The Duration of Dry Events Promotes PVC Film Fragmentation in Intermittent Rivers

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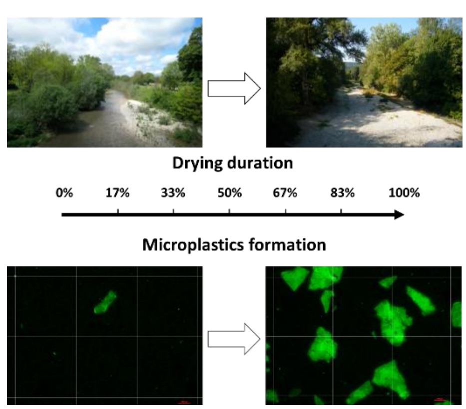
Abstract:

The majority of microplastics (MPs) found in the environment originate from plastic fragmentation occurring in the environment and is influenced by environmental factors such as UV irradiation and biotic interactions. However, the effects of river drying on plastic fragmentation remains unknown, despite the global prevalence of watercourses experiencing flow intermittence. This study investigates, through laboratory experiment, the coupled effects of drying duration and UV irradiation on PVC film fragmentation induced by artificial mechanical abrasion. This study shows that PVC film fragmentation increases with drying duration through an increase in the abundance and size of formed MPs as well as mass loss from the initial plastic item, with significant differences for drying durations >50% of the experiment duration. The average abundance of formed MPs in treatments exposed to severe drying duration was almost two times higher than in treatment non-exposed to drying. Based on these results, we developed as a proof of concept an Intermittence Based Plastic Fragmentation Index that may provide insights into plastic fragmentation occurring in river catchments experiencing large hydrological variability. The present study suggests that flow intermittence occurring in rivers and streams can lead to increasing plastic fragmentation, unraveling new insights on plastic pollution in freshwater systems.

Graphical abstract:



Synopsys:

We evidenced the substantial role of drying duration on the fragmentation of plastics exposed to UV radiation, providing a novel pathway along which plastic may contaminate river ecosystems.

Key words: *plastic fragmentation, drying and rewetting, microplastics, intermittent river, IRES, plastic pollution*

Introduction:

The overwhelming presence of plastics in modern society, coupled with an inability to efficiently treat plastic waste has resulted in large-scale plastic pollution of the environment[1–3]. Plastic debris of all sizes can be found in the environment, however, microplastics (MPs), generally defined as particles smaller than 5 mm[4], or smaller than 1 mm[5], are raising global concern due to their ubiquitous presence in ecosystems[6–8], their potential toxicity to organisms[9–12] and the threat they represent to ecosystem functioning and human health[13–15]. Microplastics can be subdivided into two categories[16] : primary MPs, manufactured purposely at these specific small sizes[17,18] and secondary MPs, that result from the fragmentation of larger plastic items due to abiotic[19,20] and biotic factors[21,22]. In the environment, secondary MPs are formed due to the weathering of plastic items, which leads to the fragmentation and degradation of plastic under the impacts of environmental factors such as temperature, wind, water motion, thawing/freezing cycles and UV irradiation[23–25]. Photodegradation associated with UV irradiation is considered one of the most important drivers of plastic weathering[24,26]. Although photodegradation alone can lead to microplastic generation[27,28], this process is enhanced by mechanical stress applied to plastic items by mechanisms such as sediment abrasion and water motion, that will fragment the weathered plastics[29–32]. In streams and rivers, mechanical stress alone can lead to plastic fragmentation. For example, during floods, the sediment transport caused by the increase of stream flow velocity and shear stress, enhances the mechanical strain and abrasion applied to the plastic debris[33]. Conversely, in aquatic ecosystems, the water column reduces the UV irradiation impacts on plastic, combined with lower oxygen level and buffered temperatures, resulting in reduced plastic weathering[34–36]. Plastic fragmentation has previously been reported to be lower in aquatic than in terrestrial environments[37–39]. However, this conclusion can actually only be applied to perennial aquatic systems that have been previously studied and not to intermittent systems that periodically dry throughout the year where the impacts of drying and rewetting dynamics have not yet been explored.

Intermittent rivers and ephemeral streams (IRES) are watercourses that periodically cease to flow or dry for some period of the year[40]. They represent the most common type of river ecosystems in the world, representing 51-60 % of world rivers by length[41]. Due to global change, IRES are expanding in space and time[42–44]. This raises substantial concerns regarding the preservation of the functional integrity of river networks and the services they provide to societies. Notably, it is still unknown whether the duration of dry conditions in IRES following water depletion alters the generation of secondary MPs in rivers and streams. In IRES, drying could affect plastic fragmentation because abiotic factors affecting plastic fragmentation drastically vary between aquatic and terrestrial phases. In marine ecosystems, plastic items present in the swash zone (i.e., the land-ocean boundary at the landward edge of the surf zone, where waves runup the beach)[45] are subjected to both terrestrial and aquatic conditions[39]. This specific exposition leads to significant plastic embrittlement, principally driven by photodegradation, that is coupled with the mechanical stress caused by water motions, leading to important plastic fragmentation[46]. To date, it has not been explored how drying can stimulate the fragmentation of plastic deposited on riverbeds, causing a critical knowledge gap, particularly considering the global expansion of IRES.

This study aimed to identify the effects of different durations of drying coupled to UV irradiation on the fragmentation of polyvinyl chloride (PVC) film commonly used in the food industry as food wrap and representing one of the most common plastic polymer [47,48]. This was achieved by measuring the plastic film mass loss as well as the abundance and size of the subsequently formed MPs (defined here as particles smaller than 1 mm) under controlled conditions in the laboratory. We first hypothesized that the number of MPs produced would increase with the duration of dry condition, because the absence of water would fail mitigating the effects of UV radiation (H1)[49]. We further hypothesized that plastic mass loss would increase with the duration of dry condition, because a positive correlation between mass loss of the plastic film and generation of MPs would exist (H2). We finally hypothesized that the mean size of fragmented MPs would decrease with drying duration, because plastic fragmentation would increase with the duration of dry condition (H3). Finally, the results obtained in controlled conditions were applied to a river catchment prone to drying, using a calibrated hydrological model. This upscaling of our results aimed to calculate, as a proof of concept, an intermittence based plastic fragmentation index at the scale of an entire river catchment and its potential evolution under future climate change scenarios.

