INSTITUT DE FRANCE
Académie des sciences

Comptes Rendus

Géoscience

Sciences de la Planète

Philippe Cecchi

Plastics on the rocks: the invisible but harmful footprint of shoe soles

Volume 355 (2023), p. 135-144

Published online: 7 February 2023

https://doi.org/10.5802/crgeos.199

Les Comptes Rendus. Géoscience — Sciences de la Planète *sont membres du*
Centre Mersenne pour l'édition scientifique ouverte
www.centre-mersenne.org
e-ISSN : 1778-7025

Comptes Rendus
Géoscience — Sciences de la Planète
2023, Vol. 355, p. 135-144
https://doi.org/10.5802/crgeos.199

Original Article — Terrestrial and aquatic ecosystems

Plastics on the rocks: the invisible but harmful footprint of shoe soles

Philippe Cecchi [a]

[a] MARBEC, Univ Montpellier, CNRS, Ifremer, IRD, Montpellier, France
E-mail: philippe.cecchi@ird.fr

Abstract. Outdoor recreational activities for leisure and for sport training have grown in popularity. Their environmental impacts remain little studied, especially the waste generated by over-frequentation. Our objective was to document how frequentation of a short mountain hiking trail can lead to significant quantities of waste. To this aim, all small objects found along a three-kilometer trail were collected and their origin determined. Polymers were predominant, and were mostly shoe sole fragments. This has never been documented and must be publicized due to the potential harmfulness to terrestrial and riparian ecosystems, and to increase the walkers' awareness.

Keywords. Hiking, Waste, Plastics, Environmental impact, Awareness.
Manuscript received 8 December 2022, revised 9 January 2023 and 12 January 2023, accepted 12 January 2023.

1. Introduction

In 2019, plastic production reached 368 million metric tons (Mt) worldwide, 200 times more than in 1950 when it started to become popular [Plastics Europe, 2020]. Plastic waste is increasing also because less than 10% is actually recycled and most unwanted plastic products are simply discarded [UNEP, 2021]. Nowadays, plastic litter is a global issue and sometimes is considered a footprint of the Anthropocene [Zalasiewicz et al., 2016, Kramm et al., 2018]. It has been estimated that between 1950 and 2017, 9200 million Mt of virgin plastics were produced worldwide. This has led to ~7000 million Mt of plastic waste of which ~5300 million Mt were disseminated in the environment [Geyer, 2020]. As plastic materials are hardly degradable through weathering and ageing, they persist in the environment for decades and up to centuries, first in terrestrial landscapes [Hoellein and Rochman, 2021] where they accumulate and disintegrate progressively to create harmful secondary microplastics [Frias and Nash, 2019] and nanoplastics [Gigault et al., 2018]. Abundant and growing scientific evidences have documented their impacts on terrestrial [Malizia and Monmany-Garzia, 2019] and aquatic environments [see Ostle et al., 2019 for oceans; Blettler et al., 2018 for freshwater] and also on living organisms [Beaumont et al., 2019, Galgani et al., 2019], possibly including humans [Carbery et al., 2018, Rodrigues et al., 2019]. Land-based plastic sources provide ~80% of marine plastic litter [Lebreton et al., 2017], mainly via riverine discharge [Meijer et al., 2021]. In the last decade, approximately ten million tons of plastic debris have entered the oceans each year [Jambeck et al., 2015]. A recent study predicted that the amount of plastic waste entering the world's aquatic ecosystems could reach 90 million Mt/year by 2030, if waste generation trends continue as expected without improvement in waste management [Borrelle et al., 2020]. Therefore, an emerging challenge is related to the identification of plastic waste sources [Black et al., 2019], with the aim of tackling the issue before the release and dispersion of such products into the oceans where their collection is very expensive and moderately effective [Compa et al., 2019]. "*The current clean-up initiative of surface ocean plastics does not sufficiently address the long-term mobilization of the legacy plastics pool on land*" is clearly underlined by Sonke et al. [2022]. The most significant plastic losses are use-related (e.g. microbeads of personal care products, fibers of synthetic textiles, tire wear) and linked to the throw-away culture (e.g. single-use plastics). They account for ~36% and 55% of all losses, respectively [IRP (International Resource Panel), 2019]. The extension of urban and suburban areas and the required provision for their dwellers are mainly responsible. Natural areas, such as mountains, are not spared [Padha et al., 2022] due to the aerial transportation of microplastics to such remote regions [see for example Allen et al., 2021], and also due to direct pollution caused by traditional activities (e.g. pasturing) and/or visitors (e.g. recreational and sport activities). In direct pollution, the social responsibility of individuals is engaged and may constitute a lever to decrease plastic waste. Clean-up operations are regularly carried out by volunteers, notably on beaches [Jorgensen et al., 2020], and they are low-cost and effective [Nelms et al., 2017]. Besides cleaning, such operations contribute to increase the population's awareness and can lead to positive changes in behaviors and attitudes [Wyles et al., 2016]. It is known that volunteer groups are more aware and more concerned than other beach users [Owens, 2018] who often lack information about litter and its multiple implications besides the visual discomfort [Rayon-Viña et al., 2019]. Moreover, regular beach users may not be necessarily aware that they are the main sources of the litter present on the beach, suggesting that information sharing is crucial for influencing their willingness and commitment to behavioral changes [Portman et al., 2019]. Similar observations were made on the anglers' perception concerning their contribution to marine litter and the levers to be actioned to increase their "plastic awareness" and strengthen their commitment towards modifying their behaviors and actual practices regarding plastic management [Lewin et al., 2020]. As observed in many places worldwide, for example German Baltic beaches [Schernewski et al., 2018], tourism contributes massively to the total litter discharge. Even in remote sites, for example the Espiguette Beach (South of France), one of the least affected beaches in Europe, single-use plastics (mainly cigarette butts/filters and plastic caps/lids from drinks), which are intrinsically associated with local recreational activities, constitute approximately half of the items collected during surveys [Vlachogianni et al., 2020]. In marine protected areas, local human activities also constitute substantial sources of plastic pollution [Guerrini et al., 2019]. In many cases, there may not be any intentional degradation purpose, but plastic waste is voluntarily dropped and left in the environment, whatever the ecological and iconic value of the location, and whatever the waste impact. Overall, the lack of information is the most crucial factor to explain such inappropriate behaviors. Therefore, providing relevant and convincing information is a clear target in order to changes the attitudes/behaviors of natural site visitors towards more eco-friendly practices.

