased MP deposition and retention in the environment.

1. Introduction

Microplastics (MPs) are ubiquitous in terrestrial environments, stemming from the widespread use of plastic materials in modern society. Although most abundant in agricultural, industrial and urban environments, MPs have also been detected in remote areas (Allen et al., 2019; Napper et al., 2020). In protected areas of the natural environment, public access is highly regulated and MP pollution is thought to occur predominantly from direct deposition during outdoor recreation (Barrows et al., 2018; Forster et al., 2023a) or atmospheric deposition from diffuse sources (Brahney et al., 2020). Current MP research within conservation and protected areas focuses on aquatic ecosystems (Driscoll et al., 2021;

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Godoy et al., 2022), and very little is known about MPs in the soil environment.

Protected and conservation environments are characterised by high biodiversity and natural, ecological or cultural significance. Approximately 17 % of terrestrial and inland water areas across the globe are designated as protected or regions for "other effective area-based conservation measures" (OECMs) (UNEP-WCMC and IUCN, 2021) and in Australia, this value is approximately 20 % (DCCEEW, 2021). Land managers aim to safeguard biodiversity and the natural environment whilst simultaneously providing opportunities for visitor use and recreation (e.g. hiking, trail running, mountain biking) (NSW National Parks and Wildlife Service, 2005). To meet this potentially contradictory mandate, access is typically regulated by restricting activity in protected or conservation areas to recreational trails (Wolf et al., 2019).

Nonetheless, preliminary studies report outdoor recreation is a source of plastic pollution in protected and remote wilderness areas. Macroplastics (plastic items >5 mm) were detected on glacial access trails in Italy from the fragmentation of clothing, food packaging and mountaineering equipment (Parolini et al., 2021). Microplastics found in river systems and snow near trails and access routes in wilderness areas of the US, Italy and Mt Everest were ascribed to a combination of atmospheric deposition and shedding of visitor's clothing, footwear, mountain bike tires, and mountaineering equipment (Barrows et al., 2018; Napper et al., 2020).

Visitation to protected environments is increasing worldwide, which may lead to increased plastic pollution in these areas. In the US, mountain biking and hiking increased by 26–89 % between 2007 and 2021, and adventure racing and trail running rose by 162–197 % (Outdoor Foundation, 2022). In Australia, visitors to New South Wales (NSW) national parks rose to approximately 60 million in 2018 (Roy Morgan Research, 2019). Globally, competitive recreation is also becoming more common, with participation in trail running and adventure racing events growing at a rate of 15 % per annum and >25,700 races taking place between 2013 and 2019 (ITRA, 2022; World Athletics, 2022). Running events may lead to a significant and rapid influx of MP pollution to conservation areas, with some events including hundreds to several thousand participants (Running Wild, 2023; Ultra-Trail Australia, 2019).

The effects of MP pollution on the capacity of protected areas to conserve biodiversity, preserve natural ecosystems, and provide habitats for rare plant and animal communities are unknown. A growing body of research indicates MPs are a chemical and physical stressor that may impact ecosystem functioning, soil-water dynamics and erosion processes, nutrient cycles, litter decomposition and plant growth (Colzi et al., 2022; Ingraffia et al., 2021; Leifheit et al., 2021; Lozano and Rillig, 2020). Adverse effects on the soil environment may vary considerably depending on MP abundance and physicochemical properties including particle size, shape, polymer type, additive chemistry, and weathering (Bucci and Rochman, 2022; Lambert et al., 2017). Our understanding of the consequences of MP pollution for the natural environment is constrained however by the lack of information on MPs in trafficked and remote sections of protected and conservation areas (Forster et al., 2020).

The objective of this study was to measure the quantity and characteristics of MPs in protected environments utilised for annual trail running events and recreational hiking and trail running, and identify potential sources. Targeted surveys of MP pollution on trail surfaces were undertaken in two conservation areas in New South Wales in south-eastern Australia. Atmospheric MP pollution was also monitored in one of these locations for six months.

2. Methods

2.1. Study design

Microplastic pollution was investigated in two conservation areas in New South Wales; 1) the Duval Nature Reserve and adjacent Dumaresq Dam Recreation Reserve, and 2) the contiguous Washpool and Gibraltar Range National Parks. Microplastic pollution was examined by undertaking surveys on trail surfaces in both locations and considering atmospheric deposition over a six-month period in the Reserves. It was not possible to measure atmospheric fallout over an extended period in the National Parks due to travel constraints.

2.2. Study locations

2.2.1. Reserves

Atmospheric deposition and MPs on trails were measured in the adjoining Duval Nature Reserve (30°24′26″S, 151°38′27″E) and Dumaresq Dam Reserve (30°25′49″S, 151°35′58″E) near Armidale in New South Wales, Australia (Fig. 1). The Duval Nature Reserve encompasses the eastern and southern sections of Mount Duval and is managed by New South Wales Parks and Wildlife (NSW Parks and Wildlife Service, 2003). The Dumaresq Dam Reserve is a recreation reserve maintained by the Armidale Regional Council and is popular for bushwalking, running, kayaking, and fishing. Linking the reserves is the Newholme Field Laboratory, which is managed by the University of New England for the purpose of native vegetation regeneration, wildlife conservation, research, and education. Recreation within the Newholme property and Duval Nature Reserve is limited as access is restricted and tracks are not signposted. The climate, flora, fauna and geology of the area are summarised in Text S1.

A walking and running trail traverses the study area and is a mix of single lane track and two lane management trail. The trail surface is predominantly compacted and loose soil with areas of exposed rock (Fig. S1). The Dumaresq Dam Loop Track is considered to have high foot traffic, whereas the Duval Loop Track has low traffic (Fig. 2a). Since 2018, the Duval Dam Buster trail running event has been held annually and includes approximately 400 participants (Armidale Athletics Club Inc, 2022).

2.2.2. National parks

Microplastics on recreational trails was also measured in the Gibraltar Range National Park (29°33′9″S, 152°19′16″E) and Washpool National Park (29°20′49″S, 152°19′58″E) in New South Wales, Australia. The National Parks are approximately 65 km east of Glen Innes (Fig. 1). Part of the Gondwana Rainforests Reserves of Australia, the Washpool and Gibraltar Range National Parks are World Heritage-listed and characterised by high biodiversity and species richness, home to a number of rare, primitive and relict plant and animal species (Text S2).