MATERIALS AND METHODS:

UV-C irradiation and fragmentation of plastic

Food grade transparent PVC thin film (~8 µm) was cut in disks of 2 cm in diameter (average mass of 3.45 ± 0.2 mg) to obtain plastic pieces of identical shape and size (Fig. S1). PVC film was chosen based on the high density of PVC allowing the disks to sink when placed into water and low thickness allowing for rapid and important weathering in presence of UV radiation[50]. The list of additives used in the fabrication of the PVC film provided by the manufacturer (Table S1), revealed the presence of several additives known for their light stabilizing effects[51]. A total of 70 plastic discs were prepared and each plastic disk was placed in a 1L glass beaker filled with vacuum filtered ultrapure water (VF-UP). All disks sank to the bottom of the beakers as the density of the PVC film (1.30 g/cm^3, density measured in the lab) is higher than water density (1 g/cm^3). Using 70 experimental units, each consisting of 1 PVC disk placed in 1L glass beaker, 7 experimental treatments, with 10 replicates per treatment (Table 1), were set up to test the influence of different artificial drying duration (DD) on plastic weathering during an experimentation of 6 days: 1) no exposure to dry conditions (0D6W), 2) 17 % of time under dry conditions (1D5W), 3) 33 % of time under dry conditions (2D4W), 4) 50 % of time under dry conditions (3D3W), 5) 67 % of time under dry conditions (4D2W), 6) 83 % of time under dry conditions (5D1W) and 7) no exposure to aquatic conditions (6D0W). The 0D6W treatment referred to perennial watercourses (i.e., rivers and streams that never cease to flow), whereas the 6D0W treatment referred to a terrestrial environment that is never submerged by water. Drying-duration in between these two extremes have been chosen as being representative of natural flow intermittence (defined as the annual proportion of no-flow days per year; FI) condition prevailing in many IRES in France[52]. For all treatments, the beakers were placed under a UV-C lamp with wavelengths centered at 254 nm (UVITEC LI-315.G, 3x15 W, intensity: 95 µW/cm²). For each experimental treatment, 10 beakers previously filled with VF-UP were emptied to switch from aquatic to dry conditions. Therefore, beakers emptied at day 0, 1, 2, 3, 4, 5, and 6 corresponded to the treatments 6D0W, 5D1W, 4D2W, 3D3W, 2D4W, 1D5W and 0D6W, respectively. Two controls accounting for the effects of the environmental matrices without UV-C exposure were set up with plastic disks spending 6 days in the dark in empty beakers (C-UV treatment, n=10 experimental units) and in beakers filled with VF-UP (C-W, n=10 experimental units). UV-C radiation was used as it allows for an intense photodegradation in a short period of time in comparison to UV-A and UV-B irradiation[53,54]. The distance between the UV lamps and the plastic disks was 41 cm, under aquatic conditions, the disks were under a water layer of 13 cm. The average air and water temperatures under the UV-C lamps did not exceed 30°C.

To assess the correspondence between UV-C and natural sunlight irradiation effects on plastic film, two 1 m² pieces of PVC film were exposed to sunlight for 12 weeks from early July to late September 2022, at the Lyon 1 University campus experimental platform “Les étangs” (45°46'47.5"N 4°52'05.6"E). The pieces of PVC film were taped to rigid polyethylene sheets, to prevent the film from being torn off by the wind, the polyethylene sheets were then placed, facing south, on top of a 2-meter-high metal structure to maximize exposure to the sun and limit potential abrasion from sediment transported by wind. Each week, 10 disks of 2 cm in diameter were cut, resulting in 12 duration treatments, one for each week of sunlight irradiation. The three months of sun exposure represented a total of approximately 846 hours of insolation with an average of 10:30 hours per day. During the whole duration of the experiment, it has been recorded 99 mm of precipitation spread over 22 days with 8 days experiencing more than 5 mm of daily precipitation. All the meteorological data were obtained from the nearest meteorological station located 8 km south from the experimental set-up (45°43'33.6"N 4°56'19.4"E).

Once the irradiation process finished (UV-C or sunlight) the plastic disks were kept at room temperature in the dark for 24 hours before fragmentation processing. This fragmentation processing consisted in applying a mechanical stress to plastic disks for simulating the abrasion that can occur during the reestablishment of continuous flows in IRES. These events are often unpredictable and can take the form of floods transporting large quantities of material with high velocity[52,55,56]. To simulate this, each plastic disk was individually weighed to determine its initial mass and then transferred into a 50 mL glass vial filled with 40 mL of VF-UP and 5 g of organic matter-free sand (burned at 500 °C during two hours, d50 = 225.5 µm). Each glass vial was sealed and then vertically mixed for 250 minutes at 1000 rpm (5 agitation periods of 10 min intercepted by breaks of 3 min, repeated five times), using an automated tissue homogenizer (Geno/Grinder SPEX sample prep). Between each agitation cycle, the position of each glass vial in the automated tissue homogenizer was randomly changed, to account for any potential effect of the positioning of the glass vials on the fragmentation process. The settings used in this abrasion process were set based on preliminary tests that determined the minimal abrasive conditions to obtain a significant fragmentation, albeit low, of disks not exposed to UV-C. In addition to all treatments, 10 glass vials containing only VF-UP and sediment were also processed as a negative control (C-).

