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Interactions Between Microplastic Exposure and Heat Stress in Soil Invertebrates

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Abstract- Microplastic contamination and rising environmental temperatures are two of the most pressing pressures on the Earth ecosystem and may have serious effects on the soil-dwelling invertebrates. Although the biological effects of microplastics and heat stress have been studied on their own, the combined impacts in soil animals and environment are not well understood. In this paper we provide a critical narrative review of the potential interactions between microplastic exposure and heat stress in soil invertebrates and examine biological effects, ecological effects and research challenges related to the combination of the two environmental stressors. It considers published studies on oxidative stress, feeding behaviour, energy utilization, growth, reproduction, survival and physiological responses of earthworms, springtails, mites and nematodes. We also study how microplastic features, including particle size, shape, polymer composition and concentration, may affect biological responses at higher temperatures. The review also explores the potential effects of combined exposure on decomposition, nutrient cycling, soil structure and soil fauna and microorganisms. It notes that the effects of combined exposure may be additive, synergistic, antagonistic or negligible depending on the organism, exposure conditions and environment. Thus, the effects of microplastic exposure and heat stress should not be expected to be more than the effects of individual stressors in every case. By combining the findings from previous literature, in this paper we have highlighted some of the major knowledge gaps in the field of realistic exposure conditions, long-term ecological response and the mechanisms of combined-stressor effects. We stress that we need to include multiple environmental pressures in soil ecotoxicology and that we need to develop evidence-based approaches to maintain soil biodiversity and ecosystem functioning under changing climatic conditions.

Keywords- Microplastics; heat stress; soil invertebrates; combined environmental stressors; soil ecotoxicology; climate change; soil ecosystem functioning; oxidative stress.

I. INTRODUCTION

Soil ecosystems are one of the most biologically diverse and functionally important components of the terrestrial environment. They support a wide range of organisms that regulate decomposition, nutrient cycling, soil aggregation, organic matter transformation and soil fertility. In fact, soil invertebrates - earthworms, springtails, mites and nematodes - are important to maintain ecological processes and supporting soil microorganisms, plants and the environment. Their actions impact soil biology, nutrient supply, and energy transport in terrestrial food webs. But soil ecosystems are being affected in different ways due to multiple anthropogenic factors such as plastic contamination, changing temperature, agricultural intensification and land use change. Determining how these pressures impact soil organisms is important for determining the long-term resilience of terrestrial ecosystems.

Microplastics are among the most widely accepted environmental contaminants and are widely accepted as such because of their abundance, persistence and possibly biological effects. Microplastics are plastic particles smaller than 5 mm in size, shape, polymer composition and chemical properties. They enter the earth through the degradation of larger plastic materials, agricultural plastic films, sewage sludge application, wastewater irrigation, compost, and atmospheric deposition. Once they enter soil, they can remain long term and undergo physical and chemical changes and interact with soil minerals, organic matter, microorganisms and soil life. They may be affected by particle properties, soil texture, moisture, temperature, and the presence of other contaminants

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in the soil. Microplastic pollution is thus not only a contamination problem but also a potential cause of physical and chemical disturbance of the soil ecosystem.

Soil invertebrates are particularly relevant to the ecological assessment of microplastic contamination because they can encounter plastic particles through ingestion, contact with contaminated soil and/or exposure to affected food resources. Exposure to food can affect the animal's feeding behaviour, energy use, growth, reproduction and survival. Ingested particles may also affect digestive system processing or feeding efficiency and chemical additives and adsorbed particles can introduce other pathways of exposure. This is not the case for all organisms or microplastic types. The size, shape, polymer composition, concentration, exposure duration and the physical and chemical properties of soil can affect biological responses. The ecological importance of microplastics would therefore be examined in terms of organism-specific characteristics and environmental conditions in the context of exposure.