Finally, even well-meaning and supposedly informed people can unintentionally contribute to the plastic pollution burden through their (seemingly invisible) ecological footprint. This is particularly the case in remote natural areas where anthropogenic impacts are mainly due to their frequentation for leisure. Forster et al. [2020] showed how the abrasion of synthetic fibers in footwear and clothing could be a major source of microplastics in wild areas that are unaffected by direct pollution sources other than human passage. After describing the actual environmental contamination associated with fragmented polymers lost by walkers on hiking trails and their immediate vicinity, Forster et al. [2020] also provided impressive data on this unknown source of potential pollution linked to the economic market of sports- and foot-wear.

The purpose of the present study was to illustrate such unexpected situation by describing observations made at the end of December 2019, when walking early in the morning along a short trail in the South of France. Different kinds of small detritus were found, and approximately half of them were shoe sole fragments unintentionally lost by hikers.

As their cumulative amount was quite important, walkers should be more aware of their potential deleterious impacts. Then, very simple recommendations are provided.

2. Materials and methods

Pic Saint-Loup (43″46′44 N; 03″48′44 E) is a small mountain (658 m) located 20 km north of Montpellier (south of France), ~30 km from the Mediterranean coast (Figure 1).

Pic Saint-Loup dominates the flat coastal region, is visible from afar, and is an important topographical point. Pic Saint-Loup is a major tourist attraction and one of the favorite excursions by local residents. The mountain is made of Jurassic limestone and is part of a large set of folded limestone reliefs (anticline) that extend from the Pyrenees to the Provence. The rock of Pic Saint-Loup was formed by accumulation of marine sediments of great thickness, shaped by temperatures and pressures over time to give an often sharp white rock that was raised by the tectonic plate movements (Pyrenean area tectogenesis). The peak is subject to the Mediterranean climate of the South of France, with significant annual precipitation (1000 to 1200 mm/year). Part of this rain infiltrates and joins the large underground karst system that fuels the Lez spring, one of the tap water sources for the ~300,000 inhabitants of Montpellier [Fourneaux et al., 1989]. A 3 km trail (South face of the mountain) allows hikers to reach the summit and return in few hours. The trail is mostly rocky, with low-slope areas and sections that are more rugged, especially near the top. An underground sensor, which counts the walkers taking the path, was installed at the start of the path in 2016. At the end of 2019, 337,772 passages were cumulated for this single year. This means that on average, 231 people took the trail every day [CCGPSL, 2016, 2017, 2018 and personal communication for 2019].

I made my annual walk on December 29, 2019. The parking at the trailhead was empty and I began walking at sunrise (~8 am). The weather was humid and mild, in perfect harmony with the landscape freshly washed by the morning dew. Unfortunately, few minutes into the hike, a small red object trapped between two stones caught my eye. I picked it up and placed it in a zip-lock bag. I encountered and picked up other objects several times during the 3 km hike. The visual opportunistic collecting of all the obviously exogenous items encountered during the promenade constitutes the sample discussed hereafter (Figure 2).

Figure 1. Pic Saint-Loup (source: https://inpn.mnhn.fr/site/natura2000/FR9101389?lg=en). The trail joins the summit from the south (on the left of the arrow).

After gentle cleaning with distilled water, all items were dried, weighed, classified into polymers, metal, glass and other, and further sorted in: "incivilities" (a butt, a beer-bottle cap, a candy wrapper) and "unintentional discards" (a shoelace, a piece of cloth, small fragments of shoe soles). Incivilities included items that were probably "deliberately" (i.e. intentionally) discarded, while unintentional discards were surely "accidentally" (i.e. unintentionally) dropped. The sample representativeness is obviously questionable because it corresponded to an accumulation of items over an unknown period. This collection occurred after five full days without rainfall following several days of mild rain (46 mm in ten days) (source: https://www.meteoblue.com/fr/meteo/historyclimate/weatherarchive/pic-saint-loup_france_2978708) that was insufficient for a significant washout. One could hypothesize that the collected items had accumulated during a two-week period.