Table 1: Summary of the DD treatments and their respective drying duration percentage

Treatment	UV-C exposure	Number of days		Drying Duration percentage
		Exposed under terrestrial conditions (D)	Exposed under aquatic conditions (W)	
0D6W	Yes	0	6	0 %
1D5W	Yes	1	5	17 %
2D4W	Yes	2	4	33 %
3D3W	Yes	3	3	50 %
4D2W	Yes	4	2	67 %
5D1W	Yes	5	1	83 %
6D0W	Yes	6	0	100 %
C-UV	No	6	0	100 %
C-W	No	0	6	0 %

Quantification of plastic fragmentation

After application of the abrasion process, each glass vial was individually emptied and rinsed with VF-UP above woven wire stainless-steel sieves with square openings mesh sizes of 1 mm and 20 µm, respectively. Woven wire steel sieves were used as they retain more efficiently thin flexible plastic particles[57]. The 1 mm sieve was used to separate macroplastics (>1 mm) and microplastics (<1 mm). Fragments retained on the 1 mm sieve, hereafter referred as Fraction 1 (F1), were placed in glass pillboxes covered in aluminum foil and left to dry at room temperature. After drying, F1 was weighed (± 0.01 mg) to quantify the mass of the plastic disk that was fragmented into particles larger than 1 mm. The difference between the initial disk mass and the mass of F1 allowed the calculation of the mass of plastic fragmented in particles smaller than 1 mm, present in the 20 µm sieve. Sediments and MPs present in the 20 µm sieve (Fraction 2 (F2)) were retrieved and placed in a separation funnel filled with a solution of filtered $ZnCl_2$ (1.5 g/cm^3, filtered using GF/F filter of 0.07 µm porosity), allowing for the separation of the plastic particles from the sediment[58]. Due to the low mass of the initial plastic disk, the mass of produced particles <20 µm was considered as negligible. Moreover, assessing the mass of particles <20 µm was difficult due to loss of particles during the density separation step but also due to the potential adhesion of these particles to the surface of larger particles present in F1[32]. After 24 hours, the supernatants that contain the MPs, were retrieved and abundantly rinsed with VF-UP in a 20 µm woven wire stainless-steel sieve. The supernatants were dyed with Nile Red (0.01 mg/mL^{-1}) and filtered on GF/F filters using a vacuum filtering device. The filters were then dried at 55°C during 48 hours for later microscopic analysis to quantify the abundance and size of F2 MPs. To avoid MPs contamination, the whole laboratory process was conducted wearing cotton lab-coats with the air conditioners turned off. Additionally, all the glassware and laboratory equipment were thoroughly rinsed with VF-UP before and between each use.

Stereo microscope for counting microplastics

Microplastics counting was conducted using a Nikon SMZ1270 fluorescent stereo microscope (magnification x15, exposure time 100 ms). On each GF/F filter used to recover MPs particles after extraction, 9 sub-areas of 5000 x 7500 µm subdivided into 6 square sections of 2500 x 2500 µm were selected, covering 33.17 % of the total colored filter area (Fig. S2). Pictures of each sub-area were taken with and without fluorescence and MPs present on pictures were manually counted and measured using the ImageJ software[59]. Particles were considered as MPs based on their size (<1 mm), form and coloration (with and without fluorescence), only plastic particles originating from the initial plastic disk were counted and measured (i.e., external contamination such as synthetic fibers were excluded). Particles <50 µm were not considered because of identification difficulties due to their small sizes, representing 1 and 4 % of the total abundance of MPs <1 mm counted for all combined treatment and controls of the UV-C exposure and sun exposure, respectively. Counted MPs from sub-areas of each filter were multiplied by 3 to express the total abundance of MPs between 50 µm and 1 mm per filter, each filter recovering all MPs produced from one PVC disk in each treatment.

Statistical analysis

The drying duration effect on plastic fragmentation was assessed across 3 variables: formed MPs abundance (H1), PVC disk mass loss (H2) and formed MPs size (H3). These variables were measured for MPs recovered in the F2 fraction; all plastic particles >1 mm found in F2 were not considered in this analysis process. These particles >1 mm likely entered F2 due to the flexibility of the PVC film that, with the weight of the VF-UP used for rinsing, might have led to folding of the particles allowing them to pass through the 1 mm sieve[57]. For H2, F2 estimated mass loss values were expressed in proportion of PVC disk mass (the sum of the two proportions F1 and F2 being equal to 1). To evaluate the correspondence between UV-C and natural sunlight irradiation effects on plastic film, we compared the abundance and size of formed MPs between the PVC disk exposed to sunlight, the C-UV control and the 6D0W treatment. For all these variables, normality and homoscedasticity were verified using the Shapiro-Wilk's test and the Bartlett's test, respectively. These assumptions were not met for all variables. Thus, non-parametric Kruskal-Wallis tests were performed, using the agricolae package[60], to compare the effects of DD treatments or duration of sunlight exposure on the three plastic fragmentation variables (number, mass, and average size of produced MPs). All analyses were conducted on R studio [R version 4.2.2 (2022-10-31)], ggplot2 package was used for graphical representations[61].

Flow intermittence: present and future projections

The results of this fragmentation experiment were coupled to hydrological modeling of the flow intermittence (FI) occurring in the Albarine river catchment, in order to extrapolate, as a proof of concept, the effect of FI on plastic fragmentation at the scale of a whole river catchment. The Albarine river catchment is a 354 km² watershed located in eastern France (Fig. S3), characterized by the presence of perennial and intermittent (with a contrasted FI magnitude) watercourses located throughout its area (Fig. S4)[62]. River intermittence was studied for more than 10 years on the Albarine river catchment[63], which is also part of the DRYvERS Horizon 2020 project (https://www.dryver.eu/). In the DRYvER project, a model of FI was developed to study the spatio-temporal patterns of drying in the Albarine river catchment and their possible future evolution under climate change.