The National Parks are popular for outdoor recreation, providing opportunities for day hikes, backpacking, trail running, adventure racing, mountain biking, and swimming (Coffs Trail Runners, 2022; NSW National Parks and Wildlife Service, 2020; NSW National Parks and Wildlife Service, 2022; Raid Adventures, 2022). There is a track network linking the National Parks, comprising a mix of single lane tracks and two lane management trails (NSW National Parks and Wildlife Service, 2005). All trails are accessible to foot traffic, with mountain biking restricted to management trails. The trail has sections of compacted and loose soil and areas of exposed rock (Fig. S2). Since 2010, there has been an annual trail running event with approximately 150 runners have participated in the annual trail running event, the Washpool World Heritage Trail Race (Coffs Trail Runners, 2022).

2.3. Sampling design and techniques

2.3.1. Sampling of microplastics on trails

The quantity of MPs on trails was investigated using a systematic/random hybrid sampling design, stratified by sampling location, then type of trail surface (designated using the combined gradient and surface material) (sampling design illustrated in Fig. S3). Three categories of trail surfaces were assessed on the Dumaresq Dam and Duval Loop Tracks; flat rock, flat soil, and sloped soil (Table S1). Four categories of trail surfaces were assessed at Washpool and Gibraltar Range National Parks; flat rock, flat soil, sloped rock, and sloped soil. The soil surfaces comprised hard, compacted soil with minimal overlaying alluvial material.

For each type of trail surface, three sections of trail (two for the flat rock on the Dumaresq Dam Loop Track) were identified as suitable for sampling

Fig. 1. The study areas Dumaresq Dam and Duval Nature Reserves, and Washpool and Gibraltar Range National Parks are shown in the Northern Tablelands region (in grey) in New South Wales, Australia.
Map modified from NSW Government (2020).

based on the consistency of the surface, and relative absence of moisture, small rocks, and organic matter such as leaves and sticks. Within each trail section, a single 1.25-metre long plot was selected at random. Gel lifter tape has been shown to be effective for quantitative recovery of MPs >100 μm from hard trail surfaces (Forster et al., 2022). For single lane trails (approximately 50 cm wide), five 5 cm × 10 cm samples spaced 25 cm apart were collected from the midline of the trail using gel lifter tape. With this method, three pieces of gel tape are applied consecutively in the same 5 cm × 10 cm area to obtain one sample. For the double lane management trails (approximately 1.2 m wide), three samples were taken from one side of the trail, and two samples from the other side. A total area of 250 cm^2 was sampled in each plot. The gel lifter tape was placed adhesive side up in individual lidded-plastic petri dishes and analysed using microscopy without any further processing as per Forster et al. (2022). Quality assurance processes, collection of blanks, and measures taken to minimise contamination are detailed in Text S3.

Trail surface conditions important for the movement and retention of water, sediment and nutrients were assessed at the time of sampling (Table S1). The trail slope was calculated based on the total fall over 50 cm. Roughness gradings were ascribed based on depressions on the trail surface (Tongway and Hindley, 2004). Vegetation type and the percent litter cover on the trail surface were estimated visually.

Sampling was undertaken at the Dumaresq Dam and Duval Nature Reserves on the 18th May 2021, and at the Washpool and Gibraltar Range National Parks on the 10th May 2022. The Northern Tablelands region in NSW experienced above average rainfall in 2021 and 2022, and 16 mm of rain was recorded in Armidale (30°25′48″S 151°38′14″E) and 21 mm of rain was recorded in Glen Elgin (20 km to the west of the National Parks) during the two weeks immediately preceding the sampling of each area (Bureau of Meteorology, 2022).

2.3.2. Atmospheric deposition

Atmospheric MP deposition was measured in the Duval Nature Reserve and Dumaresq Dam Reserve over a four- to six-month period in the winter and spring of 2021. Passive dust samplers were used and installed adjacent to the trail in five locations with varying foot traffic, vegetation density, and elevation (Table S2). Areas directly under vegetation were avoided, and the dust samplers were placed 4.0 ± 1.0 m from the trail and 1.2 ± 0.1 m above the trail surface. Rainfall and wind speed and direction were monitored remotely at the Newholme Field Laboratory weather station during the sampling period.

The dust collectors comprised 150 mm glass funnels with black neoprene gaskets attached to glass bottles (Fig. S4). The glass bottles were wrapped in black film to limit algae growth and prevent photo-oxidative damage to MPs. Sampling was undertaken approximately every two to four weeks depending on rainfall. Samples were collected by rinsing residual dust and MPs from the funnel into the bottle using <100 mL deionised water, then removing the bottle and sealing with a clean metal lid. A clean glass bottle was immediately placed under the funnel. The bottles (containing rainwater, dust, leaf debris and MPs) were transported back to the laboratory for processing and analysis. The collected samples were suction filtered through 11 μm cellulose filter paper, with the retained material then transferred into 150 mm polystyrene petri dishes and dried at room temperature. The petri dish lid was placed over the filter paper with a 5 mm air gap to allow for evaporation. Blanks were collected in triplicate by assembling a clean dust collector in the lab, immediately rinsing dust