3. Results

Sixty-four elements were found (i.e. approximately one every 100 m, considering a complete round trip) (Figure 2). Fifty-three (83%) were polymers (Figure 3A) and corresponded to half (53%) of the total (30 g) detritus mass (Figure 3B). The collected items were dusty but not dirty, and lack of weathering confirmed that they had been recently lost on the trail.

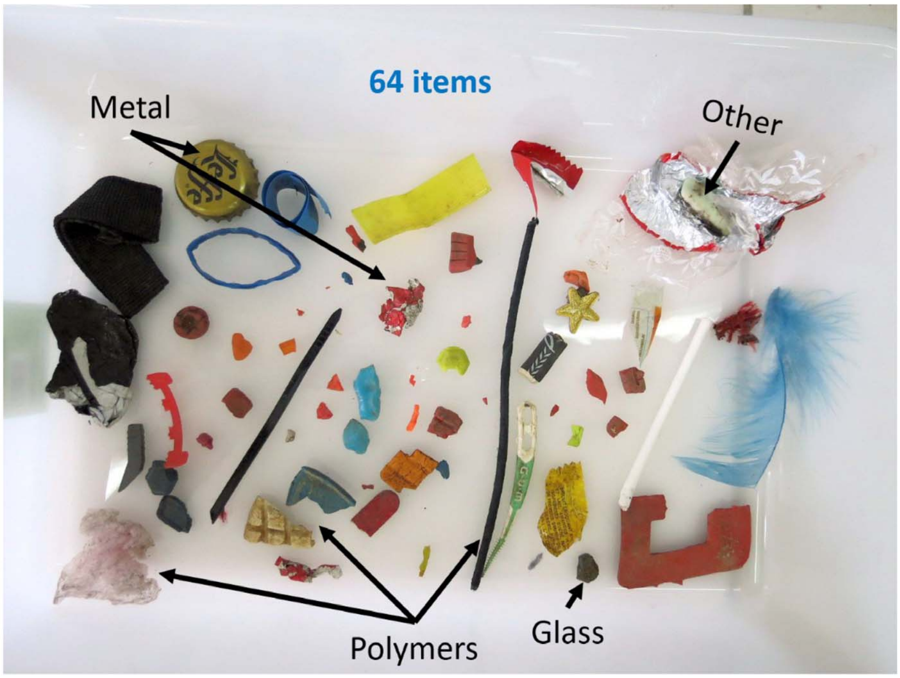

Figure 2. The 64 items found on the Pic Saint-Loup hiking trail on December 29, 2019.

Five pieces of metal and five pieces of glass were also found (8% in number; 20% and 22% in mass, respectively). One element (a chewing gum) constituted the "other" class (5% in mass). The disastrous ubiquity of plastics was sadly confirmed, but the most striking observation concerned the "archeology" or the "object narratives" of this litter sample (Figure 3C,D). "*How did these objects get here, and what behaviors caused them to follow a particular course that resulted in becoming pollution?*", p. 230 in Schofield et al. [2020]. Moreover, what actions might have prevented this outcome?

Twenty-one of the 64 items (33%) were considered incivilities (Figure 3C). All except two (a piece of nail file and a cigarette butt) were "food-related": a lollipop stick, a piece of plastic bottle cap, the chewing gum, a beer-bottle cap, and a dozen pieces of candy and biscuit wrappers that constituted half of the mass of this category. Glass pieces (from bottles) constituted the second half of deliberately discarded waste. Importantly, their number was largely underestimated due to the large quantity observed close to and on the summit. Their cumulative footprint is obvious and will be durable.

Most items (43; 67%) were lost accidentally (Figure 3D). They were made of plastics (42 items) and metal (one item: a fragment of bicycle crankset), and constituted 56% of the detritus mass. Nine of the 42 plastic items came from clothing or accessories: a blue feather, a small yellow star, a piece of black shoelace, two pieces of red fibers, several pieces of yellow, blue or black cloth. The other 33 plastic items came from bright-colored running shoe/sneaker soles (small fragments and pieces of crampons varying in size between 5 mm and 5 cm). Therefore, shoe sole fragments represented 52% of all detritus (31% in mass), 62% of polymers (58% in mass), and 79% of the accidentally discarded items (55% in mass).

The extrapolation over a complete year, based on a two-week accumulation period, led to dramatic results: up to 1500 small items discarded every year, corresponding to 720 g of waste including ~380 g of plastics. Approximately a thousand of them (~400 g) will be accidentally lost, including ~800 small pieces of shoe soles (~220 g). To date, the dynamics of secondary microplastic (<5 mm in size) formation has not been fully understood. Undoubtedly, our