For this study, the FI model was used to simulate the state of flow (flowing or dry) at daily time step in each of the 495 river sections of the Albarine river catchment. The detailed method is fully described in Mimeau et al. (2024)[64]. A reference simulation was carried out for the period 1991-2020 using ERA5-land climate reanalysis data as model input to simulate FI in the Albarine in the present climate[65]. For future climate simulations, climate projections from global climate models (GCMs) from the CMIP6 project used in the last Intergovernmental Panel on Climate Change report were used (data was retrieved from the ISIMIP project and is available on the website www.isimip.org/)[66,67,68]. To consider the level of uncertainty in climate modeling, downscaled climate data from 5 GCMs were used (GFDL-ESM4 / IPSL-CM6A-LR / MPI-ESM1-2-HR / MRI-ESM2-0 / UKESM1-0-LL) and 2 Shared Socio-Economic Pathways (SSPs) representing the quantity of greenhouse gas emissions were considered: SSP3-7. 0 regional rivalry, SSP5-8.5 fossil-fueled development[69].Both scenarios predict continuous increases in greenhouse gas emissions throughout the 21th century. FI simulations for climate change projections were carried out over the period 1991-2100. The FI simulations were then used to calculate for each reach the average percentage of year spent in dry condition during two 30-year time periods (to limit the effects of climate variability on the IBPFI calculation) for the scenarios SSP3-7.0 and SSP5-8.5. The reference period (1991-2020) and the end of the 21st century (2071-2100) were selected because of their contrasting climatic conditions.

Intermittence Based Plastic Fragmentation Index

In order to regroup reaches of the Albarine river catchment that were characterized by comparable FI magnitude, the percentage of FI per year was divided into seven FI classes based on the DD treatments used in the fragmentation experiment, and each reach was classified into these classes according to its own FI (Table S2 and Table S3). Based on this classification, the Intermittence Based Plastic Fragmentation Index (IBPFI; Eq. 1) is defined as the estimated number of formed MPs within the river catchment from an initial plastic object per year and was calculated as follows:

$$IBPFI = \sum_{i=1,n} \frac{RDi}{TR} \times FRi \qquad (1$$

Where RDi is the length in meter of the reaches of the FI class i (*i* corresponding to 1 of the 7 FI classes), TR is the total length of all reaches within the river catchment and FRi represents the average number of MPs (< 1 mm) formed by fragmentation on the associated DD treatment i. Based on the fragmentation measured in the laboratory experiment, the average number of formed MPs used in the IBPFI calculation was calibrated for the field by using the correspondence in the formed MPs abundances between plastic disks exposed 6 days under UV-C lamps and plastic disks exposed during 3 months under natural sunlight (see Fig. 2). Using this correspondence, it was decided to arbitrarily multiply the obtained number of MPs by a factor of four in order to obtain yearly estimations. Of course, this extrapolation does not take into account seasonal variations in radiation intensity, nor the future projected changes in UV radiation intensity due to human activity[70,71]. Nevertheless, the presented IBPFI was a first step toward coupling hydrological modeling and laboratory experimental approach to give a rough estimate of the role of flow intermittence on MPs formation at the river catchment scale. The IBPFI was calculated for the reference scenario (ERA5-Land) at the 1991-2020 time period and for the 5 GCMs over the 1991-2020 time period as well as for the 5 GCMs over the two SSPs for the 2071-2100 time period. The average of those results being the final reported IBPFIs (Fig. 3; Table S3).

RESULTS AND DISCUSSION:

- **Drying duration promotes MPs generation and plastic film mass loss (H1 and H2)**