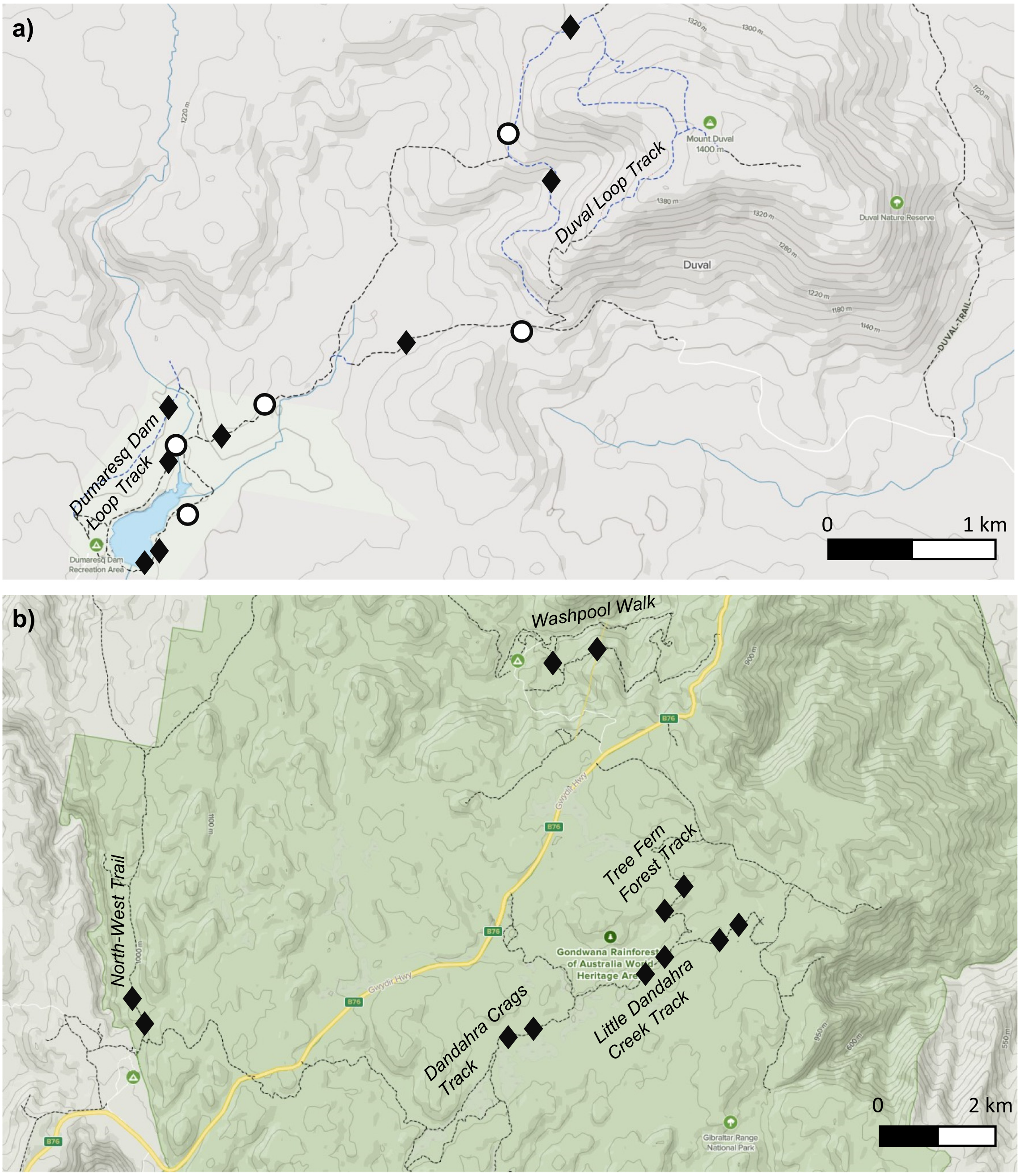

Fig. 2. Recreational trails in a) Dumaresq Dam Reserve and Duval Nature Reserve and b) Washpool and Gibraltar Range National Parks. Black diamond markers indicate location of plots on trail surfaces, and white circles represent location of dust samplers.
Maps modified from AllTrails (2022).

residue and MPs on the funnel sides into the glass bottle, and disassembling the dust collector, and filtering (Text S3).

2.4. Microplastic detection, visualisation and characterisation

Microplastics on the trail surface samples were visualised, counted, and measured using a Nikon SMZ745T microscope at x30 magnification. Microplastics from atmospheric deposition were visualised and counted using a Leica EZ4 microscope at x35 magnification. Microplastic detection and characterisation followed the method described in Forster et al. (2022), which was determined to be quantitative for MPs >100 μm. Briefly, fibres were linear particles with uniform thickness, colour and opacity (i.e. no visible micro-structures or segments). Irregular-shaped fragments were separated into two categories; rubber fragments, which showed elastic deformation, and ‘other fragments’, which were all remaining MPs. Microplastic counts for each sample was corrected by deducting the mean number of fibres in the blanks (no fragments were detected).

Approximately 20 fibres and fragments from the trail surfaces were removed from the gel tape using fine metal tweezers, gold coated and visualised using a JEOL JSM-6010LA Scanning Electron Microscope (JEOL Australasia, Frenchs Forest, NSW, Australia). Given the challenges of handling small particles, all particles chosen for SEM were approximately 200 μm or larger.

A total of 760 MPs from the trail surfaces of the Dumaresq Dam Loop Track (flat rock) and Washpool Walking Track (sloped soil) and atmospheric fallout in the open grassland were characterised with Laser Direct Infrared Imaging (LDIR) analysis at Eurofins Environment Testing (Melbourne, Australia) using an Agilent 8700 LDIR system with Clarity v1.10.0 software (Agilent, Melbourne, Australia). Microplastics were prepared for LDIR analysis using the method described in (Forster et al., 2023b) (Text S4).

Spectra were generated for individual particles >20 μm in the mid-infrared range (975 cm^{-1} to 1800 cm^{-1}) and compared against the Eurofins provided reference library to identify MPs. Polymer types were determined using a confidence threshold of 75 %. Microplastic identification using this reference library has been validated by Eurofins for eight polymers: polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), polyethylene terephthalate (PET), polycarbonate (PC), polymethylmethacrylate (PMMA), and polyamide (PA). Other reported polymers may be under-estimated as the reference library does not contain spectra for all molecular permutations.