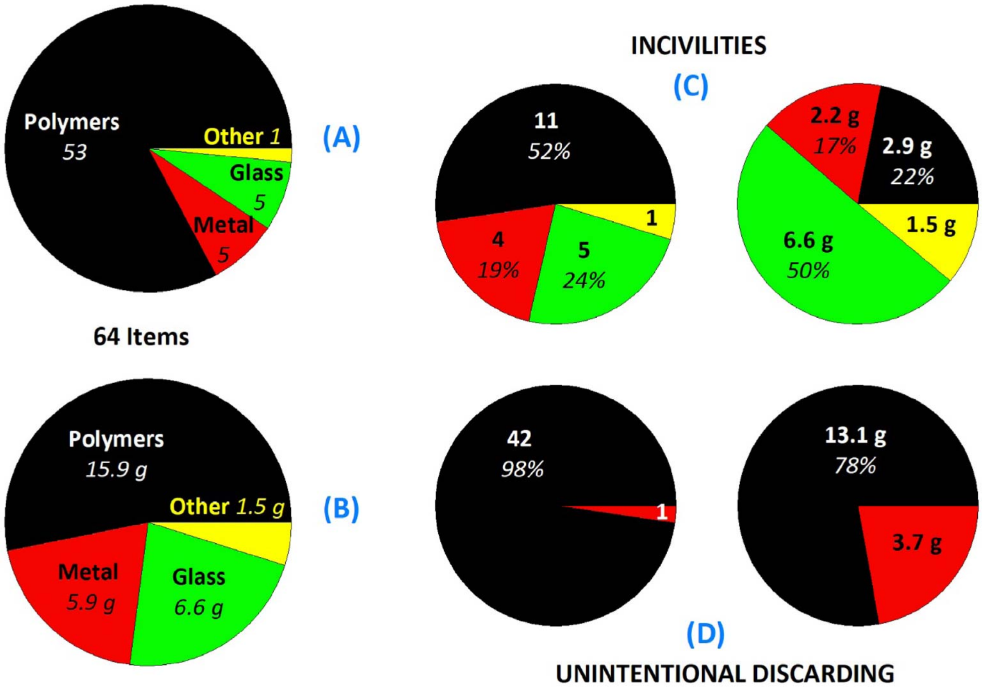

Figure 3. Distribution of the 64 items found on the Pic Saint-Loup hiking trail on December 29, 2019. (A) Total number of items per category (polymers, metal, glass, other). (B) Total mass per category. (C) Number and mass per category of deliberately discarded waste. (D) Number and mass per category of accidentally discarded items.

findings are probably only the "tip of the iceberg" due to the short length of the trail (3 km, compared with the 180,000 km of marked trails in France).

Two main categories of visitors use the Pic Saint-Loup trail: families/social groups and athletes. One may suspect that "incivilities" are mainly due to the first category, while "unintentional discards" could be mostly linked to the second. This second category is also clearly growing: many athletes are increasingly looking for performance training and cardiovascular fitness improvement. This suggests that runners who climb the Pic Saint-Loup are among the main polluters, unintentionally contributing to half of the plastic waste with a lifespan that extends to centuries and with largely unknown associated hazards.

4. Discussion

All trail-based human activities have some effects on the environment. The impact of outdoor activities in remote areas has been sparsely assessed, and studies rarely focused on pernicious pollutions. Until recently [Forster et al., 2020], the environmental impact assessment of hiking in natural areas never mentioned anthropogenic waste as a meaningful threat, but only soil and vegetation degradation [Evju et al., 2021], dispersal of weed seeds [Pickering, 2022, Dolman and Marion, 2022], or spreading of antibiotic-resistant bacteria and genes [Scott et al., 2021]. Particularly, the polluting effect of shoes has been completely overlooked [Horton, 2022], although microplastics from footwear abrasion may be significant contaminants in high traffic areas of natural environments. Indeed, it is easy to assume that shoes are sources of microplastics, mainly due to the shoe sole wear and tear due to friction with surfaces, as observed for tires that represent globally the largest source of microplastics lost in the environment [Heller et al., 2020, Knight et al., 2020]. Therefore, the shoes of people using running/walking tracks can release large amounts of microplastics that can easily reach natural environments through rainwater runoff and wind. A Danish Environmental Protection Agency report estimated that in 2015, the total annual abrasion from shoe soles was between 100 and 1000 tons in Denmark alone [Lassen et al., 2015]. Moreover, a German study calculated that shoe sole wear (109 g per capita per year) was the seventh largest contributor of microplastics in the country [Bertling et al., 2018]. Many different materials are used to manufacture a single shoe. The sole is usually made of leather, vulcanized rubber, thermoplastic rubber, polyurethanes, thermoplastic polyurethanes, or ethylene vinyl acetate [Muthu and Li, 2021]. In addition, synthetic shoes contain elevated concentrations of hazardous substances [Herva et al., 2011] that represent a worrying issue.

Microplastic pollution in karst aquifers remains largely unknown [Panno et al., 2019]. The elevated porosity of the Pic Saint-Loup soils may lead to migration and recharge of the karst aquifer by materials left on its surface [Viaroli et al., 2022]. Only four studies assessed the toxicity of shoe sole microplastics [Ingre-Khans et al., 2010, Kim et al., 2022, Lee et al., 2022, da Costa Araújo et al., 2022] and found that it is related to chemicals leached in aquatic organisms (algae, crustaceans, amphibians, and fish) and in bean plants. Fourneaux et al. [1989] experimentally traced (fluorescein) the connectivity of groundwater masses down the Pic Saint-Loup, and found that during the dry season, 95% of the marked flow was retrieved in the Lez spring (~7.5 km south of the Pic Saint-Loup). This spring partly provides freshwater to the Montpellier city and is also an important biodiversity hotspot (Natura 2000) where lives the endemic Lez sculpin (*Cottus petiti*), one of the most endangered freshwater fish species in Europe [Persat et al., 1996]. The hydrology of this karst system is complex [Fleury et al., 2009] and depending on the season, rainwater infiltrates when the aquifer is at low water level, or flows away when the system is fully recharged. Therefore, the Pic Saint-Loup plastic waste may affect both riverine terrestrial and freshwater systems, and also the aquifer.

