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RESEARCH ARTICLE

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Effects of microplastics and drought on soil ecosystem functions and multifunctionality

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Abstract

1. Microplastics in soils have become an important threat for terrestrial systems as they may potentially alter the geochemical/biophysical soil environment and can interact with drought. As microplastics may affect soil water content, this could exacerbate the well-known negative effects of drought on ecosystem functionality. Thus, functions including litter decomposition, soil aggregation or those related with nutrient cycling can be altered. Despite this potential interaction, we know relatively little about how microplastics, under different soil water conditions, affect ecosystem functions and multifunctionality.
2. To address this gap, we performed an experiment using grassland plant communities growing in microcosms. Microplastic fibres (absent, present) and soil water conditions (well-watered, drought) were applied in a fully factorial design. At harvest, we measured soil ecosystem functions related to nutrient cycling (β-glucosaminidase, β-D-cellobiosidase, phosphatase, β-glucosidase enzymes), respiration, nutrient retention, pH, litter decomposition and soil aggregation (water stable aggregates). As terrestrial systems provide these functions simultaneously, we also assessed ecosystem multifunctionality, an index that encompasses the array of ecosystem functions measured here.
3. We found that the interaction between microplastic fibres and drought affected ecosystem functions and multifunctionality. Drought had negatively affected nutrient cycling by decreasing enzymatic activities by up to ~39%, while microplastics increased soil aggregation by ~18%, soil pH by ~4% and nutrient retention by up to ~70% by diminishing nutrient leaching. Microplastic fibres also impacted soil enzymes, respiration and ecosystem multifunctionality, but importantly, the direction of these effects depended on soil water status. That is, under well-watered conditions, these functions decreased with microplastic fibres by up to ~34% while under drought they had similar values irrespective of the microplastic presence, or tended to increase with microplastics. Litter decomposition had a contrary pattern increasing with microplastics by ~6% under well-watered conditions while decreasing to a similar percentage under drought.

4. *Synthesis and applications*. Single ecosystem functions can be positively or negatively affected by microplastics fibres depending on soil water status. However, our results suggest that microplastic fibres may cause negative effects on ecosystem soil multifunctionality of a similar magnitude as drought. Thus, strategies to counteract this new global change factor are necessary.

KEYWORDS

enzymatic activities, grasslands ecosystem, litter decomposition, nutrient cycling, nutrient leaching, soil aggregation, soil pH, soil respiration

1 | INTRODUCTION

Microplastics are a group of polymer-based particles with a diameter under 5 mm (Hidalgo-Ruz et al., 2012), which occur in many shapes, and possess a high physical and chemical diversity (Helmberger et al., 2020; Rillig, Ryo, Lehmann, et al., 2019). These particles can originate from many sources, including tire abrasion, the loss of fibres from synthetic textiles during washing or the environmental degradation of larger plastic objects (Boucher & Friot, 2017). In addition, many plastics are already produced as microplastics (primary microplastics), for example, for use in the cosmetics industry (Boucher & Friot, 2017). Therefore, microplastics are ubiquitous around the globe and may pollute not only oceans but also terrestrial systems through soil amendments, plastic mulching, irrigation, flooding, atmospheric input and littering or street run-off (Bläsing & Amelung, 2018; Rillig, 2012; de Souza Machado et al., 2018).

Our knowledge about microplastic effects on ecosystem functions is limited (Rillig & Lehmann, 2020) and potential interactive effects of microplastics with soil water availability are unknown. Among microplastics, fibres are considered one of the most abundant microplastic types in the soil (Dris et al., 2015; Zhang & Liu, 2018), and due to their linear shape, size and flexibility, can potentially affect soil–water dynamics mainly through links with soil aggregation. Fibre shape, which roughly mimics that of the roots, may entangle soil particles promoting aggregation. They also might form large pores between aggregates allowing the water to enter the soil profile, and could create small pores within aggregates helping to hold the water. Likewise, the hydrophobicity of microplastic fibres (Prorokova et al., 2012) may contribute to the soil aggregation (Zheng et al., 2016) as they would serve as a binding agent. However, microplastic fibres could also decrease soil aggregation (Lozano, Lehnert, et al., 2021) by preventing microaggregates from being integrated into macroaggregates (Zhang & Liu, 2018) and, as soil biota enhance soil aggregation by providing mucilages and extracellular compounds that bind particles together (Bronick & Lal, 2005), the presence of fibres could reduce the stability of soil aggregates by affecting soil biota (Lehmann et al., 2019; Liang et al., 2019; de Souza Machado et al., 2019).

