Microplastics as habitat-dependent ecological filters: facilitating plant invasion in water while reinforcing biotic resistance on land

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Research Article

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Abstract

Background and aims

Global plastic pollution and biological invasions are two defining features of the Anthropocene, yet their interactive effects across different ecosystems remain poorly understood. We investigated whether microplastics act as context-dependent ecological filters that differentially influence the performance of the invasive *Alternanthera philoxeroides* and its native congener *A. sessilis* across aquatic and terrestrial habitats.

Methods

In a fully crossed factorial experiment, both species were grown independently and exposed to three polymer types—polyethylene (PE), nylon (PA6), and biodegradable polylactic acid (PLA)—across two particle sizes (micro and macro) under both aquatic and terrestrial conditions. These treatments were applied to evaluate habitat-specific responses. Growth performance was quantified using biomass accumulation and relative effect sizes.

Results

A striking habitat-switch in growth performance patterns was uncovered. In aquatic environments, microplastics acted as an "invasion catalyst": they significantly stimulated the biomass accumulation of the invader *A. philoxeroides*—particularly under macro-PE and micro-biodegradable treatments—while suppressing the native A. sessilis, especially under nylon exposure. In sharp contrast, terrestrial soil pollution reinforced biotic resistance: microplastics generally inhibited the invader's growth while unexpectedly facilitating the native species, effectively reversing the performance hierarchy.

Conclusions

Our findings indicate that microplastics function as habitat-specific modifiers of plant growth rather than uniform environmental stressors. By differentially influencing invasive and native plant species in aquatic versus terrestrial systems, plastic pollution may alter vegetation dynamics across ecosystems. These results highlight the importance of considering habitat context and plastic characteristics when evaluating ecological impacts of microplastics in invaded environments.

Introduction

We are living in what some have called the Plastic Age (Thompson et al. 2009). Global plastic production has surged over recent decades, causing widespread environmental accumulation, most notably as microplastics (MPs)—particles smaller than 5 mm. These contaminants pervade nearly every

ecosystem, from deep-sea sediments to agricultural soils (Browne et al. 2011; Geyer et al. 2017; Jambeck et al. 2015; Thompson et al. 2004; Wright and Kelly 2017). The escalating presence of microplastics in both aquatic and terrestrial environments poses significant ecological risks (Geyer et al. 2017; Thompson et al. 2004). While microplastic impacts on animal physiology and lower trophic levels are well documented (Sussarellu et al. 2016; Wright and Kelly 2017; Zhu et al. 2021), their effects on plants remain poorly understood, despite the foundational role plants play in ecosystem functioning and primary productivity (de Souza Machado et al. 2018; Rillig et al. 2019; Zhang et al. 2019).

Plants are exposed to microplastics directly in their growth environment—whether in soil, water, or sediment. In terrestrial systems, microplastics primarily alter soil structure —changing bulk density, water retention, and aggregation —which indirectly affects root development and nutrient availability(de Souza Machado et al. 2018; Lozano et al. 2021; Rillig et al. 2019). These changes often impair seedling establishment, growth and even suppress reproductive output (Boots et al. 2019; de Souza Machado et al. 2019; Lee et al. 2025; Zhang et al. 2024b). Conversely, in aquatic habitats, plants face direct physical and chemical stressors:microplastics influence plants primarily through physical and chemical pathways: suspended particles reduce light availability for photosynthesis, cause physical damage to tissues, and may interact with biofilms to deliver adsorbed pollutants (Chaudhary et al. 2025; Kalčíková et al. 2017; Larue et al. 2021; Sun et al. 2023; Zhu et al. 2025).This dichotomy implies that terrestrial plants likely experience chronic soil-structural stress, whereas aquatic species face acute physiological disruption, suggesting that microplastic effects are strongly habitat-dependent.

To disentangle how these habitat-specific stressors interact with species traits, comparative studies of closely related invasive and native species are essential. The amphibious genus *Alternanthera* offers an ideal model system. The invasive *A. philoxeroides* (alligator weed) is globally notorious for its rapid clonal spread and high phenotypic plasticity across both aquatic and terrestrial settings (Pan et al. 2006; Wu et al. 2017). In contrast, its congener *A. sessilis* (sessile joyweed) is a native species in Asian wetlands, occupying similar riparian zones but typically exhibiting lower performance dominance (Chen et al. 2013; Wang et al. 2016). Since invasive species often possess superior resource acquisition and stress tolerance traits (Li et al. 2024a; Zhang et al. 2024a), they may respond more favorably—or be more resilient—to anthropogenic disturbances like microplastic pollution compared to their native counterparts.