At the same time, rising environmental temperatures have become an important issue for soil biodiversity in the current climate change context. Soil temperature affects metabolism, development, reproduction, feeding and water balance for soil-dwelling organisms. While most invertebrates can tolerate temperatures above their optimal value, increased temperatures will increase the maintenance cost, energy cost and reduce biological performance. Higher temperatures may also affect soil moisture with more evaporation and may add to physiological stress for organisms that depend on moist microhabitats. Also, temperature affects microbial activity and organic matter decomposition and changes food availability and the environmental conditions for the soil organisms. The ecological impact of heat stress, then, goes beyond physiological response and can also relate to changes in the interactions that sustain soil ecosystem functioning. A major issue in soil ecotoxicology is that organisms in natural environments rarely encounter individual stressors in isolation. Microplastic contamination and high temperatures in the environment can occur at the same time, so that the biological response to one stressor can be affected by the other. For instance, temperature-driven changes in metabolism of organisms could affect energy requirements and sensitivity to microplastic exposure. Microplastic particles have the ability to alter soil structure, moisture retention and organic matter distribution, and thus the microhabitats in which soil invertebrates experience thermal stress. Such pathways are likely to explain the interactions between the two stressors, but their direction and importance will probably depend on particle properties, soil conditions, species tolerance and exposure intensity. It is therefore crucial to distinguish between the findings of established methods from those of the proposed mechanisms so that combined exposure does not necessarily lead to more severe biological effects. The types of combined-stressor effects are especially important in understanding ecological risk. When two stressors act simultaneously, their combined effect is additive (the combined effect has a general effect with respect to the expected contribution of each stressor); synergistic (the combined effect is significantly more than expected under the appropriate reference model); or antagonistic (the combined effect is weaker than expected). In some situations one stressor might not have much additional impact, or the response may depend on the sequence and duration of exposure. These are important factors for interpreting experimental findings. A study demonstrating harmful effects of microplastics under ordinary temperature conditions cannot establish the effects of the same particles during heat stress. In the same way, evidence for temperature-related changes in soil invertebrates does not imply that microplastics amplify such changes. Therefore, a meaningful assessment of combined exposure must take into account evidence of both individual and simultaneous stressors.

The effects of these interactions could extend beyond individual organisms to the functioning of terrestrial ecosystems. Earthworms contribute to soil mixing, aggregate formation, organic matter incorporation and water flow through channels. Springtails and mites play a role in detrital food webs and control microbial communities, while nematodes have different trophic positions and occupy unique roles in nutrient mineralization and microbial interaction. If microplastic exposure and heat stress affect the abundance or behaviour of these organisms, the effects of such

stress on their decomposition, nutrient availability, soil structure, and interaction with soil fauna and microorganisms may be significant for the ecosystem. Such effects are ecologically important because soil processes are based on many species' actions, not a single species. But organism-level responses should not be taken as direct evidence of ecosystem-wide disruption unless corresponding ecological consequences have been demonstrated. Although the issue of microplastic pollution and climate-related stress has increased, many questions remain about their impacts on soil invertebrates. The plastic materials examined in the present research might be different; particle sizes, exposure concentrations, temperature treatments, experimental durations, and biological endpoints measured might be different. Laboratory experiments do provide important mechanistic information, but these findings may not reflect the reality of the nature of soils in which moisture, organic matter, microbial communities, and temperature can impact exposure. Furthermore, sensitivity may differ between species and functional groups, and one model organism's results may not be generalizable to all soil communities. The review of the published evidence is essential to determine the mechanisms of combined exposure, the patterns of exposure, and the limits of the knowledge.

We therefore consider the interactions between microplastic and heat stress as a problem in soil invertebrates in a critical narrative review of existing literature. Our focus is on the biological effects of microplastic exposure and high temperatures first and how these two stressors can interact, with particular attention given to the physiological responses (feeding and reproductive performance, survival, and differences among the major groups of soil invertebrates). We look at the possible contribution of combined exposure to decomposition, nutrient cycling, soil structure, and ecosystem functioning, as well as the methodological limitations and future research directions. Based on evidence on individual and combined environmental stressors, this research review will help to build a more holistic picture of the multiple-stressor effects of soil ecotoxicology and how to protect soil biodiversity under environmental stress at the same time as plastic pollution and climate change.

II. REVIEW APPROACH AND CONCEPTUAL FRAMEWORK

The literature review in this paper is based on a critical narrative literature review for the interplay of microplastic exposure with heat stress in soil invertebrates. This is an appropriate tool for integrating existing research and knowledge from different organisms and environments and identifying the mechanisms by which many stressors may impact soil biodiversity. We draw on published experimental and observational evidence and scholarly studies about terrestrial microplastic contamination, temperature-related physiological stress, soil invertebrate ecology, and ecosystem functioning in this review and the need for a more conceptual understanding rather than more empirical observations or quantitative estimates.