Therefore, microplastic fibres through their effects on soil aggregation can potentially alter soil water holding capacity and so lead to differential retention of water, thus altering soil water conditions, and potentially influencing other ecosystem functions. Indeed, microplastic fibres may promote plant growth and other processes (de Souza Machado et al., 2019), and this could alleviate drought conditions promoting plant productivity at the community level (Lozano & Rillig, 2020). All this evidence suggests that drought effects on ecosystem functionality may be altered when other global change factors, such as microplastics, come into play.

This potential interaction between microplastics in the soil and drought can affect multiple ecosystem functions involved in nutrient cycling, litter decomposition and soil aggregation. However, research on how microplastics and drought affect such functions is limited. For example, nutrient cycling and energy flows are closely related to soil enzymes produced by microbes and plants (Stark et al., 2014), and enzymatic activity is highly influenced by environmental factors such as soil pH, nutrient availability and soil water content (Paul & Clark, 1989). By altering these factors, microplastics may potentially affect soil enzymatic activities. Indeed, there is evidence for microplastic influencing some enzymes, depending on the microplastic polymer type. For instance, polyamide (PA), polyester fibres (PES) and polypropylene (PP) can stimulate the activity of fluorescein diacetate hydrolase (Liu et al., 2017; de Souza Machado et al., 2019), while polyethylene (PE) and polyvinyl chloride (PVC) can show the opposite effect (Fei et al., 2020). Likewise, PP, PE and PVC can stimulate phenol oxidase, urease and acid phosphatase activities (Fei et al., 2020; Liu et al., 2017). In contrast, data on the effect that microplastic may have on key enzymes related to C, N, P-cycling (such as β-glucosidase and β-D-cellobiosidase involved in cellulose degradation, or β-glucosaminidase involved in chitin degradation) are missing or limited (as in the case of phosphatases).

Litter decomposition is also a key ecosystem function with a crucial role in carbon cycling (Schmidt et al., 2011). This process depends on many factors including soil water content, litter quality and the decomposer community (Paul & Clark, 1989). Microplastics may directly affect decomposition by modifying some of these factors, or indirectly through its effects on soil aggregation (a function that is highly correlated with decomposition). So far, empirical evidence of the effect of microplastics on litter decomposition is sparse (Barreto et al., 2020; Lehmann et al., 2020), and we know even less about how decomposition might be affected under different water regimes (e.g. well-watered, drought conditions).

The trends summarized above not only illustrate the scarce knowledge on the effects of microplastic on terrestrial ecosystem functions but also highlight the potential link between microplastics and drought, as the addition of microplastics may exacerbate the magnitude of the drought effects and its direction (positive or negative depending on the function measured). In addition, the net effect of each ecosystem function can alter the overall functioning of the soil. Given this heterogeneity of effects, and that ecosystem functioning is inherently multidimensional, addressing how microplastics influence multifunctionality (defined as the ability of an ecosystem to deliver multiple functions simultaneously (Hector & Bagchi, 2007), could generate an integrative understanding of the terrestrial systems response to this global change factor.

Thus, in this study, we determined the potential interactive effects that microplastics and drought have on ecosystem functions linked to nutrient cycling, litter decomposition and soil aggregation. To do that, we established microcosms of plant communities, on which we measured the effect of microplastic fibre addition and a drought treatment in a factorial design on different ecosystem functions such as nutrient cycling (e.g. soil enzymatic activities, respiration, nutrients and soil pH), soil aggregation and litter decomposition (Giling et al., 2019) and on ecosystem multifunctionality. We expected that microplastic fibres would affect single ecosystem functions and ecosystem multifunctionality in a positive or negative way depending on soil water conditions.