Globally, the footwear industry is responsible for important waste at the end of the shoe life (one year for sneakers) that are most often disposed in landfills. Between 2015 and 2020, the worldwide footwear production was ~22–25 billion pairs per year [Statista, 2022]. The global athletic footwear market is currently worth ~$90 billion, and is expected to reach over $93 billion by 2025. The global footwear consumption has been doubling every 20 years since the 1950s, and each individual now buys three new pairs of shoes every year [Van Rensburg et al., 2020], with important variations around the world (<1 in India and Vietnam; >5 in Europe and USA). Most shoes are made of complex mixtures of various polymers sewn and glued together, thus making them difficult to recycle [Muthu and Li, 2021]. Manufacturing a single shoe involves at least 40 different materials [Van Rensburg et al., 2020], which is one of the main reasons for the high environmental impact of this sector. The end-of-life fate of 95% of all shoes is a landfill where a shoe can take up to 40 years to decay, and synthetic materials up to several centuries. Therefore, the escalating consumption of footwear contributes to increasing the accumulation of synthetic polymers as waste in our environment.

Due to their light weight and durability, plastic waste can be easily transported in terrestrial environments where it can accumulate in freshwater systems [Blettler and Wantzen, 2019]. Thus, the use of sports shoes during physical exercise (beneficial to human health) can add an environmental stress factor to aquatic and terrestrial organisms, potentially far away from the places where sports are practiced. Moreover, shoes are products rich in meaning and their purchase is linked to and strengthen the customer's cultural identity. Sustainability is a critical issue worldwide, and customers do exert increasing pressure on companies to engage in and to adopt positive attitudes towards environmental and social issues. "*It is the product, not the polymer that is driving the issue of plastic waste*" [Stanton et al., 2021].

5. Conclusion

Contemporary practices of consumption and discharge ("cradle to grave") are the main source of anthropogenic waste in the environment. To be effective, environmental actions to minimize waste release must be informed by objective science to drive changes in the users' consumption practices, and also in product design. Recycling and circular economy ("cradle to cradle") is one way currently explored by the main sportswear brands.

Dolman and Marion [2022] indicated that the COVID-19 pandemic has led to ~20% increase in outdoor activity participation in the United States in 2020. Traditional hot spots for nature outings are in great demand, and a forthcoming over-frequentation of such sites might be expected. I think that it is possible to identify and anticipate direct or indirect detrimental consequences to this trend; however, the main offenders might not be those we spontaneously think about. Most of our readers are assiduous nature observers; many of them are also enthusiastic outdoor activity practitioners. The aim of this note it to increase their awareness and maybe also their commitment to fight this shocking situation. This study may draw their attention and call for their vigilance. Environmental knowledge plays an essential role in influencing decision-making processes and actual actions: people who perceive environmental risks are more likely to behave in an environmentally friendly manner [Yoon et al., 2021]. Providing and publicizing robust scientific information is definitively crucial [Charitou et al., 2021]. This is also the aim of this small note.

6. Immediate recommendations

- Regular cleaning of the trail: this can be encouraged through specific sessions that involve citizens.
- Information: placing posters on the parking site to inform visitors about the risks associated with waste and to encourage them to pay attention about their own waste.
- Incitation: clearly indicating the locations of garbage bins.
- Scientific: microplastic monitoring in the Lez spring.

Conflicts of interest

The author has no conflict of interest to declare.

Acknowledgements

To F.F. who patiently waited for me while I was looking for and collecting waste during this hike. To the editor and reviewer who helped to improve the manuscript.

References

Allen, S., Allen, D., Baladima, F., Phoenix, V. R., Thomas, J. L., Le Roux, G., and Sonke, J. E. (2021). Evidence of free tropospheric and long-range transport of microplastic at Pic du Midi observatory. *Nat. Commun.*, 12(1), 1–10.

Beaumont, N. J., Aanesen, M., Austen, M. C., Börger, T., Clark, J. R., Cole, M., Hooper, T., Lindeque, P. K., Pascoe, C., and Wyles, K. J. (2019). Global ecological, social and economic impacts of marine plastic. *Mar. Pollut. Bull.*, 142, 189–195.

Bertling, J., Bertling, R., and Hamann, L. (2018). Kunststoffe in der Umwelt: Mikro- und Makroplastik. Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Oberhausen.

Black, J. E., Kopke, K., and O'Mahony, C. (2019). A trip upstream to mitigate marine plastic pollution—a perspective focused on the MSFD and WFD. *Front. Mar. Sci.*, 6, article no. 689.