As such, the review is organized in three interconnected dimensions. The first is the biological impact of microplastics and elevated temperatures on the body itself (feeding behaviour, growth, reproduction, survival, metabolism, etc.). The second is the interaction between these stressors and how microplastic properties and environmental conditions can impact the biological response to elevated temperatures and other factors. The third is the ecological impact of these interactions on soil structure, decomposition, nutrient cycling, microbial life in the soil ecosystem, and plant biodiversity. This is why we are able to integrate organism-level responses with terrestrial ecological consequences. One of the main parameters that can influence biological exposure is microplastics: the size, shape, polymer composition, concentration, surface properties, and chemical content. Also, environmental conditions such as soil texture, moisture content, organic matter, and temperature are important because they affect particle distribution, organismal exposure, and physiological response. Heat stress is also related to the thermal conditions of soil invertebrates such as exposure intensity, duration, temperature changes, and the possibility of soil moisture change in the same time interval. These are important because the overall effects of combined exposure may be quite different from the experimental environment to the environment in which the experiment is performed.

One major point of this framework is the difference between individual stressors and combined stressors. Microplastics can inflict physical or chemical effects, while high temperature can result in higher metabolism, water metabolism, and biological functioning. Therefore, the fact that we have two stressors in the environment does not mean that the two creating stronger-than-additive toxicity. We investigate whether there is indeed an interaction between the stressors or merely a hint at an interaction calling for deeper studies.

The article also differentiates between the direct biological effects and the broader ecological effects. When something happens to the survival, feeding, growing, and reproducing of the organisms, this is an organism-level effect, whereas when something happens to decomposition, nutrient cycling, and soil structure, this ecological effect involves the interaction of many organisms and is dependent on the environment. Thus, a certain effect would not be able to prove the presence of the other. It reviews and synthesizes published research to identify areas of agreement and uncertainty and develops a conceptual framework for understanding the relationship between microplastic contamination and thermal stress in soil ecosystems. Based on this, the paper is designed to understand the potential effects of a multitude of environmental pressures on soil invertebrates and why cumulative exposure should be a more salient issue in terrestrial ecotoxicology. As well as integrating biological factors with ecosystem-level effects, the review has been used to assess research gaps and determine the importance of soil biodiversity protection in changing climate scenarios.

III. BIOLOGICAL EFFECTS OF MICROPLASTICS AND HEAT STRESS

According to the argument presented, both microplastic interaction and elevated temperature may pose issues for soil invertebrates through one or several biological mechanisms. The presence of microplastics may lead to physical disturbance, increase feeding conditions and the level of contact with other substances, while high temperatures have an impact on metabolism, water balance, growth, and energetic implications. The biological impact produced will depend not only on the source of stress but also on the organism and the location of exposure. Each of these effects is essential for evaluating whether simultaneous exposure leads to the presence of effects that differ from the impact caused by either stress.

The microplastics can enter the soil through the breakdown of plastics, agriculture, wastewater irrigation, sewage sludge application, composting, and atmospheric deposition. When they reach the soil, particles can be consumed either by invertebrates or directly interact with contaminated soil. Worms, for example, are especially important since their food consumption and burrowing allow them to ingest the elements from the soil. Other species, though, such as springtails and mites, will contact the soil organic matter and microorganisms, while nematodes will live in water films and pores.

Microplastics impact organisms based on characteristics such as their size, type, polymer composition, concentration, and time of exposure. Under the right conditions, exposure can affect organisms' feeding and digestion processes, and thereby their energy and body condition. Sharp or irregular particles might have different impacts from smooth particles, but this depends on the type of plastic and species exposed. Microplastics likewise contain some chemicals or contaminants on their surface, which creates additional pathways for exposure. Still, this does not necessarily mean that they become biologically significant. The effects depend on the nature of the substance, environmental conditions, and the type of exposed organism.

Effects on feeding and energy budgeting are important, as invertebrates in the soil need to ensure the functioning of multiple physiological processes of development and reproduction. If microplastic exposure leads to reduced feeding efficiency, or other changes, the organism might have fewer resources for its growth. Changes in the digestive functioning may also lead to physiological stress. Nevertheless, the outcomes of tests done with high levels of microplastics and/or specific kinds of particles must be treated with care, since the data obtained may not correspond to the real-life soil condition.