2 | MATERIALS AND METHODS

2.1 | Microplastics and soil preparation

In Dedelow, Brandenburg, Germany (53°37′N, 13°77′W), we collected dry sandy loam soil from grasslands communities (0.07% N, 0.77% C, pH 6.66). Soil was sieved (4 mm mesh size), homogenized and mixed with microplastic fibres at a concentration of 0.4% w/w (0.4 g of microplastic fibres for each 100 g of dry soil). This concentration aimed to simulate higher levels of microplastic pollution (Scheurer & Bigalke, 2018; Xu et al., 2020; Zhu et al., 2019), while in soils of strongly polluted areas, a microplastic concentration up to ~7% (w/w) was observed (Fuller & Gautam, 2016). To do so, we manually cut with scissors polyester fibres (Rope Paraloc Mamutec polyester white, item number, 8442172, Hornbach.de) to generate microplastic fibres that had a length of 1.28 ± 0.03 mm and a diameter of 0.030 ± 0.0008 mm. Polyester fibres are made to at least 80% of polyethylene terephthalate (PET; Council Directive, 2011). See details in Table S1 about polyester fibres properties. Twelve grams of microplastic fibres (~763,333 fibres g^{-1} microplastic) was mixed into 3 kg of soil for each pot (16 cm diameter, 16.5 cm height, 3,000 ml). For each experimental unit, fibres were separated manually and mixed with the soil in a large container before placing into each individual pot, to help provide a homogeneous distribution of microplastic fibres throughout the soil and the intended concentration. Twenty experimental units (pots) were established. Half had soil with microplastic fibres, while the other half had soil without added microplastic fibres. Soil was mixed in all experimental units in order to provide the same level of disturbance.

2.2 | Experimental setup

In May 2019, we established the experiment in a temperature-controlled glasshouse with a daylight period set at 12 hr, 50 klx, a temperature regime at 22/18°C day/night and a relative humidity of ~40%. We selected seven grassland plant species (*Festuca brevipila*, *Holcus lanatus*, *Calamagrostis epigejos*, *Achillea millefolium*, *Hieracium pilosella*, *Plantago lanceolata* and *Potentilla argentea*) frequently co-occurring in Central Europe. Seeds were obtained from a commercial supplier in the Brandenburg region (Rieger-Hofmann GmbH) in order to shape a plant community consisting of three individuals per species. We will refer to plant species by their generic names from now on. For additional details, see Lozano and Rillig (2020).

Pots were well watered (100 ml twice a week) during the first 3 weeks of growth. Then, half of them were kept at ~70% of soil water holding capacity (WHC) by adding 200 ml of water, while the other half were kept at ~30% WHC by adding 50 ml of water. Pots were watered from the top twice a week for 2 months with distilled water. We thus had a design that includes two microplastic fibre treatments (with and without added microplastic fibres, also called 'present' and 'absent') and two drought treatments (with and without drought, also called 'drought' and 'well-watered'), with five replicates each (n = 5). Pots were randomly distributed in the chamber and their position was shifted twice to homogenize environmental conditions during the experiment.

We measured 11 variables that capture aspects of nutrient cycling (β-glucosidase, β-glucosaminidase, β-D-cellobiosidase, phosphatase, soil respiration, leaching of NO_3^-, SO_4^{2-}, PO_4^{3-}), decomposition (litter decomposition), soil aggregation (water stable aggregates) and soil pH, functions thereafter. At harvest, pots were watered to saturate the soil to roughly 10% beyond the water holding capacity to induce leaching; then soil samples for enzymes and respiration measurements, and litter bags used for litter decomposition were collected. Finally, soil was dried at ~22°C for 1 month and a sample for water stable aggregates measurement was obtained.

2.3 | Measurement of soil ecosystem functions

We measured the functions related to soil nutrient cycling by fluorometry as described in Bell et al. (2013). Soil respiration was determined via an infrared gas analyzer, while litter decomposition was measured by using a composite sample that reflected the proportion of plant biomass of each plant species in the field. Water stable soil aggregates, a proxy of soil aggregation, were measured following a modified version of the method of Kemper and Rosenau (1986). Soil nutrients were analysed using ion chromatography (Dionex ICS-1100, AS9-HC, Thermo Scientific) while soil pH was determined with a Hanna pH meter (Hanna Instruments GmbH). For additional details, see Appendix S1.