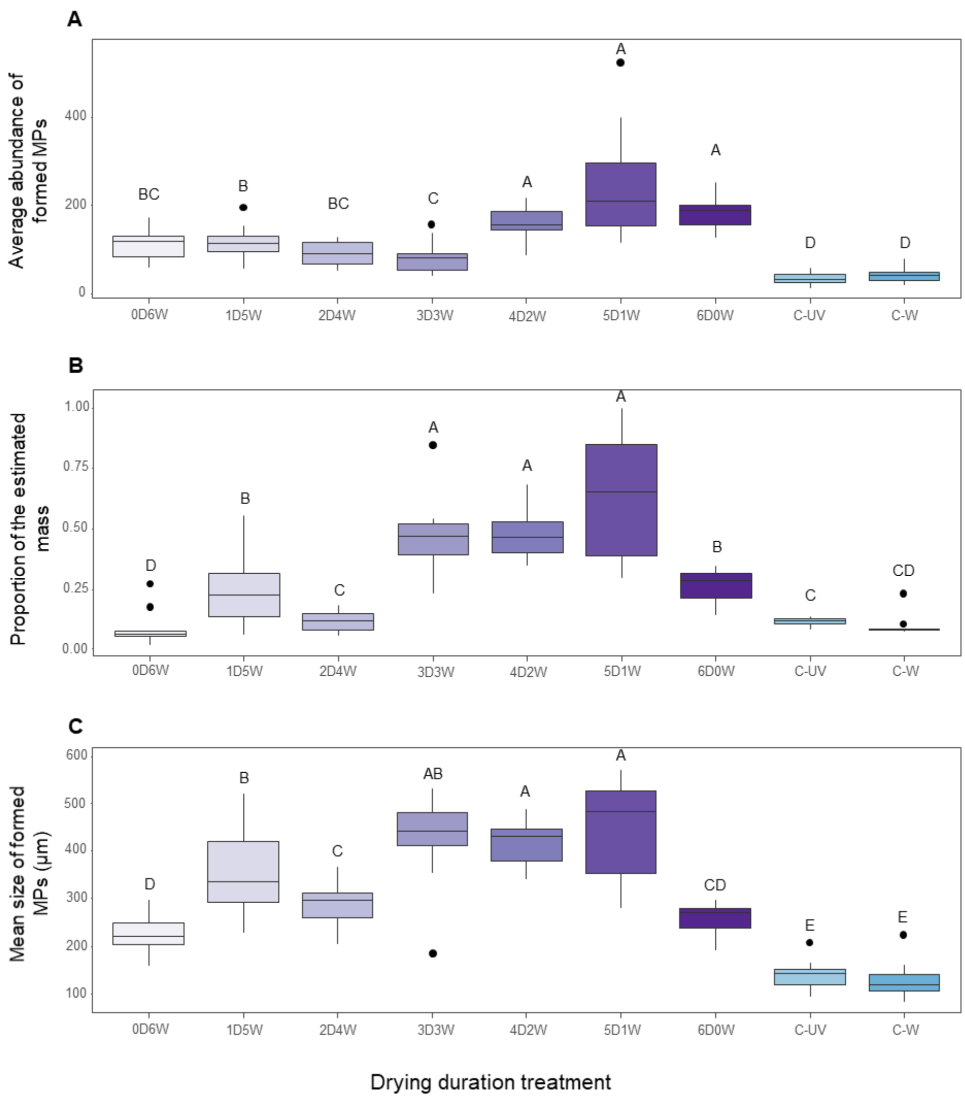


Fig. 1: **A)** Average abundance of MPs recovered in the F2 fraction depending on the DD treatment. **B)** Estimated mass proportion of the MPs recovered in the F2 fraction depending on the DD treatment. **C)** Mean size of the MPs recovered in the F2 fraction depending on DD treatment. Different letters indicate significant differences between each treatment.

The laboratory experiment with PVC disks exposed to seven DD treatments evidenced that the abundance of formed MPs, between the size of 50 µm and 1 mm, increased with the duration of dry conditions (Fig. 1A, $p<0.05$). As expected, lower MPs abundances were recovered from the controls (C-UV and C-W) than from the other treatments Fig. 1A, $p<0.05$). Disks exposed to radiative forcing related to dry duration $\leq$ 50 % of irradiation process duration (0D6W, 1D5W, 2D4W, and 3D3W) produced lower abundances of MPs than disks exposed to radiative forcing related to dry duration >50 % (4D2W, 5D1W, 6D0W; all $p<0.05$). The abundances of MPs formed were comparable among the 4D2W, 5D1W and 6D0W treatments (Fig. 1A, all $p>0.05$). A total of 20 MPs were found for all C-negative control, even when multiplied by 3, the average MPs contamination per filter remained low (n=6) and negligible when compared to the abundances obtained in the others treatments. The mean estimated masses recovered in F2 (i.e., masses of MPs) also varied among DD treatments (Fig. 1B, $p<0.05$). The highest mean estimated masses were obtained from the 5D1W, 4D2W and 3D3W treatments (all $p>0.05$). Surprisingly, the treatment representing terrestrial conditions (6D0W) resulted in a significantly lower mass of MPs than these treatments (Fig. 1B, $p<0.05$). Despite this last observation, the obtained results validate the initial hypotheses stating that the abundance of formed MPs and the mass loss of the initial plastic item would increase with dry duration. It confirms the conclusion of several studies that demonstrated that plastic weathering and fragmentation tended to be higher under terrestrial conditions[37–39,72]. Furthermore, the present study highlights that in cases of long dry duration (i.e., when there is a presence of water for short periods (less than 33 % of time)), reduced UV exposure did not cause a reduction in plastic weathering resulting in fragmentation that were comparable with a terrestrial exposure (i.e., the 6D0W treatment). Conversely, in the case of low and medium dry duration (i.e., dry conditions that last less than 67 % of time), disk fragmentation was similar to that obtained in aquatic environments (0D6W).

Overall, the abundance of formed MPs and mass loss of the plastic films showed comparable patterns with treatments producing high abundances of formed MPs and high mass losses (4D2W, 5D1W) and treatments leading to low abundances of formed MPs associated with low mass losses (0D6W, 2D4W). This is not unexpected because the mass loss of a plastic item due to fragmentation would be positively linked with an increase in the abundance of MP originating from the plastic item[57,73]. However, this link was not observed in the 3D3W and 6D0W treatments, which produced higher and lower mass losses than those expected from the abundances of MPs formed, respectively (Fig. 1). This discrepancy between the abundances and the masses of formed MPs may be explained by different sizes of PVC formed particles (e.g. PVC particle mass increases with its size). Our results suggest that formed MPs would be of higher mean size in the 3D3W treatment than in the settings having comparable abundances of formed MPs (2D4W). It would also be expected that MPs of smaller sizes would be obtained from the 6D0W treatment than from the 4D2W and 5D1W treatments. These expectations were validated by the results on the sizes of formed MPs (Fig. 1C). Thus, the relationship between the abundance of formed MPs and mass loss of initial plastic item strongly depended on the size of formed MPs. Although this observation seems trivial, most works on plastic fragmentation focused on one or two of the three variables considered in the present study[22,39,53,74,75]. Consequently, the links among the abundance, the mass and the size of MPs should be more thoroughly investigated in future studies to better characterize MPs particles resulting from plastic fragmentation.

Surprisingly, the highest abundance of formed MPs and mass loss of plastic film were not observed in the 6D0W treatment but in the 5D1W treatment (Fig. 1). Although the difference is slight and statistically non-significant this result remains unexpected. We expected photodegradation to be more efficient in complete terrestrial conditions (6D0W) than in conditions experiencing aquatic phases, due to the reduced UV impact caused by water and the higher oxygen availability in the air. These aforementioned parameters, coupled with UV irradiation, have previously shown to induce free radicals along the polymer chain that lead to the formation of peroxy free radicals resulting in the embrittlement and loss of mechanical properties of plastic items[27,76–79]. Our results demonstrate that the presence of water covering the PVC plastic film for at least 50 % of the irradiation exposure time is necessary to partially mitigate the above-mentioned photodegradation effects, unraveling new perspectives on the effects of river drying on plastic fragmentation.