Oxidative stress represents an alternate mechanism through which microplastics can influence soil invertebrates. In fact, reactive oxygen species might be produced in quantities that exceed the antioxidant system's capability to control the oxygen radicals, causing damages to the cell's structures. Nonetheless, it should be noted that these oxidative stress-associated effects do not affect all species equally, so changes in antioxidant systems cannot be regarded as evidence of irreversible damage of a species or decline in its population. The consequences of heat stress on soil invertebrates vary. Since the majority of soil invertebrates are ectothermic organisms, their body temperature and metabolic processes are largely affected by environmental factors. It is known that, when temperatures remain within certain ranges, their increases usually speed metabolic and development processes. The response varies depending on the species, its thermal background, its acclimation potential, and temperature exposure duration and intensity. High temperature is not always bad; it depends on whether the temperature conditions are tolerable for the organism, Water balance is one of the key factors regarding thermic stress in soil. Higher temperatures may increase evaporation and change the moisture distribution in the soil, which will make it less possible to find suitable microhabitats. This is especially vital for the organisms that depend on wet soil for movement or respiration/physiological functioning. For instance, worms are sensitive to soil moisture, and some small invertebrates need water films and moist places in soil pores. Therefore, drying caused by heat will provide additional challenges, but the degree of effect will depend on soil texture, organic matter, vegetation cover, and refuge presence in the soil.

Temperature affects growth, reproduction and development, and if the environment is not favorable, feeding rates may decrease or delay development, reproductive yield may be reduced, and mortality might increase. The effects of temperature change in invertebrates are different because of the thermal tolerances of the species and their life histories. Some invertebrates may temporarily overcome this (behavioral or physiological) change, whereas others are more sensitive to long-term exposure. The short-term results in laboratory experiments on the effects of temperature change may not be representative of long-term responses to repeated heat or long-term changes in temperature in nature. At last, heat stress can affect the soil in which invertebrates are found in general. Temperature affects microbial activity, organic matter decomposition, nutrient changes, and soil moisture. In some cases, these changes will change food availability and the environment that the soil fauna live in. For instance, microbial activity may change the food resources available to organisms that feed on microorganisms and/or microbially conditioned organic matter. These pathways can be used to study the effects of exposure in the combined exposure to the stressors but must be demonstrated based on evidence rather than a single stressor effect alone. And the biological interactions of microplastics and heat stress are what will help in understanding their interactions. Microplastic exposure can affect feeding, health and energy supply and metabolism while high temperatures can impact metabolism and water balance and thermal activity. Together with these pressures, they may affect some of the same biological processes and/or change the environment where the exposure takes place. But individual stressors alone are not enough to determine if combined exposure is additive, synergistic or antagonistic. There are so many pressures on soil invertebrates and they are responsible for a multitude of life systems on earth, and we need to understand the interactions between these environmental pressures and how they affect both sides of the biological processes and their ecological function.

IV. INTERACTIONS BETWEEN MICROPLASTICS AND HEAT STRESS

The simultaneous exposure to microplastic contamination and high temperature poses a challenge for terrestrial ecotoxicology because organisms in natural soils are subject to a wide range of environmental stressors with different levels of individual stressors. The biological impacts of microplastics and heat stress can be evaluated separately but their combined effect may be influenced by the interaction between the physiological processes that affect particles, particle properties, and environmental conditions. Soil invertebrates may respond differently to their

simultaneous exposure to both stressors than to one stressor or the other. We need to know about these interactions to assess environmental risks in changing climatic conditions, especially when plastic contamination is happening at a time of more frequent or intense heat events.

One of the basic issues is that combined-stressor effects can be different. Additive effects are the ones when the combined response is in line with the expected contribution from the individual stressors in a reference model. Synergistic effects are when the combined response is larger than expected, and antagonistic effects are when the combined response is weaker than expected. In other situations, one stressor may have little effect on the other, or the outcome will depend on the exposure conditions and biological endpoint considered. These differences are important because microplastics and high temperatures are not the same and the toxicity is not necessarily increased with them. Instead, the interaction should be evaluated in relation to the organism, the type of plastic, temperature, and exposure conditions.