2.4 | Assessing ecosystem multifunctionality

To calculate ecosystem multifunctionality, we followed the ecosystem function multifunctionality method proposed by Manning et al. (2018). Briefly, four clusters were identified for the 12 ecosystems functions, and ecosystem multifunctionality was calculated by using the threshold approach. See details in Appendix S2.

2.5 | Statistical analyses

The experimental design was a fully crossed orthogonal design where microplastic fibres, drought and the interaction were considered fixed factors. Each function was analysed using linear models. Model residuals were checked to validate normality and variance homogeneity assumptions. We implemented the 'varIdent' function to account for heterogeneity in the microplastic fibre treatment for β-D-cellobiosidase, soil aggregation and in the water treatment for soil respiration. The effect of microplastics and drought on the ecosystem multifunctionality index was analysed using generalized linear models with a quasibinomial distribution and a logit link function to avoid overdispersion. We also assessed the contribution of each function to multifunctionality by using the downweighting data after clustering and the metric 'pmvd' from the package RELAIMPO (Grömping, 2006). Statistical analyses were done with R version 3.5.3 (R Core Team, 2019).

3 | RESULTS

Ecosystem functions were affected by microplastic fibres, drought and their interaction (Table 1). While enzymatic activities and soil respiration were on average higher under well-watered than under drought conditions, these trends changed in the presence of microplastics, decreasing under well-watered conditions but increasing under drought. As for enzymatic activity, β-glucosaminidase decreased by ~35% with drought and was not affected by microplastic fibres (Table 1; Figure 1). β-D-cellobiosidase decreased by ~39% with drought ($p = 0.02$), while soil respiration was marginally affected by microplastic fibres and drought ($p = 0.1$). Phosphatase and β-glucosidase were affected by the interaction between microplastic fibres and drought ($p = 0.03$, $p = 0.1$ respectively). Both decreased with microplastic fibres in soil by 27% and 17% under well-watered while increasing by 75% and 40% under drought conditions respectively (Table 1; Figure 1). By contrast, litter decomposition increased with microplastic fibres by 6.4% under well-watered conditions while decreasing by 6.6% under drought conditions ($p = 0.09$, Figure 1). Likewise, soil aggregation increased with microplastic fibres under both well-watered and drought conditions by 15% and 21.7% respectively ($p = 0.07$). Overall, soil leachate nutrients increased with drought and decreased with microplastic fibres in the soil. Specifically, leachate NO_3^- decreased by 70% with microplastic fibres under drought conditions ($p = 0.01$, Figure 1), a similar trend was found under watered conditions. Leachate SO_4^{2-} decreased with microplastic fibres under either well-watered or drought conditions by 52% and 37% respectively ($p = 0.01$). PO_4^{3-} in leachate was not clearly affected by drought or microplastic fibres, while soil pH increased both with drought and microplastic fibres in the soil ($p < 0.01$, Figure 1).

Ecosystem multifunctionality was affected by the interaction between microplastic fibres and drought (Table 1; Figure 2). That is, the effect of microplastics on ecosystem multifunctionality strongly depended on the drought treatment ($p = 0.01$), a treatment that alone tended to decrease ecosystem multifunctionality ($p = 0.10$). Regarding the interaction, under well-watered conditions, microplastic fibres

TABLE 1 Results from linear models on 11 ecosystems functions and multifunctionality response to microplastic fibres (M), drought (D) and their interaction (M × D). Multifunctionality also included shoot mass (data extracted from Lozano & Rillig, 2020). Degrees of freedom of each factor ($df = 1$). F values and p values (in parentheses) are shown; $p < 0.1$ in bold; $n = 5$