- **Increasing dry duration generates large MPs (H3)**

Contrary to our expectations, the size of formed MPs (between 50 µm and 1 mm) increased with the duration of dry condition for settings experiencing aquatic conditions (Fig. 1C, $p<0.05$). Indeed, treatment 5D1W produced a high number of MPs (Fig. 1A) which were characterized by the highest mean particle size of all treatments (Fig. 1C). In contrast, treatments leading to low abundances of formed MPs (0D6W, C-UV, C-W) produced MPs of low mean sizes (Fig. 1C). In these treatments, the photodegradation process was limited due to the presence of a constant water column or null due to the absence of UV exposure[80,81]. Due to this low photodegradation, the plastic disks were mostly unaltered or fragmented into only two or three coarse particles (>5 mm) and the few formed MPs likely originated from the edge of these newly formed particles. Thus, even with low photodegradation effects, mechanical stress alone can lead to plastic fragmentation[29,53,57,82]. In contrast, in treatments where plastic disks were weakened substantially by UV exposure, high numbers of MPs were formed and characterized by high mean sizes (e.g. treatment 5D1W). These plastic disks were completely fragmented into a multitude of fragments of a wide size range, among which some have not been investigated due to the detection limits of the stereo microscope (<50 µm).

Furthermore, the presence of large particles might have also led to the concealing of smaller particles. As discussed above, the fact that the treatments 6D0W and 5D1W produced comparable abundances of formed MPs but of different mean sizes was likely due to the lack of an aquatic phase in the 6D0W treatment. A lack of physical and chemical interactions between water and PVC disks might have affected the disk fragmentation, modifying the size of formed MP particles. Although the present study focused on PVC as one specific polymer, the influences of complex interactions between aquatic/dry periods and UV irradiation on the size of formed MPs are likely to be not dissimilar for other polymers and could have significant ramifications on ecosystem functioning, as the impact of MPs on aquatic organisms is often negatively correlated with the size of the MPs[10,83]. However, more experimental evidences considering a wider range of plastic polymers and properties will be required to understand the full complexity of mechanisms involved in these interactions. Overall, our results showed that the aquatic treatment and those with low dry duration led to low plastic film fragmentation, whereas high dry duration led to increased levels of plastic fragmentation with coarse MPs being formed. Conversely, under terrestrial exposure, plastic film fragmentation was high, causing rather small MPs to be formed. More precisely, we demonstrated that drying can lead to substantial plastic fragmentation, providing new insights on environmental controls of the fate of plastic items in streams and rivers. The alternance of aquatic and terrestrial phases occurring in IRES is known to lead to expansion and contraction cycles of terrestrial and aquatic habitats through time[84]. This strong hydrological variability can promote transfers of MPs towards the adjacent terrestrial ecosystems as well as downstream aquatic ecosystems through multiple possible pathways[52,85,86]. Such pathways could be related to the different phases of drying and flooding, wind dispersal during dry phases as well as the significant transfer of resources between the aquatic and terrestrial environments governing these ecosystems[7,87,88]. IRES could be considered both as hotspots for plastic fragmentation and dispersal-corridors of the formed plastic particles. However, future studies should investigate other mechanisms leading to plastic fragmentation, such as biological degradation, throughout microbial activities, as well as thermal degradation of plastic exposed to drying[26,89].

Correspondence between UV-C and sunlight irradiation on plastic film fragmentation