One path in this direction is to change energy allocations. Soil invertebrates need energy to perform basic physiological functions, grow, reproduce, and respond to environmental stress. Under certain circumstances, microplastic exposure may affect feeding efficiency or resource acquisition, and high temperatures may increase metabolic demands when organisms have a higher temperature than they are at thermal optimum. If both effects occur at the same time, organisms will face competition for limited energy resources. If the exposure to microplastics is long or food resources are limited, there can be a reduction in energy available for growth or reproduction. However, this pathway is a mechanistic hypothesis without direct evidence for the specific species and the exposure conditions we are discussing. The outcome can be affected by thermal acclimation, compensatory feeding, and differences in metabolic requirements.

Oxidative stress is another possible link between the two stressors. Some microplastic exposure has been linked to changes in antioxidant responses and cellular stress, while unfavourable temperatures could affect how reactive oxygen species are versus antioxidant defences. If the two stressors affect the same processes at the same time, their interaction would intensify physiological stress in susceptible organisms. Conversely, if stress response pathways change or different mechanisms are activated for each stressor, the combined effect could be weaker than expected. It is important to differentiate evidence of oxidative responses under one exposure from evidence of an interaction for the two stressors under simultaneous exposure. Measurements of antioxidant activity too may be insufficient to establish severe biological damage without physiological or ecological consequences.

The physical characteristics of soils also provide another mechanism through which temperature and microplastic contamination could affect soil structure and water properties. Microplastic particles can affect soil structure and water properties but the direction and magnitude of these effects are dependent on the shape, concentration of particles, polymer type, soil texture and organic matter content. Higher temperatures may lead to evaporation and soil moisture changes and the movement and distribution of particles in soil and how they are transported, distributed and accessible. This may impact the frequency with which invertebrates encounter microplastics or when they are exposed to them. Such effects cannot be generalized for different soil types (for example, sandy, clay-rich soils and organic soils). Soil moisture is particularly important to earthworms and other organisms that live in humid microhabitats. Drying can reduce the availability of suitable living conditions and increase stress at high temperatures. If microplastic contamination also changes pore structure, aggregation and/or water retention processes, the response of organisms might also determine the ability to maintain water balance or to avoid the most difficult situations. But the direction of these interactions is context-dependent. Microplastic particles do not necessarily reduce soil moisture or habitat suitability and their physical effects depend strongly on the type of material and the soil. The interaction may be more varied among soil invertebrate groups. Earthworms are exposed to particles by ingesting and interacting with soil as they

burrow and feed. Springtails and mites live in a wide array of microhabitats and they could encounter particles by interacting with organic matter and microbial sources. Nematodes live in water films or in soil pores so that they are most effectively exposed to moisture. The thermal tolerance of the species, feeding strategies, life stage and behavioral avoidance may all play a role. Another important aspect of microplastics is the characteristics of the microplastics themselves. The size, shape, polymer composition, concentration, weathering processes, and chemical composition, as well as the release of microplastics and associated compounds, can change biological responses. Heat can affect the environmental behavior of some plastics or the release and availability of the relevant chemical substances if conditions are favorable to a certain level of heat, but that depends on the polymer, temperature range, exposure time, and soil chemistry. Higher temperatures can make any chemical in microplastics more toxic, and it is not a good idea to assume that high temperatures increase the release of the chemical element from the polymer and all microplastics. Research on these pathways in an environmentally sensitive situation is needed to clarify their importance to soil invertebrates.

The exposure duration and temperature variability also complicate the relationship between microplastics and heat stress. Short temperature increases may produce responses that differ from those associated with long-term warming or repeated heatwaves. Similarly, exposure to high microplastic concentrations in the small world may not be a good measure of the effects of chronic exposure at low environmental concentrations. Some organisms may acclimate to some of the conditions while others are chronically stressed, and some responses are delayed and are not immediately visible. Studies that account for exposure duration, life stage, recovery time, and realistic fluctuations in temperature would provide a better understanding of the combined-stressor effects. The combination of microplastic exposure and heat stress is likely to be a context-dependent ecological process rather than a general phenomenon of increased toxicity. The two stressors may have overlapping physiological pathways, impact soil conditions, and change the biological significance of exposure. However, the specific effects and direction of their effects are complex and dependent on organism-specific characteristics and environmental conditions. The relationship between these two stressors must be evaluated to differentiate established findings from plausible mechanisms and to determine the circumstances under which combined exposure could threaten soil invertebrate populations.