Ecosystem functions	Microplastic fibres (M)	Drought (D)	M × D
β-glucosaminidase	0.14 (0.70)	2.98 (0.10)	1.08 (0.31)
β-glucosidase	0.02 (0.89)	**6.88 (0.01)**	2.31 (0.14)
Phosphatase	0.07 (0.79)	**3.55 (0.07)**	**5.53 (0.03)**
β-D-cellobiosidase	2.14 (0.16)	**6.32 (0.02)**	1.49 (0.23)
Soil respiration	2.49 (0.13)	2.29 (0.14)	1.37 (0.25)
Litter decomposition	0.002 (0.95)	0.88 (0.36)	**3.13 (0.09)**
Soil aggregation	**3.54 (0.07)**	2.51 (0.13)	0.03 (0.84)
NO_3^-	**10.66 (0.004)**	**24.93 (0.0001)**	**7.85 (0.01)**
PO_4^{3-}	0.36 (0.55)	0.25 (0.62)	0.08 (0.77)
SO_4^{2-}	**6.75 (0.01)**	**3.66 (0.07)**	0.00 (0.99)
pH	**12.38 (0.002)**	**9.14 (0.008)**	0.47 (0.50)
Multifunctionality	3.16 (0.09)	3.02 (0.10)	**7.23 (0.01)**

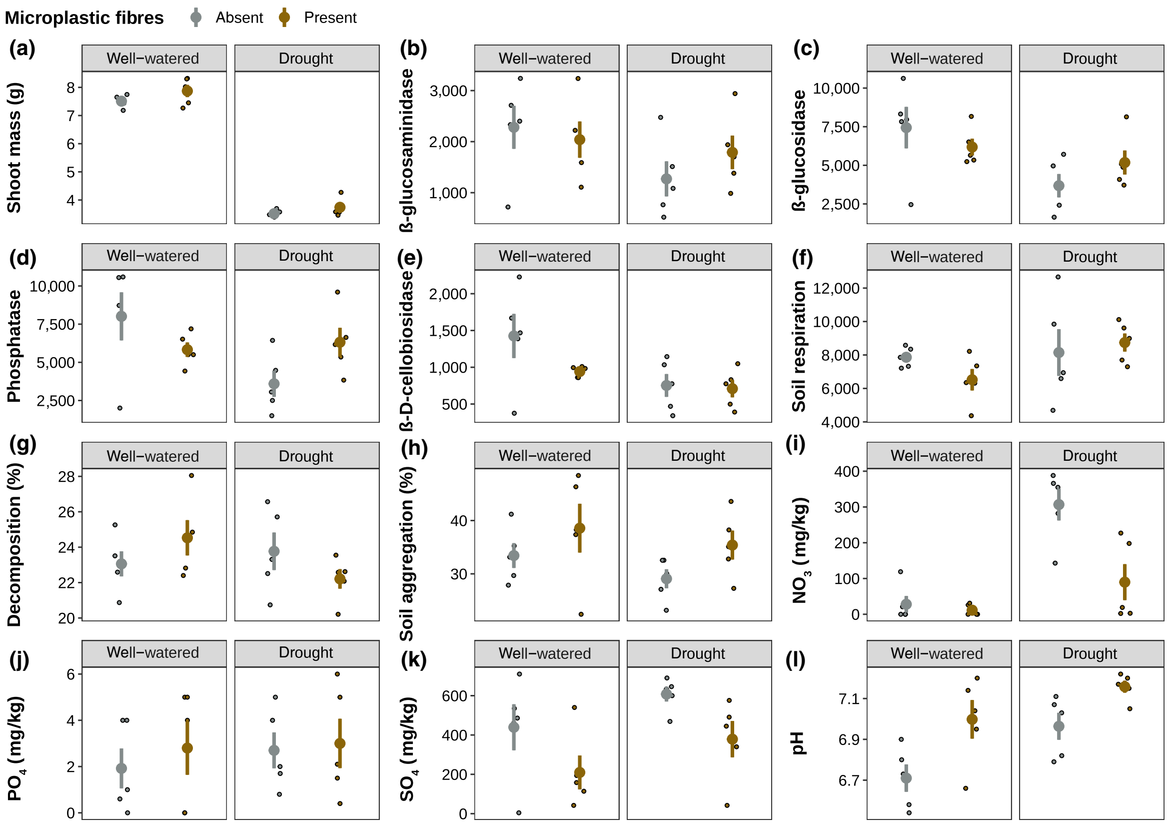

FIGURE 1 Microplastic fibers and drought effects on 12 ecosystem functions: (a) shoot mass, (b) β-glucosaminidase, (c) β-glucosidase, (d) phosphatase, (e) β-D-cellobiosidase, (f) soil respiration, (g) litter decomposition, (h) soil aggregation, (i) NO_3, (j) PO_4, (k) SO_4, (l) soil pH. Mean and standard error are represented. Data points are shown as circles. Enzymes and soil respiration units (μmol g^{-1} dry soil hr^{-1}, ppm). *p* values in Table 1; *n* = 5