2.5. Data analysis

To assess MP abundance on trails, the mean number of MPs per 5 cm × 10 cm sample was calculated for each plot, then converted into MPs per linear metre (MPs/lm) using Eq. (1). The results represent MP pollution across a 10 cm wide section in the centre of the trail (1000 cm^2).

$$\text{MPs/lm} = \textit{MP counts}_{(5\ \text{cm}\times 10\ \text{cm}\ \textit{sample})} \times 20 \qquad (1)$$

Microplastic counts for the atmospheric samples were converted to average daily MP deposition per square metre based on the surface area of the passive dust collector and the number of days between sampling (Eq. (2)).

$$\text{MPs m}^{-2}\ \text{day}^{-1} = \frac{\textit{MP counts}}{177\ \text{cm}^2} \times 10,000\ \text{cm}^2 \div \textit{Days since sampling} \qquad (2)$$

All data was analysed using R Studio version 2021.9.2.382 (RStudio Team, 2022) and R version 4.1.2 (R Core Team, 2021), with the nlme (Pinheiro et al., 2013) and predictmeans (Luo et al., 2021) libraries. Microplastic occurrence on trails was assessed using linear mixed effects modelling using a compound variable of slope and surface as fixed effects, with the varIdent function used to model different variances per plot. Multiple comparisons were assessed using Tukey's analysis.

Average atmospheric deposition across both Reserves was determined for the four-month period between the 24th June and 9th November 2021. Storm damage to the dust samplers at the Dumaresq Dam Reserve precluded measurements before and after these dates. Climactic effects were investigated using data from the Duval Nature Reserve for the six-month period spanning the 19th May to the 25th November 2021. The association of rainfall with daily atmospheric deposition of fibres and fragments was assessed using Pearson's correlation. Rainfall was assessed according to the following categories; total rainfall since the previous sampling date, average rainfall per rain day, and the frequency of days with rain (any amount), light rain (<1 mm), light-moderate rain (<5 mm), and moderate to heavy rain (>5 mm). A p value of 0.05 or less was taken as indicating statistical significance. All assumptions of statistical tests were checked and met.

3. Results

3.1. Microplastics on trail surfaces

3.1.1. Reserves

Microplastics were detected on all trails at the Duval Nature Reserves and Dumaresq Dam Reserve, with an overall average of 162.5 ± 41.6 MPs/lm. Over three times more MPs were detected on the Dumaresq Dam Loop Track (296.0 ± 27.2 MPs/lm), compared with 82.4 ± 18.8 MPs/lm on the low traffic connecting tracks and Duval Loop Track. Fibres were dominant, accounting for 47 % of the detected MPs. Rubber fragments comprised 38 % of the MPs, with 'other fragments' accounting for 15 %. Microplastics identified via microscopy ranged from 33 to 4593 μm in size, with fibres longer than fragments. On average, fibres were 791 ± 40 μm, whereas rubber MPs were 194 ± 8.0 μm and 'other fragments' were 149 ± 11 μm.

The quantity of fibres detected on the trail surfaces did not differ significantly due to high variation ($F_{2,5} = 3.24$, $p = 0.13$) (Fig. 3). There was an apparent but non-significant trend towards higher frequency of fibres on rock and flat surfaces however, with 81 % more fibres found on flat rock compared to the flat soil, and 146 % more MPs on flat soil compared to sloped soil.

In comparison, there were significant differences for rubber MPs ($F_{2,5} = 15.57$, $p < 0.01$) and 'other fragments' on the trail surfaces ($F_{2,5} = 5.82$, $p < 0.05$). Rubber MPs were most abundant on flat and rock surfaces, with 128.0 ± 12.0 MPs/lm on the flat rock surface, followed by the flat soil (61.3 ± 24.0 MPs/lm) and the sloped soil (17.3 ± 8.1 MPs/lm). 'Other fragments' were also most abundant on the flat rock surface (46.0 ± 2.0 MPs/lm), followed by the sloped soil (22.7 ± 5.8 MPs/lm) and flat soil (10.7 ± 3.5 MPs/lm).

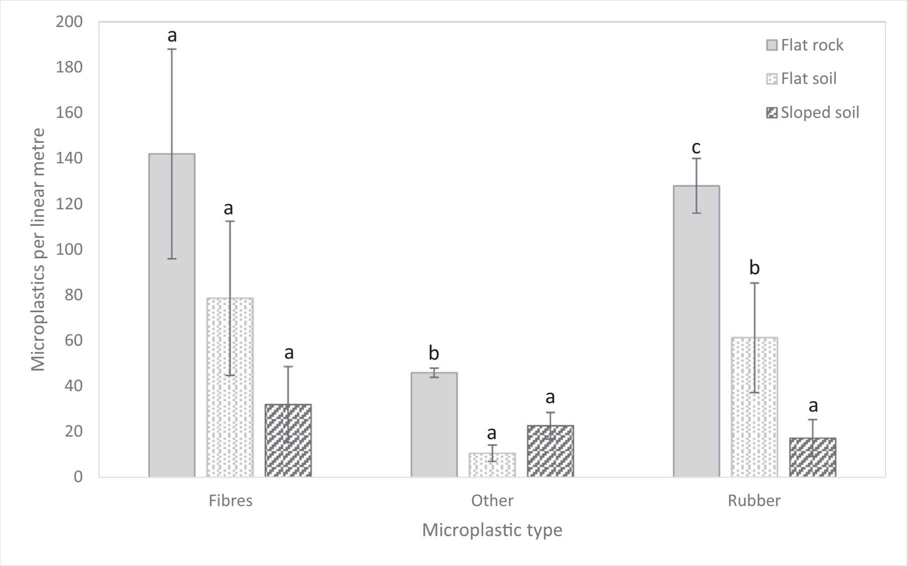

Fig. 3. Microplastics on trail surfaces at Duval Nature Reserve and Dumaresq Dam Reserve. Different lower-case letters denote statistically different groups for deposition of each type of MP (fibres, other fragments, rubber) on different trail surfaces.