V. CONSEQUENCES FOR SOIL ECOSYSTEMS

The effects of microplastic exposure and heat stress may be more than just for the individual soil invertebrates. Soil ecosystems are interrelated to the biological processes of invertebrates, microorganisms, plants and the physical environment and are dependent on them all. Earthworms, springtails, mites and nematodes decompose organic matter, convert nutrients into soil, create soils and control microbial communities. If the combination of environmental stressors affect the abundance, behaviour and function of individual organisms in a given ecosystem, the effects of such stressors will be visible and potentially also affect ecosystem processes that contribute to soil fertility, plant growth and terrestrial productivity. In reality, the degree to which individual impacts can translate to ecosystem disruption and the scale of the impact on ecosystem function will depend on the role of the affected species and how other organisms can also respond.

One important effect is soil structure and physical function. Earthworms are responsible for soil mixing, organic matter incorporation, aggregate formation and burrows and can influence aeration and water movement. Their burrowing and feeding can have an impact on the distribution of nutrients for other organisms and create habitats. Microplastic contamination can change some soil physical properties and heat stress may affect earthworm activity by affecting their body temperature and soil moisture. If both pressures are to prevent burrowing or feeding some soil functions could be inhibited. But such effects cannot be ruled out from the lack of survival or from changes in behaviour. The size and extent of the consequences depends on the species involved, the time of exposure, the soil characteristics

and the extent to which other soil organisms perform the same.

Decomposition and nutrient cycling are also important areas through which combined stressors may affect soil systems. Soil invertebrates break up organic material, redistribute decomposing residues and interact with microorganisms that break down food. Springtails and mites, for instance, contribute to detrital food webs and may influence microbial activity via grazing and the processing of organic matter. Nematodes occupy multiple trophic levels and have a role in interactions among microorganisms and other organisms in soil. Microplastic exposure can affect feeding or the biological status of these invertebrate species and higher temperatures may affect metabolic demands, moisture availability and microbial activities. The combined influence of these changes could affect the rate and pattern of organic matter decomposition. In fact, the direction of the outcome may vary because temperature can stimulate some decomposition processes within a suitable range while at the same time creating stressful conditions for sensitive organisms.

The relationship between soil fauna and microorganisms is particularly important in this context. Microorganisms are critical to nutrient mineralization and the transition of organic matter, soil invertebrates feed off the microbial communities through grazing, physical disturbance and redistribution of organic matter. Microplastics may change microbial habitats or change the distribution of organic material in some conditions. The microbial activity and community composition can also be influenced by temperature changes and therefore the resources available to soil invertebrates. These processes can have indirect consequences in the way that cumulative exposure affects ecosystem functioning. For example, changes in microbial food resources could affect organisms that depend on microbial biomass, while changes in invertebrate activity could alter microbial regulation and thus also the microbial ecology. But the nature of these interactions is complex and their direction is also based on soil, moisture, microbial composition, and plastic particles.

Loss of soil invertebrate communities and ecosystem processes may also lead to a change in plant and soil relationships. Soil organisms provide nutrients for plant growth and structure can affect root penetration, water movement and aeration. If microplastic contamination and heat stress are combined with soil processes, changes in nutrient cycling or soil physical characteristics could affect the conditions experienced by plants at higher temperatures. Also, higher temperatures will increase plant water requirements and soil moisture, which may increase the ecological significance of changes in soil functions. However, the relationship between exposure and plant performance should be considered cautiously due to many interacting factors - nutrient availability, moisture, soil chemistry and microbial associations.

Another potential consequence for soil food web structure and ecological resilience can be the soil food-web structure and resilience. Soil populations are composed of organisms with different feeding strategies, thermal tolerance and predisposition to contaminants. If we see that the combination of exposure to different functional groups impacts on the same functional groups rather than only two or three groups, the balance of ecological interactions may be affected. If some of the detritivores, or microbial grazers are reduced, for example, we would observe that resource processing and relationships between microorganisms and higher trophic levels may be affected by reduced populations and the relationships between such organisms. Other species may not be able to cope with the same conditions or do not have to compete for some ecological purposes. So the same situation might not mean that changes in individual populations do not necessarily translate into a diminution in overall ecosystem performance. Therefore in order to assess resilience, community composition, functional diversity and how well ecological processes can persist under environmental disturbance are important.