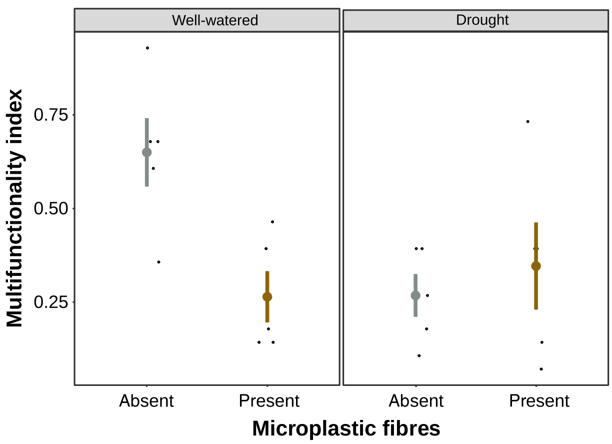

FIGURE 2 Microplastic fibers and drought effects on ecosystem multifunctionality. Mean and standard error are represented. Multifunctionality was calculated based on the threshold approach in which each function that exceeds 70% of the standardized maximum contributes to the multifunctionality score. Data points are shown as circles; *p* values in Table 1; *n* = 5

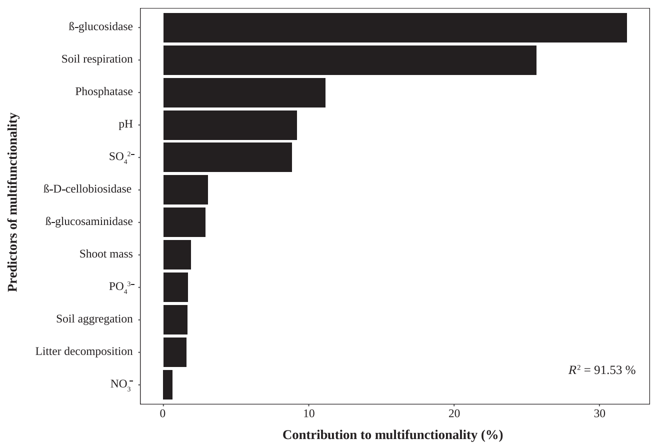

FIGURE 3 Relative importance of each predictor to multifunctionality. The proportionate contribution of each function considered both its direct effect (i.e., its correlation with multifunctionality) and its effect when combined with the other variables in the regression equation. The metrics 'pmvd' was used for the calculation and the down-weighting via the cluster was taken into account

addition to the soil decreased multifunctionality, while under drought conditions, microplastic addition did not affect multifunctionality (Figure 2). Different thresholds when calculating multifunctionality showed similar trends (Figure S2, see Table S1 for statistical results). The analysis of the relative importance of each function showed that β-glucosidase (31.87%), soil respiration (25.65%), phosphatase (11.14%), pH (9.16%), SO_4^{2-} (8.84%), β-D-cellobiosidase (3.03%), β-glucosaminidase (2.88%), shoot mass (1.88%), PO_4^{3-} (1.67%), soil aggregation (1.63%), litter decomposition (1.56%), NO_3^- (0.62%) contributed in this order to multifunctionality (R^2 = 91.53%, Figure 3).

4 | DISCUSSION

As hypothesized, microplastic fibres and drought affected ecosystem functions linked with soil aggregation, nutrient cycling and decomposition as well as ecosystem multifunctionality. Overall, drought had a negative impact on ecosystem functions, while the impact of microplastic fibres depended on the soil water status and the function considered. Below, we discuss likely mechanisms behind these complex outcomes.