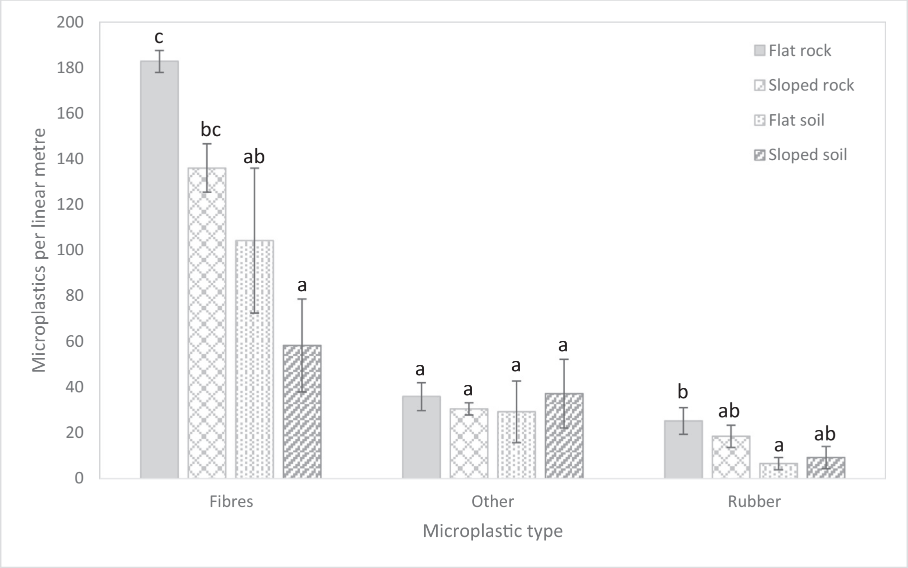

Fig. 4. Microplastics on trail surfaces at Washpool and Gibraltar National Parks. Different lower-case letters denote statistically different groups for deposition of each type of microplastic (fibres, other fragments, rubber) on different trail surfaces.

3.1.2. Washpool and Gibraltar Range National Parks

As with the Reserves, MPs were present on all trails at the Washpool and Gibraltar Range National Parks, with an overall average of 168.7 ± 18.5 MP/lm. Overall, fibres accounted for the majority of MPs, comprising 71 % of the detected MPs. The remaining particles were 'other fragments' (20 %) and rubber MPs (9 %). Microplastics identified via microscopy ranged from 35 to 4700 μm in size, with fibres larger than fragments. On average, fibres were 792 ± 36 μm, whereas other fragments were 135 ± 9 μm and rubber MPs were 179 ± 10 μm.

Fibre deposition varied significantly on the trail surfaces ($F_{3,8} = 6.70$, $p < 0.05$), with a trend towards higher numbers of MPs on flat and rock surfaces. Fibres were most abundant on the flat rock trail sections (182.7 ± 4.8 MPs/lm), and least abundant on the sloped soil surfaces (58.4 ± 20.3 MPs/lm) (Fig. 4).

In contrast, there were no significant differences between the trail surfaces for rubber MPs ($F_{3,8} = 3.05$, $p = 0.09$) and 'other fragments' ($F_{3,8} = 0.19$, $p = 0.90$). Despite this, rubber MPs tended to be more frequent on rock surfaces, with 280 % more detected on flat rock sections compared to flat soil (25.3 ± 5.8 and 6.7 ± 2.7 MPs/lm respectively), and 100 % more on sloped rock compared to sloped soil (18.7 ± 4.8 and 9.3 ± 4.8 MPs/lm). Other fragments varied from 29.3 ± 13.5 on flat soil to 37.3 ± 15 MPs/lm on sloped soil surfaces.

3.2. Atmospheric deposition

Daily atmospheric MP deposition across the Reserve averaged 17.4 particles m^{-2} day^{-1}, with fibres accounting for 84 % of MPs. There were minimal rubber MPs (1 %), with the remainder classified as 'other fragments' (15 %). Vegetation type and meteorological factors appeared influential, with deposition ranging from 10.3 MPs m^{-2} day^{-1} in the open forest area, to 14.8 ± 3.3 MPs m^{-2} day^{-1} in the woodland areas, to 32.3 MPs m^{-2} day^{-1} in the open grassland area (Fig. S5).

Increased MP precipitation was associated with frequent light-moderate rainfall (<5 mm). Higher numbers of fibres were detected in the atmospheric fallout following increased incidence of light-moderate rainfall ($R^2 = 0.61$, $p < 0.05$) (Fig. 5), but fragments were not (including all types) ($R^2 = 0.01$, $p = 0.85$). Atmospheric MP

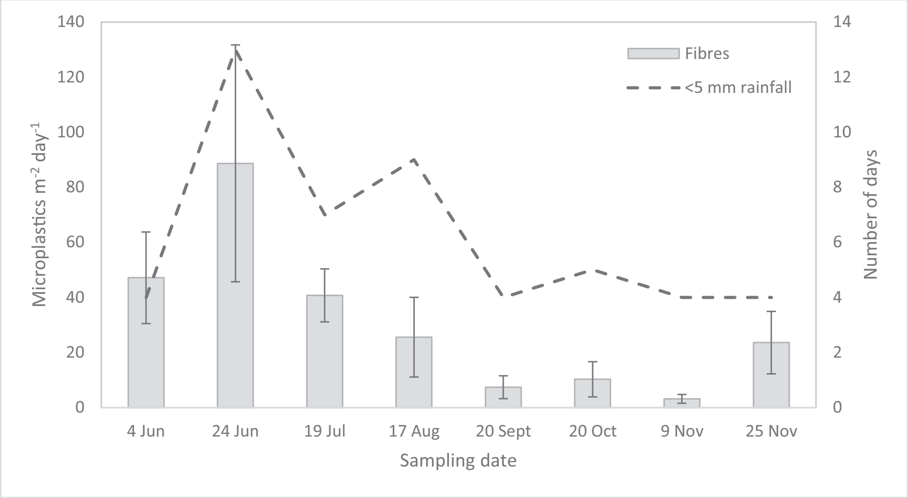

Fig. 5. Association between atmospheric deposition of fibres and frequency of light to moderate rainfall.

deposition was lower with occasional but moderate-heavy rainfall, with a negative relationship between numbers of fibres and average rainfall per rain day ($R^2 = 0.59$, $p < 0.05$) (Fig. S6). In comparison, atmospheric MP deposition was not related to total rainfall volume since the preceding monitoring point, with R^2 values of <0.25 for fibres and fragments ($p > 0.05$).

3.3. Microplastic morphology

All MPs were visualised using microscopy and a subset were visualised using scanning electron microscopy (SEM). The MPs comprised a wide variety of colours, with black, grey, blue, green, red, and purple fibres (Fig. S7a–c), and black, aqua, and blue fragments (Fig. S7d–i).