In this study, we experimentally exposed *A. philoxeroides* and *A. sessilis* to varying microplastic types and sizes under both aquatic and terrestrial conditions. This full-factorial design allows us to determine whether the renowned plasticity of invasive species provides a potential competitive advantage under microplastic stress. Specifically, we address the following hypotheses: (1) The effects of microplastics on plant growth are strongly habitat-dependent; (2) The invasive *A. philoxeroides* will demonstrate higher phenotypic plasticity and stress tolerance than the native *A. sessilis*, resulting in less growth inhibition (or even compensatory growth) under microplastic exposure.; (3) Smaller microplastic particles exert stronger negative impacts on plant growth due to their distinct physicochemical properties.

Materials and Method

Study species and Propagation

Two congeneric amphibious species were used in this study: *A. philoxeroides* (Mart.) Griseb. (alligator weed) and *A. sessilis* (L.) R. Br. ex DC. (sessile joyweed). *A. philoxeroides* is a stoloniferous perennial herb native to South America that has become a globally invasive species in aquatic and riparian habitats (Pan et al. 2006). In contrast, *A. sessilis* is widespread in tropical and subtropical Asia as a native species, typically inhabiting seasonally flooded wetlands and agricultural margins (Chen et al. 2013). Both species are capable of rapid clonal propagation and tolerate fluctuating water regimes.

Source materials were collected from a rice land of Lanxi Town (30°18'15.76" N, 115°8'55.48" E, 25.6 m elevation), Xishui County, Hubei Province, China in August 2022. To minimize maternal effects and ensure genetic uniformity, clonal seedlings were propagated from stem cuttings of mature plants. Cuttings, each containing two nodes with lower leaves removed, were cultivated in big container with 0-6mm Pindstrup Peat moss (Pindstrup Mosebrug A/S) under high humidity for one weeks to promote rooting. Prior to the experiment, seedlings of similar height (approx. 10 cm) were selected for transplantation.

Experiment Design

The experiment employed a fully crossed factorial design: 2 habitats (aquatic, terrestrial) × 2 species (*A. philoxeroides*, *A. sessilis*) × 3 plastic types × 2 particle sizes (macro, micro), with 10 replicates per treatment. Additionally, a plastic-free control was established for each habitat–species combination, resulting in a total of 280 experimental units.

Substrate and Plastic Treatments

The substrate was a mixture (1:1:1 by volume) of surface soil (0–20 cm depth, yellow-brown soil collected from a local vegetable field in Huanggang Normal University, river sand, and 0-6mm Pindstrup Peat moss (Pindstrup Mosebrug A/S). The field soil was air-dried, cleared of debris, and sieved (5 mm) prior to mixing.

Three polymer types were used: polyethylene (PE), nylon (PA6), and a biodegradable plastic (PLA). Plastic particles were prepared in two size classes:

Macro-plastics (> 5 mm): PE mulch film, nylon rope, and biodegradable plastic bags were cut into strips or fragments (approx. 5–10 cm length).

Micro-plastics (< 5 mm): PE and biodegradable polymers (PLA) were ground using a cryogenic milling machine and sieved through a 5 mm mesh. Nylon microfibers were produced by cutting nylon strands to

lengths < 5 mm.

Plastics were amended into the substrate at a concentration of 1% (w/w). Control groups received no plastic addition.

Experimental Conditions

The experiment was conducted from September to November 2022 in a greenhouse at Huanggang Normal University. Plants were grown in transparent plastic containers (top radius 10 cm, bottom radius 9 cm, height 27 cm) filled with 1.5 kg of substrate.

Aquatic habitat: Maintained with a ~ 5 cm water layer above the soil surface.

Terrestrial habitat: Maintained at field capacity (moist soil) without standing water.

Watering was performed every three days. Plants were harvested after 80 days of growth. Plants were separated into aboveground (stems and leaves) and belowground (roots) fractions, carefully washed, oven-dried at 80°C for 72 h, and weighed. We calculated aboveground biomass (AG), belowground biomass (BG), total biomass (Total), and shoot-to-root ratio (SR).

Data Analysis

All statistical analyses were conducted in R version 4.3.3.

Plant Growth Response (Raw Data)

To account for non-normality and heteroscedasticity in the growth data, we fitted Generalized Linear Models (GLMs) or parametric survival models based on the best-fit error distribution for each variable (determined via AIC minimization and residual inspection):

Biomass (AG, BG): Analyzed using GLMs with a Gamma distribution (log link).

Total Biomass: Fitted using a Weibull distribution via the survreg() function in the survival package.

Shoot-to-Root Ratio (SR): Fitted using a Lognormal distribution (survreg()).

Estimated marginal means (EMMs) were calculated using the emmeans package. Pairwise comparisons for main and interactive effects were adjusted using the Tukey HSD method. For habitat-specific responses (data stratified by habitat), pairwise comparisons were conservatively adjusted using the Šidák method.