The ecological significance of the exposure to microplastics and heat stress in combination also depends on whether they are lasting. On the one hand, short-term studies may have observed immediate changes in feeding, physiological stress or survival but long-term effects might include altered

reproduction, population recruitment, community structure and ecosystem recovery. Repeated heat exposure can result in different responses from constant temperature treatment; long-term exposure to microplastics would differ from short-term exposure to higher concentrations. Natural soils also have spatially different microhabitats that can act as shelter from environmental stress and laboratory evidence must be considered along with experimental circumstances and the complexity of natural ecosystems. All these potential consequences for soil ecosystems show why interactions between microplastics and heat stress should be considered not only as individual toxicity issues but also as environmental stressors. The physiology or behaviour of invertebrates may affect soil structure, decomposition, nutrient cycling, microbial relationships, and plant/soil interaction. However, these broader effects are dependent on the biological effects, the ecological functions of such organisms, and the capacity of soil communities to cope with them. Discerning ecosystem-level effects and possible indirect effects is crucial to a scientifically valid understanding of the impact of these environmental stressors on soil health.

VI. RESEARCH GAPS AND FUTURE DIRECTIONS

Although microplastic contamination and climate-related stress are increasingly recognized in the literature, the combined effects of these pressures on soil invertebrates are still poorly understood in terms of species, soil types and environment. Recent studies have provided important insights into the individual effects of microplastics and temperature and there is little evidence of the impact of both of them in combination and these effects are difficult to compare because the experimental design, exposure and biological endpoints are different. In order to determine whether the combined effect is additive, synergistic, antagonistic or negligible, these effects of microplastics and high temperatures must be considered in the context of a realistic environment.

A major research gap exists because soil invertebrate diversity is not well represented. Earthworms have received a lot of attention in soil ecotoxicology but other species in the soil as well such as springtails, mites and nematodes may respond differently because of body size, feeding strategies, habitat use and heat tolerance. Even within a single group, different species of closely related organisms may be sensitive to microplastics and heat stress. Further research should therefore cover a wider range of soil organisms and consider differences between species, life stages and functional groups. This would help us to see if the effects seen in specific model organisms can be generalized to more general soil communities.

In second place we need to use environmentally realistic exposure conditions. In laboratory experiments we can use controlled temperature and microplastic concentrations to identify biological responses. While these approaches are useful and may help us to identify mechanisms, these conditions might not be the same as in the natural soil in which plastic particles are scattered and the temperature and humidity vary over time. In the future it would be important to consider the environment, realistic particles, weathered plastic and variations in soil texture and organic matter. In addition the soil moisture must be considered because the drying temperature could also affect the physiological state of an invertebrate and the environmental conditions in which it is exposed to microplastics.

The mechanisms of combined stressors are still to be studied in detail. Possible pathways include energy allocation, oxidative stress, feeding efficiency, water balance, and physiological tolerance. However, these mechanisms should not be assumed to work as well in different organisms and exposure conditions. Future investigations should distinguish between direct and indirect interactions in the physiological environment as well as in the soil, microbial communities and food availability. Tracking biological endpoints would help to determine whether biochemical indicators at different levels of life are associated with meaningful consequences for growth, reproduction, survival and population performance.

Another important gap is the temporal one of combined exposure. While short-term experiments might reveal immediate responses, they do not necessarily establish whether those responses are

stronger, weaker or diminish over time. Repeated heatwaves and long microplastic exposure may have different results from brief or constant exposure. Studies on long-term exposure, recovery periods and acclimation and effects on life stages would be important to understand long-term ecological risks. Such studies should also look to see if organisms can recover after exposure is over and whether any recovery is accompanied by restoration of normal ecological functions.