Scanning electron microscopy revealed extensive morphological and surface variation. Microfibre cross-section varied from circular (Fig. 6a), to concaved (Fig. 6b) to a scalloped square (Fig. 6c). Mechanical and physical damage to fibres was evident, including compressed sections (Fig. 6a) and fraying (Fig. 6d). Some fibres also exhibited weathering, with fibre surfaces ranging from smooth to cracked and irregular.

Microplastic fragments classified as 'other' were highly irregular and lacked any distinguishing features. Edges were sharp and rounded, and surfaces ranged from glossy smooth to rough to cracked (Fig. 6e–f). Rubber MPs were also highly variable, with the three-dimensional structure and surface properties varying within a single particle. Some areas of rubber MPs were observed to be solid and contain lumps (Fig. 6g), whereas other sections were porous and globular (Fig. 6h).

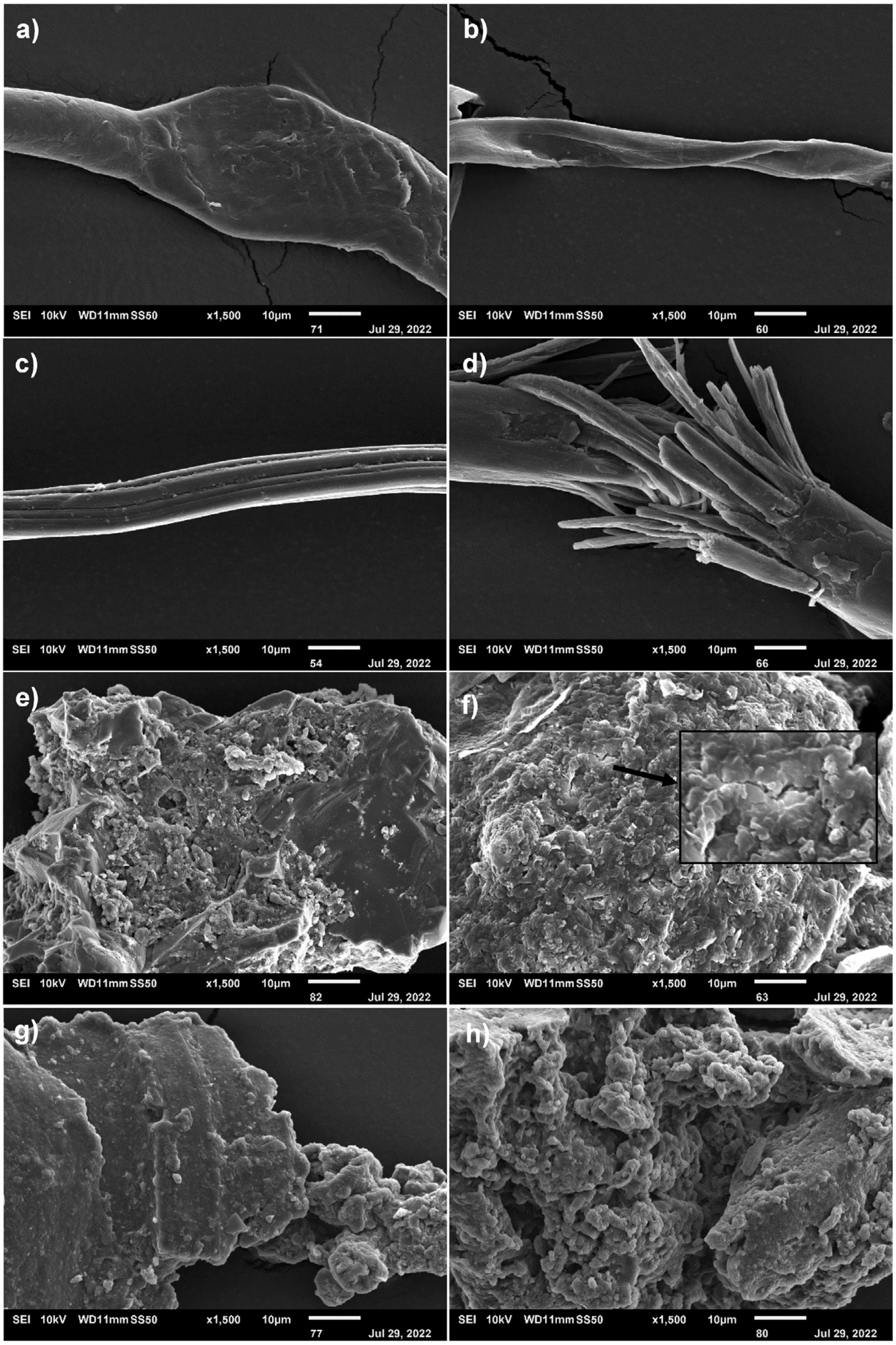

Fig. 6. SEM images of a–d) fibres, e–f) other fragments, and g–h) rubber fragments detected on trail surfaces. Surface cracking is enlarged and indicated in f.

3.4. Microplastic characterisation

The types of MPs on the trail surfaces differed between the flat rock at Dumaresq Dam and the sloped soil at Washpool National Park. Laser Direct Infrared (LDIR) Imaging identified 462 MPs in the flat rock sample at Dumaresq Dam, with the predominant polymers being polyurethane (PU), polyethylene terephthalate (PET) and polystyrene (PS), followed by small amounts of polypropylene (PP) and polyamide (PA) (most abundant polymers are reported in Table 1, full set of results in Table S3).

The broadest range of polymer types were detected on the sloped soil surface at Washpool National Park. Of the 226 microplastic particles detected, the most abundant polymers were PS, PU, PET, followed by small amounts of PA, polyethylene (PE) and polyvinyl chloride (PVC).

Laser Direct Infrared (LDIR) Imaging of the microplastics from atmospheric fallout from the open grassland area of the Duval Nature Reserve identified 72 microplastics. Four polymer types accounted for 85 % of microplastics, including PET, chlorinated PE, PA and polycarbonate (PC).