Analysis of Effect Sizes

To quantify the magnitude of plasticity and facilitate interspecific comparisons independent of baseline size differences, we calculated the Relative Effect Size (Rela): Rela = (Treatment - Control) / Control

Absolute Effect Size (Abs = Treatment − Control) was also calculated to document the specific magnitude of biomass change. However, as Abs trends largely mirrored the raw data, these results are presented in the Supplementary Material to maintain concise reporting, while Rela is used in the main text to highlight proportional responses.

Since the relative effect size data contained negative values and did not meet parametric assumptions, they were analyzed using the non-parametric Aligned Rank Transform ANOVA (ART-ANOVA) via the ARTool package. Post-hoc comparisons were performed using Dunn's test with Benjamini–Hochberg (BH) correction.

Results

Biomass Accumulation and Allocation Patterns (Raw Data)

Aboveground Biomass

Microplastic exposure significantly altered aboveground biomass, primarily driven by complex interactions among treatment, habitat, and species (Table S1; Treatment × Habitat × Species: $P < 0.05$).

In aquatic habitats, the invasive *A. philoxeroides* generally outperformed the native *A. sessilis*, accumulating significantly greater biomass under macro-PE, micro-BDP, macro-nylon and micro-nylon treatments (Fig. 1). Notably, *A. philoxeroides* exhibited a trend of increased growth under plastic exposure relative to its plastic-free control, with a significant stimulation observed in the macro-PE treatment. Conversely, the native *A. sessilis* showed limited responsiveness, except for a significant biomass reduction under micro-nylon exposure.

Group named by following meanings: A-Aquatic,T- Terrestrial, CK-control, Ma-Macro, Mi-Micro, B-biodegradable plastic, N-nylon, P-polyethylene, group labels are consistent across Figs. 1–8.

A. philoxeroides is represented by blue bars, *A. sessilis* by green bars; Bar sharing a common letter are not significantly different ($P > 0.05$). The same annotation is used in Figs. 1–8.

In terrestrial habitats, treatment effects were subdued. No significant differences were detected between the two species across most treatments, with the sole exception of the micro-PE group where *A. philoxeroides* maintained higher biomass. Neither species showed significant deviations from their respective controls (Fig. 1).

Belowground Biomass

Belowground biomass was governed largely by habitat and species identity rather than plastic treatment alone (Table S1; Habitat: $P < 0.001$; Species: $P = 0.018$).

In aquatic environments, the native *A. sessilis* tended to allocate more biomass to roots than *A. philoxeroides*, a difference that was statistically significant under micro-PE exposure. However, neither species showed significant plastic-induced changes relative to controls.

In terrestrial environments, the pattern reversed: *A. philoxeroides* developed significantly larger root systems than *A. sessilis* in the control, micro-nylon, and micro-PE treatments. Similar to aquatic findings, no plastic treatment significantly altered belowground biomass relative to controls for either species (Fig. 2).

Total Biomass

Total biomass patterns largely mirrored those of aboveground biomass, showing significant sensitivity to treatment and species (Table S1; Species: $P < 0.001$).

In aquatic habitats, *A. philoxeroides* maintained a clear growth advantage over *A. sessilis*, particularly under nylon (both sizes). Crucially, macro-PE exposure significantly stimulated total biomass production in *A. philoxeroides* relative to its control, whereas *A. sessilis* remained unaffected by any treatment.

In terrestrial habitats, interspecific differences were minimal, with *A. philoxeroides* exceeding *A. sessilis* only under micro-PE exposure. No significant plastic-induced biomass shifts were observed for either species compared to controls (Fig. 3).

Shoot-to-Root Ratio (SR)

Biomass allocation was strongly habitat- and species-dependent (Table S1; Habitat × Species: $P < 0.001$).

In aquatic habitats, *A. philoxeroides* consistently allocated more resources aboveground, maintaining a significantly higher SR than *A. sessilis* across all treatments. While *A. philoxeroides* maintained a stable SR under plastic stress, *A. sessilis* exhibited a significant shift toward root allocation (reduced SR) under micro-BDP and micro-nylon treatments.

In terrestrial habitats, the invasive *A. philoxeroides* generally displayed a lower SR than the native *A. sessilis*, with significant differences in control, macro-BDP, and micro-nylon groups. No treatments significantly altered SR relative to controls for either species (Fig. 4).

Relative Magnitude of Microplastic Effects (Effect Sizes)

Responses of Aboveground Biomass (Rela AG)

The relative impact of microplastics on aboveground growth was highly context-dependent, showing a clear divergence between species and habitats (Table S2; Species × Habitat: $P < 0.001$).