4.1 | Soil aggregation increased with microplastic fibres irrespective of drought

Microplastic fibres promoted soil aggregation either under well-watered or drought conditions, likely due to positive effects of fibres on soil bulk density, aeration and water retention (de Souza Machado et al., 2019), which may promote root growth (Lozano & Rillig, 2020) and hyphal extension (Elliot & Coleman, 1988; Wang et al., 2017). Therefore, roots, hyphae and microplastic fibres might together have helped entangle soil particles, promoting soil aggregation. In addition, microplastic fibres are generally hydrophobic (Prorokova et al., 2012), a property that is positively correlated with soil aggregation (Zheng et al., 2016). As soil aggregation may help hold water, thus enhancing soil microbial activity, the provision of extracellular compounds that help to bind soil particles could have been promoted (Bronick & Lal, 2005), which in turn may also have contributed to the observed soil aggregation response.

4.2 | Microplastic fibres reduce soil enzyme activity and soil respiration only under well-watered conditions

We observed that microplastic fibres affected potential enzymatic activities and soil respiration depending on soil water conditions. That is, under drought, enzymes and soil respiration increased when microplastic fibres were added, probably because soil water content and aeration (Rillig, Lehmann, de Souza Machado, et al., 2019; Rillig, Lehmann, Ryo, et al., 2019; de Souza Machado et al., 2019), increase with microplastic fibres which in turn may promote microbial activity (Alster et al., 2013; Nannipieri et al., 2002; Sanaullah et al., 2011). By contrast, under well-watered conditions, enzymes and soil respiration decreased with microplastic fibres in the soil, probably linked with a decline in soil microbial community richness and diversity as seen by Fei et al. (2020). Changes in soil porosity and soil water content with microplastic fibres may alter the flow of oxygen in the soil, with consequences on the relative distribution of anaerobic and aerobic microorganisms (Rubol et al., 2013). Alterations in pore space may also lead to their habitat loss. Likewise, as microplastic fibres may potentially release harmful contaminants into the soil in the form of additives (Kim et al., 2020) or organic pollutants associated with fibre manufacturing (Hermabessiere et al., 2017), specific microorganisms could have been affected by these new environmental conditions (Rillig, de Souza Machado, et al., 2019).

4.3 | Microplastic fibres increase litter decomposition only under well-watered conditions

Litter decomposition increased under well-watered conditions when microplastic fibres were added. Our results suggest that the increase in litter decomposition may be related to an increase in soil aggregation. Soil aggregation promotes oxygen diffusion within larger soil pores and regulates water flow, which in turn stimulate microbial activity (Six et al., 2004) promoting litter decomposition. In addition, soil pH, a parameter influenced by soil aggregation (Jiang et al., 2013), that affects soil microbial community structure (Fierer & Jackson, 2006) could also have played a role. In fact, recent research found that an increase in litter decomposition was linked with better soil aggregation (Yang et al., 2019). By contrast, the combined effect of drought and microplastic in soil decreased litter decomposition, which can be related to a decrease in microbial activity as water becomes limiting (Six et al., 2004). Our results suggest that microplastics in interaction with drought may have large consequences for ecosystem C stocks and fluxes, as changes in litter decomposition may influence the feedback to the atmosphere from terrestrial ecosystems.

4.4 | Microplastics fibres reduce soil nutrient leaching

Nutrient leaching, after a simulated rain event, increased under drought but decreased when microplastic fibres were added to the soil. Drought conditions might have led to the formation of cracks as preferential flow paths in the soil, increasing the leaching of nutrients when the soils were rewetted. In support of this, in fertilized soils, the leachate NO_3^- was threefold higher under drought than under non-drought conditions (Klaus et al., 2020). Nutrient leaching is also known to be related to change in the structure of plant and microbial communities (Mueller et al., 2013), biotic factors that are indeed affected by drought (Fitzpatrick et al., 2018; Lozano, et al., 2020). Likewise, we observed that leachate PO_4^{3-} was not affected by drought, most likely because phosphates are more strongly bound to soil particles than nitrate or sulphate (Paul & Clark, 1989). By contrast, nutrient leaching decreased with microplastic fibres (i.e. more nutrient retention). This can be related to the positive effect that microplastic fibres had on soil aggregation, which may have increased the soil capacity to retain nutrients. This positive relation between soil nutrients retention and soil aggregation has been reported by Liu et al. (2019).