4. Discussion

4.1. Sources of microplastics

Microplastic pollution in protected environments may occur from direct or atmospheric deposition, or a mix thereof. In this study, the atmospheric fallout was predominantly fibres. As PET and PA were abundant and almost all types of synthetic fibres are used for apparel (Geyer, 2020), these fibres are most likely sourced from polyester and nylon clothing. Other polymers detected in the atmospheric fallout (e.g. PC and chlorinated PE) are common in the construction, automotive, cabling, and electronic industries and may originate from urban or industrial areas (Iranmanesh et al., 2012; Kausar, 2018).

The majority of MPs on the trail surface were ascribed to clothing, footwear, litter and diffuse sources. Plastic materials are widely utilised in outdoor clothing, footwear and equipment (e.g. backpacks, tents, sleeping mats) (Simon and Alagona, 2013) and abrasive forces may cause MP shedding and local deposition. Fibres comprised the majority of MPs on the walking trails and may originate from visitors' clothing or atmospheric deposition. Preliminary research shows synthetic fabrics can shed up to 403 MP fibres per gram in as little as 20 min of gentle activity such as walking, or at rates up to 2.0 ± 0.3 fibres/linear metre whilst trail running (De Falco et al., 2020; Forster et al., 2023b). Polyethylene terephthalate (PET), PA and PP are common in outdoor clothing (Morrissey and Rossi, 2013) and were present on the trail surfaces in both locations. Although backpacks and tents are potential sources of fibres, MP shedding is more likely to occur in designated campgrounds than on walking trails, where these materials may receive more use and abrasive wear.

Table 1
Composition of microplastics (MP) (20–500 μm) from trail surface (flat rock at Dumaresq Dam and sloped soil at Washpool National Park) and atmospheric fallout (open grassland). Microplastics were detected using LDIR and the polymer type was identified by matching spectra against a reference library using a 75 % confidence threshold.

Polymer	Trail Surface				Atmosphere	
	Dumaresq Dam Loop Track		Washpool Track		Duval Nature Reserve	
	Flat rock		Sloped soil		Open grassland	
	MP counts	%	MP counts	%	MP counts	%
Polyurethane (PU)	191	41 %	41	18 %	2	3 %
Polyethylene terephthalate (PET)	77	17 %	37	16 %	31	43 %
Polystyrene (PS)	61	13 %	43	19 %	2	3 %
Polypropylene (PP)	35	8 %	14	6 %	0	0 %
Polyamide (PA)	29	6 %	20	9 %	9	13 %
Polyvinyl chloride (PVC)	20	4 %	16	7 %	0	0 %
Polyethylene chlorinated	9	2 %	6	3 %	13	18 %
Polyethylene (PE)	9	2 %	15	7 %	1	1 %
Polycarbonate (PC)	1	0 %	4	2 %	8	11 %

Polymers associated with footwear were present on the trail surface, but not in the atmospheric fallout. Polyurethane (PU) MPs were abundant and most likely produced by shoe outsoles or waterproof materials (Ames, 2004; Shishoo, 2002). Ethylene vinyl acetate (EVA) and rubber MPs were absent in the LDIR analysis of the trail surface samples despite widespread use in shoe midsoles and outsoles. This was most likely due to less contact between midsoles and the trail surface, and ongoing challenges detecting black rubber particles using microscopy and spectroscopy. Rubber MPs on trails may also be underestimated as particles from abrasion or fragmentation may be as small as 1–5 μm, but sampling using gel lifter tape is not quantitative for MPs smaller than 100 μm (Forster et al., 2022; Wu, 2016).

A wide range of other polymer types were detected on the trail surfaces (but not in the atmospheric fallout) that potentially originate from litter or equipment, including PE, PP, PS and PVC. Macroplastics containing the same polymers were detected on access trails in Italy, where they were determined to be fragments of food packaging and clothing (Parolini et al., 2021). Polyvinyl chloride (PVC) MPs on recreational trails may also originate from sports equipment, clothing, and coated fabrics (Morrissey and Rossi, 2013).

4.2. Factors influencing microplastic occurrence on trails

Microplastic abundance on recreational trails may differ regionally, locally and seasonally depending on visitation rates, types of recreation, trail surface conditions, proximity to urban areas, and meteorological factors influencing MP deposition and erosion (e.g. wind, rainfall). Similar quantities of MPs were detected at Dumaresq Dam Reserve and Duval Nature Reserves compared with Washpool and Gibraltar Range National Parks, however the morphology and chemical profile varied. Shoe abrasion and rubber fragments were detected more frequently on the trails around Dumaresq Dam and Duval Nature Reserves than the National Parks. A relatively narrow subset of polymers was detected on the flat rock sampled at the Dumaresq Dam Reserve, with 79 % being PU, PET, PS and PP. In comparison, a broader range of polymers were detected on the sloped soil surface sampled at Washpool National Park, with PU, PET, PS and PP present, but also relatively more PA, PE, PVC. The differences in the two regions may be due to variation in the amount of direct versus atmospheric deposition, or may reveal a trend towards differences in preferred clothing, food and equipment for the National Parks compared with the more accessible Reserves. Microplastic mobility and retention are size-, shape-, and density-dependent however, and the composition of MPs retained on flat rock and sloped soil surfaces with differing roughness and litter coverage may be expected to vary (Forster et al., 2023a; Zhang et al., 2022).

Trail topography and vegetation type also affect MP deposition and retention on trail surfaces, influencing the local distribution of MPs. In this study, MP occurrence was greater on flat surfaces compared with sloped trail surfaces at both sites. In prior work we saw MP shedding may be higher on rough, rock and sloped surfaces due to increased abrasive force against footwear and clothing (Forster et al., 2023b; Lorenz et al., 2011; Özdil et al., 2012). Microplastic movement on trail surfaces is highly variable however, and MP mobility may increase on steeper gradients and decrease in areas with vegetation, litter or irregular micro-relief (Forster et al., 2023a; Laermanns et al., 2021). In the long-term, this may lead to lower numbers of MPs on sloped surfaces and higher amounts retained on flat, vegetated or rough accrual areas. In this study, MPs in the centre of the trail were measured, however distribution across the trail may vary depending on trail and meteorological factors that influence foot position, deposition of fibres from clothing, and MP movement. Atmospheric deposition may also differ within protected areas as trees can intercept airborne MPs (Huang et al., 2022; Liu et al., 2020). Our initial assessment indicates MP deposition may be lower in areas with dense vegetation, although further research is needed to assess the proportion of MPs that are re-suspended in the atmosphere or fall to the ground with rainfall. In order to assess what sections of protected areas are most at risk from MP pollution, comprehensive surveys are required to assess the spatial and seasonal distribution of MPs on and adjacent to trails, and in more remote sections.