Blettler, M. C. M., Abrial, E., Khan, F. R., Sivri, N., and Espinola, L. A. (2018). Freshwater plastic pollution: recognizing research biases and identifying knowledge gaps. *Water Res.*, 143, 416–424.

Blettler, M. C. M. and Wantzen, K. M. (2019). Threats underestimated in freshwater plastic pollution: mini-review. *Water Air Soil Pollut.*, 230, article no. 174.

Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G. H., Hilleary, M. A., Eriksen, M., Possingham, H. P., De Frond, H., Gerber, L. R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., and Rochman, C. M. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science*, 369(6510), 1515–1518.

Carbery, M., O'Connor, W., and Palanisami, T. (2018). Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. *Environ. Int.*, 115, 400–409.

CCGPSL (2016, 2017, 2018). Annual Reports of the "*Communauté de Communes du Grand Pic Saint Loup*". https://grandpicsaintloup.fr/la-communaute-de-communes/publications/rapports-annuels/.

Charitou, A., Aga-Spyridopoulou, R. N., Mylona, Z., Beck, R., McLellan, F., and Addamo, A. M. (2021). Investigating the knowledge and attitude of the Greek public towards marine plastic pollution and the EU single-use plastics directive. *Mar. Pollut. Bull.*, 166, article no. 112182.

Compa, M., March, D., and Deudero, S. (2019). Spatio-temporal monitoring of coastal floating marine debris in the Balearic Islands from sea-cleaning boats. *Mar. Pollut. Bull.*, 141, 205–214.

da Costa Araújo, A. P., da Luz, T. M., de Oliveira Gonçalves, S., Rajagopal, R., Rahman, M. M., e Silva, D. D. M., and Malafaia, G. (2022). How can my shoes affect the amphibian health? A study of the toxicity of microplastics from shoe sole (polyvinyl chloride acetate) on physalaemus cuvieri tadpoles (Anura, Leptodactylidae). *J. Hazard. Mater.*, 440, article no. 129847.

Dolman, M. R. and Marion, J. L. (2022). Invasive plant hitchhikers: Appalachian trail thru-hiker knowledge and attitudes of invasive plants and leave No trace practices. *J. Outdoor Recreat. Tour.*, 40, article no. 100581.

Evju, M., Hagen, D., Jokerud, M., Olsen, S. L., Selvaag, S. K., and Vistad, O. I. (2021). Effects of mountain biking versus hiking on trails under different environmental conditions. *J. Environ. Manage.*, 278, article no. 111554.

Fleury, P., Ladouche, B., Conroux, Y., Jourde, H., and Dörfliger, N. (2009). Modelling the hydrologic functions of a karst aquifer under active water management–the Lez spring. *J. Hydrol.*, 365(3–4), 235–243.

Forster, N. A., Tighe, M. K., and Wilson, S. C. (2020). Microplastics in soils of wilderness areas: What is the significance of outdoor clothing and footwear? *Geoderma*, 378, article no. 114612.

Fourneaux, J.-C., Couturier, B., and Sommeria, L. (1989). Analyse d'une opération de traçage dans la région du Pic Saint-Loup (Hérault-France). *Karstologia*, 13, 50–53.

Frias, J. P. G. L. and Nash, R. (2019). Microplastics: finding a consensus on the definition. *Mar. Pollut. Bull.*, 138, 145–147.

Galgani, L., Beiras, R., Galgani, F., Panti, C., and Borja, A. (2019). Editorial: impacts of marine litter. *Front. Mar. Sci.*, 6, article no. 208.

Geyer, R. (2020). Production, use, and fate of synthetic polymers. In Letcher, T. M., editor, *Plastic Waste and Recycling: Environmental Impact, Societal Issues, Prevention, and Solutions*, pages 13–32. Academic Press, Cambridge, MA.

Gigault, J., ter Halle, A., Baudrimont, M., Pascal, P.-Y., Gauffre, F., Phi, T.-L., El Hadri, H., Grassl, B., and Reynaud, S. (2018). Current opinion: what is a nanoplastic? *Environ. Pollut.*, 235, 1030–1034.

Guerrini, F., Mari, L., and Casagrandi, R. (2019). Modeling plastics exposure for the marine biota: risk maps for fin whales in the Pelagos Sanctuary (North-Western Mediterranean). *Front. Mar. Sci.*, 6, article no. 299.

Heller, M. C., Mazor, M. H., and Keoleian, G. A. (2020). Plastics in the US: toward a material flow characterization of production, markets and end of life. *Environ. Res. Lett.*, 15(9), article no. 094034.

Herva, M., Álvarez, A., and Roca, E. (2011). Sustainable and safe design of footwear integrating ecological footprint and risk criteria. *J. Hazard. Mater.*, 192(3), 1876–1881.

Hoellein, T. J. and Rochman, C. M. (2021). The "plastic cycle": a watershed-scale model of plastic pools and fluxes. *Front. Ecol. Environ.*, 19(3), 176–183.

Horton, A. A. (2022). Plastic pollution: when do we know enough? *J. Hazard. Mater.*, 422, article no. 126885.

Ingre-Khans, E., Rudén, C., and Breitholtz, M. (2010). Chemical risks and consumer products: the toxicity of shoe soles. *Ecotoxicol. Environ. Saf.*, 73(7), 1633–1640.