4.5 | Microplastic fibres and drought effects on ecosystem multifunctionality and ecosystem services

Our results showed that microplastic fibres and drought impacted not only single functions but also multifunctionality, and that such impact depended on the interaction between these two global change factors. Specifically, with the addition of microplastic fibres, ecosystem multifunctionality decreased under well-watered conditions, while it was maintained at similar levels under drought conditions. This trend mirrors the one observed for nutrient cycling functions (i.e. β-glucosidase, soil respiration), as they are the ones that contribute most to multifunctionality. This highlights the importance of considering nutrient cycling functions when managing microplastics in soils. Drought and microplastic fibres under well-watered conditions had similar negative effects on ecosystem multifunctionality, suggesting that microplastics in soils may negatively impact ecosystem functionality as much as drought.

Microplastic effects on ecosystem functions and multifunctionality can be related with their shape (Lozano, Lehnert, et al., 2021; Rillig, Ryo, Lehmann, et al., 2019) and very likely with the leaching of additives to the soil matrix. Indeed, recent research showed that microplastic fibres of polyacrylicnitrile may cause toxicity in the soil inducing negative effects on soil biota due to their extractable additives (Kim et al., 2020). Polyester fibres contain different water soluble hazardous additives (Table S1), which can potentially be released into the soil, affecting soil biota communities and therefore ecosystem functionality.

Our results showed that two global change factors (i.e. microplastics and drought) influence ecosystem functions and multifunctionality, which in turn may affect ecosystem services (Díaz et al., 2018; Manning et al., 2018) and thus impact various aspects of human well-being. In the short term, microplastic fibres may contribute to plant productivity or soil aggregation; however, we do not currently know what the long-term responses will be, as additional factors could come into play. Indeed, microplastic fibres may release harmful chemical substances into the soil (Fred-Ahmadu et al., 2020) and affect nutrient cycling processes, with consequences for soil quality, and thus on the provision of different services, such as food and water (MEA, 2005). This becomes relevant as agricultural lands are often managed with sewage sludge or compost, which contains a large amount of microplastic fibres (Wang et al., 2019; Weithmann et al., 2018). Indeed, it has been estimated that between 125 and 850 tons of microplastics per million inhabitants are added annually to European agricultural soils through the application of sewage sludge (Nizzetto et al., 2016), whose concentrations in the soil can range from 1,500 to 56,400 particles/kg (Zhu et al., 2019). Few studies describe the degree of microplastic pollution in terms of mass concentration (weight of microplastic per kilogram of soil) (Xu et al., 2020; Zhu et al., 2019), which would allow the comparison with other microplastic types and in different soil environments. Nonetheless, microplastics in soil can be found in a wide range of concentrations including the one we used in the study. For example, in floodplain and agricultural soils, both low (~0.0055%–0.00129%) and medium (0.022%–0.03%) levels of microplastics concentration have been reported (Scheurer & Bigalke, 2018; Xu et al., 2020; Zhu et al., 2019), while high levels of microplastic concentration (~7%) can be found in industrial soils (Fuller & Gautam, 2016). Likewise, it is not necessarily the current levels of microplastic contamination that we should be most concerned about, but future levels—just like is the case for other factors of global change. Our results showed that relatively high levels of microplastic concentration in soil (i.e. 0.4%), as may occur in the future more widely if plastic use is not curtailed, may affect different soil ecosystem functions and multifunctionality.

As soils are increasingly polluted with microplastics worldwide, it is becoming more necessary to understand how the properties of this material (including shape and polymer type) interact with other global change factors such as drought. This experiment conducted in microcosms suggests that microplastic fibres in soil may cause effects on ecosystem multifunctionality of a size comparable to drought. Further research under field conditions has to be performed in order to test the applicability of these results. Our findings also highlight the potential of microplastic to affect Earth system feedbacks of terrestrial ecosystems, especially via observed changes in litter decomposition, respiration fluxes and soil aggregation.

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AUTHORS' CONTRIBUTIONS

Y.M.L., C.A.A.-T., G.O. and M.C.R. conceived the ideas and designed methodology; Y.M.L., C.A.A.-T., G.O. and S.M. established and maintained the experiment in the greenhouse; T.Z. analysed the soil enzymatic activities; Y.M.L. analysed the data and wrote the first draft of this manuscript. All authors contributed to the final version and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.nvx0k6drc (Lozano, Aguilar-Trigueros, et al., 2021).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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