Further studies are needed to understand the effects of combined exposure at the ecosystem level. Changes in individual survival or feeding behaviour do not automatically lead to changes in decomposition, nutrient cycling, soil aggregation, or plant productivity. Future investigations should be able to link organism-level responses to functional indicators of soil ecosystem performance. Soil invertebrates, microorganisms and plants' interactions in the ecosystem would provide evidence for whether changes in one part of the soil community have a direct effect on the functioning of the whole ecosystem. This would be particularly interesting if community composition changes cause measurable loss of ecological functions or if other organisms can compensate.

The impact of microplastics on heat stress is also relevant in the context of climate change. Rising temperatures may accompany changes in rainfall patterns, the frequency of droughts, soil moisture, and agricultural management. The impact of microplastics on soil invertebrates and the impact of plastic on soil diversity and biotechnology may therefore be examined in combination with the temperature and humidity, but not under the assumption that all the external effects are additive. Comparative research from different climate regions would also provide insights into the conditions where combined exposure is the most problematic for soil biodiversity.

Finally, more methodological consistency would help to improve comparisons across published studies. The differences in plastic polymer, particle size, concentration, temperature treatment, exposure duration, and biological endpoints can make it difficult to detect general patterns. A more consistent description of these variables would help to interpret experimental results and to give more data for evidence-based environmental assessments. Critical synthesis should also distinguish studies that directly investigate simultaneous exposure from those that examine the two stressors separately because the evidence regarding individual stressors cannot be divorced from the extent of all of them.

Overall, however, future research should focus more on multifactorial assessment of microplastic toxicity or thermal stress and not on a single issue of any single field of study. The objectives should include wider taxonomic coverage, realistic exposure conditions, longer observation periods, mechanistic investigations and more interaction between organismal responses and ecosystem functioning. Although we still have some uncertainty about the direction and magnitude of such combined effects, these gaps contribute to the necessity to consider microplastic contamination in a changing climate. Better evidence is needed in soil ecotoxicology and this would help inform better policies for soil biodiversity and ecosystem resilience.

VII. CONCLUSION

Microplastic exposure and heat stress are an important emerging concern in soil ecotoxicology, especially given plastic contamination still exists in outdoor environments and climate changes. Soil invertebrates like earthworms, springtails, mites, and nematodes are essential for soil structure, decomposition, nutrient cycling, and interaction of microorganisms with plants. So exposure to different environmental stressors may have consequences beyond individual organisms and can therefore affect the ecosystem processes that maintain soil fertility and the functioning of the terrestrial ecosystem. The present review highlights several potential pathways via which microplastic exposure and high temperatures can impact soil invertebrates. Microplastics can cause feeding behaviour, energy gain, and physiological development at certain exposure conditions, and heat stress can impact metabolism, water balance, development, and reproduction. When these stressors are present at the same time, their effects can be associated with the same physiological processes in cells and soil properties. But the nature of such mutual

effects is not uniform. Combined exposure may have additive or synergistic, antagonistic, or no effect in the organism, particle shape, temperature regime, exposure time, and environmental context. And as such, the presence of multiple stressors should not be taken as evidence of increased toxicity.

The potential ecological implications are especially significant since soil invertebrates participate in the processes of ecosystem decomposition, nutrient conversion, soil aggregation, and microbial regulation in general. The abundance and function of invertebrates is likely to affect how they perform and thus the effects of these processes may be altered, but organism-level effects are not necessarily the cause of ecosystem damage. A better understanding would require research into physiological and population-level effects and changes in soil ecosystem function. There are still some knowledge gaps, such as limited evidence of a wide range of soil invertebrate groups, the lack of realistic exposure conditions, and the uncertainty about the long-term effects of repeated heat events and chronic microplastic contamination. Future work should focus on mechanistic studies, longer-term studies, standardized exposure assessments, and ecosystem response at the ecosystem level. Specific attention should be paid to soil types, moisture levels, microplastic properties, and species-specific thermal tolerances. In the end, understanding the cumulative impact of microplastic contamination and heat stress has to be integrated rather than focused on individual environmental pressures individually to understand the interaction of multiple stressors. To do so would enhance the interpretation of existing research, clarify the ecological impact of the combined exposure, and the scientific foundation for soil conservation in changing environmental conditions. While there are still key questions that need to be answered, the incorporation of plastic pollution and thermal stress in soil biodiversity research is essential to gain a wider understanding of terrestrial ecosystem resilience and the long-term sustainability of soil resources.

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