IRP (International Resource Panel) (2019). Global resources outlook 2019: natural resources for the future we want. In Oberle, B., Bringezu, S., Hatfield-Dodds, S., Hellweg, S., Schandl, H., Clement, J., Cabernard, L., Che, N., Chen, D., Droz-Georget, H., Ekins, P., Fischer-Kowalski, M., Flörke, M., Frank, S., Froemelt, A., Geschke, A., Haupt, M., Havlik, P., Hüfner, R., Lenzen, M., Lieber, M., Liu, B., Lu, Y., Lutter, S., Mehr, J., Miatto, A., Newth, D., Oberschelp, C., Obersteiner, M., Pfster, S., Piccoli, E., Schaldach, R., Schüngel, J., Sonderegger, T., Sudheshwar, A., Tanikawa, H., van der Voet, E., Walker, C., West, J., Wang, Z., and Zhu, B., editors, *A Report of the International Resource Panel*. United Nations Environment Programme, Nairobi, Kenya, https://www.resourcepanel.org/reports/global-resources-outlook.

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

Jorgensen, B., Krasny, M., and Baztan, J. (2020). Volunteer beach cleanups: civic environmental stewardship combating global plastic pollution. *Sustain. Sci.*, 16(1), 153–167.

Kim, L., Kim, D., Kim, S. A., Kim, H., Lee, T. Y., and An, Y. J. (2022). Are your shoes safe for the environment?—Toxicity screening of leachates from microplastic fragments of shoe soles using freshwater organisms. *J. Hazard. Mater.*, 421, article no. 126779.

Knight, L. J., Parker-Jurd, F. N., Al-Sid-Cheikh, M., and Thompson, R. C. (2020). Tyre wear particles: an abundant yet widely unreported microplastic? *Environ Sci. Pollut. Res.*, 27, 18345–18354.

Kramm, J., Völker, C., and Wagner, M. (2018). Superficial or substantial: why care about microplastics in the Anthropocene? *Environ. Sci. Technol.*, 52, 3336–3337.

Lassen, C., Hansen, S. F., Magnusson, K., Hartmann, N. B., Rehne Jensen, P., Nielsen, T. G., and Brinch, A. (2015). *Microplastics: Occurrence, Effects and Sources of Releases to the Environment in Denmark*. Danish Environmental Protection Agency, Copenhagen, https://backend.orbit.dtu.dk/ws/portalfiles/portal/118180844/Lassen_et_al._2015.pdf.

Lebreton, L. C. M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nat. Commun.*, 8, article no. 15611.

Lee, T. Y., Kim, L., Kim, D., An, S. H., and An, Y. J. (2022). Microplastics from shoe sole fragments cause oxidative stress in a plant (*Vigna radiata*) and impair soil environment. *J. Hazard. Mater.*, 429, article no. 128306.

Lewin, W.-C., Weltersbach, M. S., Denfeld, G., and Strehlow, H. V. (2020). Recreational anglers' perceptions, attitudes and estimated contribution to angling related marine litter in the German Baltic Sea. *J. Environ. Manage.*, 272, article no. 111062.

Malizia, A. and Monmany-Garzia, A. C. (2019). Terrestrial ecologists should stop ignoring plastic pollution in the Anthropocene time. *Sci. Total Environ.*, 668, 1025–1029.

Meijer, L., van Emmerik, T., van der Ent, R., Schmidt, C., and Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Sci. Adv.*, 7, article no. eaaz5803.

Muthu, S. S. and Li, Y. (2021). The environmental impact of footwear and footwear materials. In *Handbook of Footwear Design and Manufacture*, pages 305–320. Woodhead Publishing.

Nelms, S. E., Coombes, C., Foster, L. C., Galloway, T. S., Godley, B. J., Lindeque, P. K., and Witt, M. J. (2017). Marine anthropogenic litter on British beaches: a 10-year nationwide assessment using citizen science data. *Sci. Total Environ.*, 579, 1399–1409.

Ostle, C., Thompson, R. C., Broughton, D., Gregory, L., Wootton, M., and Johns, D. G. (2019). The rise in ocean plastics evidenced from a 60-year time series. *Nat. Commun.*, 10, article no. 1622.

Owens, K. A. (2018). Using experiential marine debris education to make an impact: collecting debris, informing policy makers, and influencing students. *Mar. Pollut. Bull.*, 127, 804–810.

Padha, S., Kumar, R., Dhar, A., and Sharma, P. (2022). Microplastic pollution in mountain terrains and foothills: a review on source, extraction, and distribution of microplastics in remote areas. *Environ. Res.*, 207, article no. 112232.

Panno, S. V., Kelly, W. R., Scott, J., Zheng, W., McNeish, R. E., Holm, N., Hoellein, T. J., and Baranski, E. L. (2019). Microplastic contamination in karst groundwater systems. *Groundwater*, 57, 189–196.

Persat, H., Beaudou, D., and Freyhof, J. (1996). The sculpin of the Lez spring (South France) *Cottus petiti* (Bacescu and Bacescu-Mester, 1964), one of the most threatened fish species in Europe. In *Conservation of Endangered Freshwater Fish in Europe*, pages 321–328. Birkhäuser, Basel.