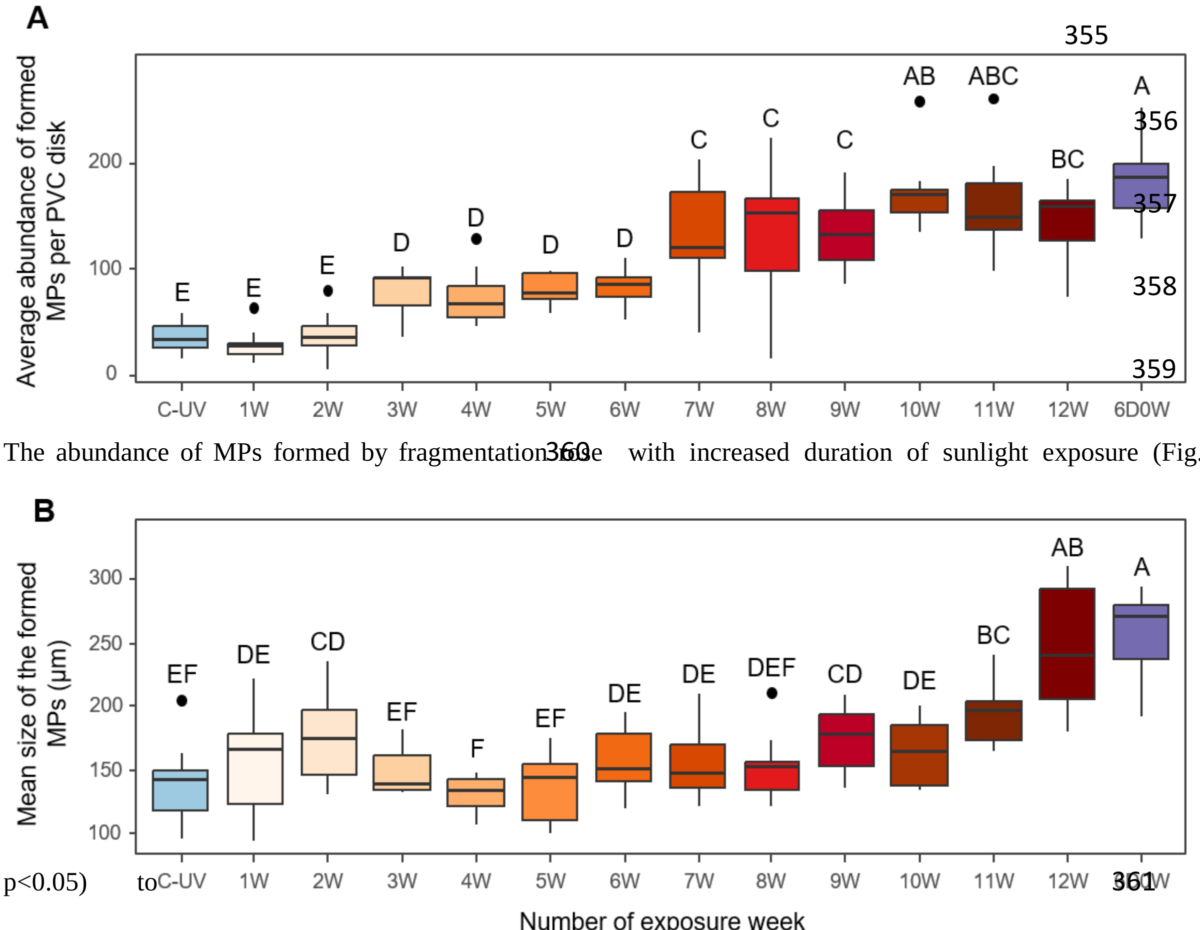


Fig. 2: Abundance (A) and mean size (B) of MPs recovered in the F2 fraction according to the number of weeks spent exposed to sunlight compared to plastic disk exposed for 6 consecutive day to UV-C (6D0W) and non-exposed to any UV irradiation (C-UV). Different letters indicate significant differences between each treatment.

The abundance of MPs formed by fragmentation rose with increased duration of sunlight exposure (Fig. 2A, $p<0.05$) to reach MPs abundances comparable to values obtained from PVC disks exposed to UV-C during 6 days (6D0W treatment displayed on Fig. 1A) after 10 weeks of sunlight exposure ($p>0.05$). As observed after UV-C exposure, the mean size of the formed MP rose with increased duration of sunlight exposure (Fig. 2B, $p<0.05$). Mean MP size reached comparable values than those measured in the 6D0W treatment after 12 weeks of sunlight exposure (Fig. 2B, all $p>0.05$). These results showed that a continuous six-days (=144 hours) terrestrial exposure to UV-C radiation produced weathering effects comparable to 3 months (≈ 846 hours) of direct sunlight exposure in a terrestrial environment during the summer season and under temperate climate. This suggests that the UV-C exposure was almost 6x more intense than natural sunlight which is in line with the results of previous studies[53]. As the number of days with non-negligible precipitation was low (n=8) and that the PVC film was exposed at two-meter-high, limiting the effects of blown-sediment, it is highly likely that the photodegradation was the main factors that contributed to the weathering of the plastic film. Although concerns have been raised regarding the limited environmental transferability of accelerating plastic weathering protocols[54,77]. These approaches remain necessary in preliminary studies, enabling rapid exploratory experimental approaches to rigorously evaluate the influence of selected environmental factors on plastic fragmentation. Based on these exploratory results on the influence of drying on plastic fragmentation, the next step will be to obtain a field validation of these results by measuring the fragmentation of plastic occurring in river network exposed to a wide range of natural FI.

The Intermittence Based Plastic Fragmentation Index under different scenarios

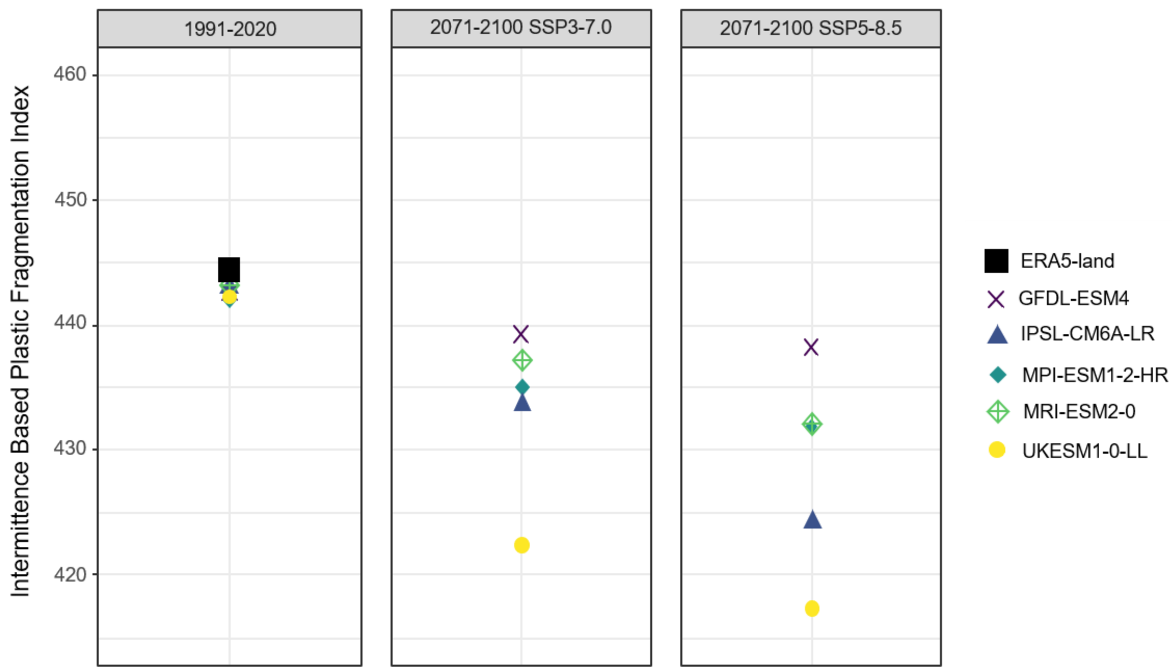


Fig. 3: IBPFI of the Albarine river catchment depending on the used model dataset, time period and scenario. The IBPFI of the reference (ERA5-land) is 444, the average IBPFI for the SSP3-7.0 at the 1991-2020 and 2071-2100 time periods are 443 (SD=0.5) and 433 (SD=6.4). For the SSP5-8.5 at the 2071-2100 time period the average IBPFI is 429