4.3. Factors influencing atmospheric microplastic deposition

Atmospheric deposition may be a significant source of MPs in conservation and protected areas. In remote areas, atmospheric fallout has varied from 59 ± 30 MPs m^{-2} day^{-1} in the Weser River catchment in Germany, to 132 MPs m^{-2} day^{-1} in national parks and wilderness areas in the US, to 365 ± 69 MPs m^{-2} day^{-1} in a catchment area of the French Pyrenees (Allen et al., 2019; Brahney et al., 2020; Kernchen et al., 2022). The mechanisms driving short- and long-range transport and deposition are not yet well understood, however recent studies indicate meteorological factors and proximity to urban areas are important factors influencing the number and morphological characteristics of aerial deposition (Brahney et al., 2020; Jia et al., 2022). Comparatively little atmospheric deposition occurred at Reserves in this study (9.9–32.3 MPs m^{-2} day^{-1}) compared with the European and American studies, which may be due to the wind conditions and distance from urban areas. The prevailing wind direction was from the west, where the districts within approximately 50 km of the reserve are predominantly agricultural, with population densities of only 0.54–1.85 people km^{-2} (Australian Bureau of Statistics, 2021b; Australian Bureau of Statistics, 2021c). The largest city in close proximity is located 12 km to the south and has a population of approximately 30,000 (Australian Bureau of Statistics, 2021a). Studies are urgently needed to evaluate the impacts and interrelationships between MP suspension, aeolian transport, aerial deposition and proximity to urban sources.

4.4. Implications of microplastics in protected and conservation environments

This study shows a wide range of MPs can occur in protected environments away from urban areas. Protected areas are created and managed to conserve vulnerable ecosystems and biodiversity, however may be at risk from exposure to MP pollution. So far, the majority of toxicology research has focused on the hazards of MPs to agricultural crops and commonly found soil invertebrates (Lahive et al., 2022; Li et al., 2021; Qi et al., 2019) and assessments specifically investigating MP impacts on endemic species and biodiversity in conservation areas are lacking. Low trafficked and remote areas are more likely to receive MPs from diffuse sources from long-range transport and atmospheric deposition, whereas areas close to trails may be exposed to MPs from both recreation activity and diffuse sources.

Microplastics may have adverse effects on soil ecosystems in protected environments, with toxicity driven by MP size, shape and chemistry (de Souza Machado et al., 2018; Lehmann et al., 2021). In this study, the majority of MPs in the atmospheric fallout and on the trail surface were fibres, which have been shown to disproportionately alter soil aggregation, soil organisms, microbiota and plant community structure (Lehmann et al., 2021; Lozano and Rillig, 2020; Song et al., 2019; Yi et al., 2020). Depending on the polymer type and additive chemistry, MPs may leach a range of compounds into the surrounding soil (Rozman et al., 2021; Sørensen et al., 2021). A number of MP types were identified in this study, indicating a very wide range of monomers, oligomers, additives, degradation by-products and processing aids may be present in the MPs. Polyethylene terephthalate (PET), PA, PU and PS were abundant and have been shown to alter soil structure and respiration, change to microbial communities in forested areas, cause oxidative stress, impaired photosynthesis and growth in plants, and alter erosion processes (Colzi et al., 2022; Ingraffia et al., 2021; Lee et al., 2022; Ng et al., 2021). Organic and inorganic additives utilised in synthetic clothing and footwear include bisphenols, benzophenones, benzothiazole, phthalates, and zinc, which may be hazardous to soil organisms and vegetation (Kim et al., 2022; Lee et al., 2022; Sait et al., 2021). Microplastics also exhibited signs of weathering and mechanical damage. Weathered particles are likely to fragment and produce smaller MPs which may have be more toxic to soil organisms (Guo et al., 2021; Ng et al., 2021). This could result in detrimental effects to the resilience of ecosystems in protected areas.

5. Conclusion

This study provides the first report of MPs on trails in protected and conservation areas. Our results show MP pollution may be present in trafficked and remote sections of protected environments due to local and diffuse deposition. A wide range of MPs were detected on trail surfaces and in the atmospheric fallout, with the majority being PET, PA, PU, and PS. Microplastic occurrence varied between and within the study areas, and visitation rates, trail characteristics and climactic conditions were identified as key factors influencing MP deposition and transport. Long-term, microplastic pollution is likely to be higher on flat surfaces with vegetation or surface roughness, where microplastic movement is restricted.

The majority of MP research focuses on urban and agricultural areas, however it is critical further research is conducted in protected environments. Ecotoxicology studies are required to understand the specific implications of MPs on endemic species, biodiversity and ecosystem functioning in protected areas. These studies need to account for varying MP size, shape, polymer and additive chemistry, and degradation, and the synergistic effects of multiple types of MPs. To identify areas most at risk, the spatial distribution of MPs needs further investigation, including on trail surfaces, adjacent to trails, in remote areas away from foot traffic, and below the soil surface. Microplastic impacts may potentially be mitigated by capping visitor numbers and diverting trails, however minimising and preventing MP pollution is complex given there are multiple direct and diffuse sources, and several factors influencing deposition and retention in different parts of the environment. Microplastic pollution from diffuse sources is ongoing, and global use and disposal of plastics needs to be addressed. Improvements to clothing manufacturing and design may be an important step in reducing global microfibre emissions.

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CRediT authorship contribution statement

Nicola A. Forster: Conceptualization, Investigation, Formal analysis, Funding acquisition, Writing – original draft. **Susan C. Wilson:** Writing – review & editing. **Matthew K. Tighe:** Conceptualization, Funding acquisition, Writing – review & editing, Supervision.

Data availability

Data will be made available on request.

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

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