Pickering, C. (2022). Mountain bike riding and hiking can contribute to the dispersal of weed seeds. *J. Environ. Manage.*, 319, article no. 115693.

Plastics Europe (2020). Plastics—the Facts 2020: an analysis of European plastics production, demand and waste data. Association of Plastics Manufacturers. https://www.plasticseurope.org/en/resources/publications/4312-plastics-facts-2020.

Portman, M. E., Pasternak, G., Yotam, Y., Nusbaum, R., and Behar, D. (2019). Beachgoer participation in prevention of marine litter: using design for behavior change. *Mar. Pollut. Bull.*, 144, 1–10.

Rayon-Viña, F., Miralles, L., Fernandez-Rodríguez, S., Dopico, E., and Garcia-Vazquez, E. (2019). Marine litter and public involvement in beach cleaning: disentangling perception and awareness among adults and children, Bay of Biscay, Spain. *Mar. Pollut. Bull.*, 141, 112–118.

Rodrigues, M. O., Abrantes, N., Gonçalves, F. J. M., Nogueira, H., Marques, J. C., and Gonçalves, A. M. M. (2019). Impacts of plastic products used in daily life on the environment and human health: what is known? *Environ. Toxicol. Phar.*, 72, article no. 103239.

Schernewski, G., Balciunas, A., Gräwe, D., Gräwe, U., Klesse, K., Schulz, M., Wesnigk, S., Fleet, D., Haseler, M., Möllman, N., and Werner, S. (2018). Beach macro-litter monitoring on southern Baltic beaches: results, experiences and recommendations. *J. Coast. Conserv*, 22, 5–25.

Schofield, J., Wyles, K. J., Doherty, S., Donnelly, A., Jones, J., and Porter, A. (2020). Object narratives as a methodology for mitigating marine plastic pollution: multidisciplinary investigations in Galápagos. *Antiquity*, 94(373), 228–244.

Scott, L. C., Wilson, M. J., Esser, S. M., Lee, N. L., Wheeler, M. E., Aubee, A., and Aw, T. G. (2021). Assessing visitor use impact on antibiotic resistant bacteria and antibiotic resistance genes in soil and water environments of Rocky Mountain National Park. *Sci. Total Environ.*, 785, article no. 147122.

Sonke, J. E., Koenig, A. M., Yakovenko, N., Hagelskjær, O., Margenat, H., Hansson, S. V., Francois De Vleeschouwer, F., Magand, O., Le Roux, G., and Thomas, J. L. (2022). A mass budget and box model of global plastics cycling, degradation and dispersal in the land-ocean-atmosphere system. *Microplast. Nanoplast.*, 2(1), 1–14.

Stanton, T., Kay, P., Johnson, M., Chan, F. K. S., Gomes, R. L., Hughes, J., Meredith, W., Orr, H. G., Snape, C. E., Taylor, M., Weeks, J., Wood, H., and Xu, Y. (2021). It's the product not the polymer: rethinking plastic pollution. *WIREs Water*, 8, article no. e1490.

Statista (2022). Quantity of footwear produced worldwide from 2015 to 2021. https://www.statista.com/statistics/1044823/global-footwear-production-quantity/.

UNEP (2021). From Pollution to Solution: A global assessment of marine litter and plastic pollution. Nairobi, 148 p. https://www.developmentaid.org/api/frontend/cms/file/2021/10/POLSOL.pdf.

Van Rensburg, M. L., Nkomo, S. L., and Mkhize, N. M. (2020). Life cycle and End-of-Life management options in the footwear industry: a review. *Waste Manag. Res.*, 38(6), 599–613.

Viaroli, S., Lancia, M., and Re, V. (2022). Microplastics contamination of groundwater: current evidence and future perspectives. A review. *Sci. Total Environ.*, 824, article no. 153851.

Vlachogianni, T., Skocir, M., Constantin, P., Labbe, C., Orthodoxou, D., Pesmatzoglou, I., Scannella, D., Spika, M., Zissimopoulos, V., and Scoullos, M. (2020). Plastic pollution on the Mediterranean coastline: generating fit-for purpose data to support decision-making via a participatory-science initiative. *Sci. Total Environ.*, 711, article no. 135058.

Wyles, K. J., Pahl, S., Holland, M., and Thompson, R. C. (2016). Can beach cleans do more than clean-up litter? Comparing beach cleans to other coastal activities. *Environ. Behav.*, 49(5), 509–535.

Yoon, A., Jeong, D., and Chon, J. (2021). The impact of the risk perception of ocean microplastics on tourists' pro-environmental behavior intention. *Sci. Total Environ.*, 774, article no. 144782.

Zalasiewicz, J., Waters, C. N., Ivar do Sul, J. A., Corcoran, P. L., Barnosky, A. D., Cearreta, A., Edgeworth, M., Gałuszka, A., Jeandel, C., Leinfelder, R., McNeill, J. R., Steffen, W., Summerhayes, C., Wagreich, M., Williams, M., Wolfe, A. P., and Yonan, Y. (2016). The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene. *Anthropocene*, 13, 4–17.