Based on the abundances of formed MPs obtained in the laboratory for the 7 DD treatments, the Intermittence Based Plastic Fragmentation Index (IBPFI) could vary from 336 to 984, in the hypothetical scenario where all reaches within the Albarine river catchment have a FI of 50 % and 83 %, respectively (Table S4). Using the FI model outputs for the Albarine River, average IBPFI varied from 429 calculated for the SSP5-8.5 at the 2071-2100 time period to 444 calculated for the reference (Fig. 3). The average IBPFI slightly decreased in both climate projections (Fig. 3) but the IBPFI changes (444 to 429) were limited compared with the potential variation of the IBPFI index (from 336 to 984) derived from laboratory results. No clear differences were observed between model outputs because, regardless of the scenario used, the majority of the reaches were within the four FI classes which experienced terrestrial conditions for less than 50 % of time and which were expected to produce comparable abundances of formed MPs (based on laboratory results displayed on Fig. 1A). Moreover, the FI class corresponding to permanent aquatic phase during UV-C exposure (0D6W) represented 92 % of all reaches within the Albarine river catchment for the reference, and, on average, 76 % for the SSP3-7.0 at the 1991-2020 time period and approx. 60 % for the other two simulations (Table S3). The proportion of reaches within the 1D5W FI class corresponding to 17 % of dry duration, was lower in the reference than in the other simulations (7 % vs 18, 19.5 and 24 %). As this 1D5W FI class had the highest mean abundance of formed MPs of all DD < 50 % treatments, we would expect the lowest IBPFI in the reference. However, the slight increase in the proportion of reach length classified in 1D5W FI class in simulations was associated with an increase in the proportion of reach length of the 2D4W FI class (33 % of DD) which had the second lowest abundance of formed MPs of all DD treatments. Finally, these multiple changes of the proportion of reach length associated with FI classes between reference and simulations canceled out the increase in IBPFI expected from the increasing proportions of reaches within the 1D5W FI class in simulations compared with the reference. These exploratory results on the IBPFI in the Albarine catchment are reassuring concerning the MP contamination in the future as the ability of the catchment to produce MPs, estimated by the IBPFI, did not increase in future scenarios.

However, this conclusion must be taken with caution as the IBPFI index is in its seminal phase of proof of concept and thus this first approach only considered a restrained number of experimental conditions. As indicated earlier, the experimental design used for the IBPFI creation only evaluates the plastic sensitivity to drying with a given, continuous and stable radiation level without considering changes in radiation intensity. There are also uncertainties in the modelling chain for the simulation of IBPFI projections under climate change, particularly with regard to the flow intermittence model. Mimeau et al. 2024 have shown that, although the model is capable to predict more than 90% of observed droughts in the Albarine river catchment, it still has significant uncertainties, which are mainly linked to the availability of observed flow intermittence data. At this stage, the IBPFI must be considered as a demonstration of feasibility giving rough estimates of the role of flow intermittence on plastic fragmentation in streams and rivers. Several steps are needed to improve the applicability of the IBPFI, the first one being to test it onto other river catchments exposed to environmental conditions and hydrological variability which differ drastically from those occurring in the Albarine river catchment. The second step would be to couple current results of the

IBPFI with fragmentation of the PVC film exposed in multiple reaches, experiencing contrasting drying intensity, within the Albarine river catchment. The final step would be to investigate the role of drying in interactions with the wide variety of environmental factors which can affect plastic fragmentation. For example, photodegradation can be affected by differences in plastic exposure to UV radiation due to adjacent vegetation canopy shading, biofilm formation or the presence of a sedimentary layer, all of which can limit UV exposure of the plastic[89,90]. Other mechanisms can lead to plastic fragmentation such as the aforementioned biological and chemical degradation of plastic items and must be implemented in future iterations of the index. In addition to sediment abrasion, other factors apply mechanical stress that will fragment the weathered plastic such as flow velocity and biotic interactions[21,53]. Furthermore, several polymers must be tested because the weathering and fragmentation of plastic depend on the type of polymer, plastic items and fabrication process[91–93]. While more and more perennial reaches are shifting intermittent due to global change[42–44,56] our preliminary application of the IBPFI at the field scale suggests that these shifts might have limited effects on IBPFI at the river catchment scale, as long as the proportion of reaches with an FI > 58.5 % within the catchment remains low. Plastic fragmentation within the catchment is thus, mostly driven by the most represented hydrological variability pattern, with potential hotspots of plastic fragmentation localized in highly intermittent reaches. This reflects what is occurring in specific areas of marine ecosystems such as the aforementioned swash zones, that are considered as MPs generation hotspots due to the important plastic fragmentation occurring in these areas[30,39]. Identifying those hotspots and understanding their specific plastic fragmentation mechanisms and patterns is essential for the development of new policies addressing MPs pollution. Moreover, the effects that small plastic particles, such as micro and nanoplastics, may have on the numerous ecosystem services provided by IRES[94], the important biodiversity of these ecosystems[95] as well as their functioning, is critically under-investigated. Unfortunately, because non-perennial rivers and streams are often not considered in management practices[96–98], and because they are increasing with global change, efforts are needed to understand the multiple ways in which plastic pollution can impact rivers and streams to secure the functional integrity of flowing waters in an uncertain future.

ASSOCIATED CONTENT:

- Supporting information:

More detailed information regarding the characteristics of the used PVC film, MPs counting methodology, the Albarine river catchment and IBPFI calculation is provided.

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- Notes

The authors declare no competing financial interest.

- Data availability

Data are available through the following link: https://github.com/NansBarthelemy/PVC_Fragmentation_Drying. Pictures of each filters sub-area are available upon request.

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