Overall, *A. philoxeroides* exhibited a "benefit-in-water, cost-on-land" strategy: it showed positive relative effect sizes (stimulation) in aquatic habitats across all plastic types but negative effects (inhibition) in terrestrial habitats (Fig. 5).

The black dashed line separates habitats, with the aquatic habitat on the left and terrestrial habitat on the right. The red dashed line denotes the zero-effect baseline; *A. philoxeroides* is represented by blue bars and points, *A. sessilis* by green bars and points. The same annotation is used in Figs. 5–8.

In contrast, *A. sessilis* displayed an opposing pattern. In aquatic habitats, it suffered growth inhibition from nylon (both sizes), though PE exerted a positive effect. In terrestrial habitats, *A. sessilis* benefited from BDP (all sizes) and macro-nylon/PE, but was inhibited by micro-sized nylon and PE.

Particle size further modulated these effects. For instance, in terrestrial *A. philoxeroides*, micro-sized BDP and nylon particles alleviated the inhibition seen with macro-sized particles (Fig. 5).

Responses of Belowground Biomass (Rela BG)

Root responses were driven primarily by habitat and plastic type (Table S2).

In aquatic settings, *A. philoxeroides* consistently exhibited positive root growth responses to all plastic treatments. *A. sessilis* also showed largely positive responses, except for an inhibitory effect from macro-nylon.

In terrestrial settings, *A. philoxeroides* experienced root inhibition under PE and macro-BDP/nylon treatments, but stimulation under micro-BDP/nylon. *A. sessilis* showed universal root stimulation under BDP, whereas nylon and PE effects were size-dependent (promotion by macro-particles; inhibition by micro-particles) (Fig. 6).

Responses of Total Biomass (Rela Total)

Patterns in total biomass effect sizes reinforced the species-specific habitat preferences (Table S2).

A. philoxeroides consistently benefited from plastic exposure in aquatic environments (positive effects across all types) but faced growth penalties in terrestrial soils (negative effects, particularly under PE and macro-BDP/nylon).

Conversely, *A. sessilis* showed a more resilient or positive response profile in terrestrial habitats compared to aquatic ones, where it was notably inhibited by nylon. Size-dependent effects were evident in terrestrial soils, where micro-sized particles generally induced more negative (or less positive) effects than macro-sized counterparts for *A. sessilis* under nylon and PE treatments (Fig. 7).

Responses of Shoot-to-Root Ratio (Rela SR)

Plastic-induced shifts in allocation were complex and driven by high-order interactions (Table S2).

A distinct interspecific divergence occurred in aquatic habitats: *A. philoxeroides* tended to reduce its SR (negative effect size, indicating increased root investment relative to shoot) under nylon and micro-PE treatments. In contrast, *A. sessilis* increased its SR (positive effect size) under almost all aquatic treatments.

In terrestrial habitats, both species generally exhibited positive effect sizes, indicating a shift toward aboveground allocation, although specific outcomes varied with polymer type and size (e.g., *A. sessilis* showed negative responses to macro-BDP/PE but positive to micro-counterparts) (Fig. 8).

Discussion

Microplastics as Habitat-Dependent Ecological Filters

Our results demonstrate that microplastics do not act as uniform stressors but rather function as habitat-dependent ecological filters that differentially regulate plant performance based on species identity, polymer type, and environmental context. This finding supports our first hypothesis that microplastic effects are strongly habitat-dependent.

In aquatic habitats, microplastic exposure generally enhanced the growth and biomass accumulation of the invasive *A. philoxeroides*, as evidenced by significant increases in above ground biomass under macro-PE treatment (Fig. 1) and consistently positive relative effect sizes across most polymer types (Fig. 5–7). In marked contrast, *A. sessilis* exhibited variable and often negative responses in water, particularly under nylon treatments (Figs. 5–7). This pattern was reversed in terrestrial habitats: *A. philoxeroides* showed predominantly negative responses (relative effect sizes < 0), whereas *A. sessilis* maintained neutral or slightly positive performance (Figs. 5–7). These contrasting patterns confirm that microplastic impacts cannot be generalized across ecosystems and underscore the need for habitat-specific risk assessments.

This distinct habitat-switch effect challenges the prevailing view that microplastics are universally detrimental to plant health (Rillig et al. 2019). Instead, our findings align with the "novel weapons" or "environmental matching" hypotheses, suggesting that anthropogenic alterations can create niches that disproportionately benefit species with high phenotypic plasticity (Davidson et al. 2011; Zhang et al. 2024a). The absolute effect sizes (Figs. S1-S3) further corroborate this divergence, revealing that *A. philoxeroides* gains a clear performance advantage in aquatic plastic-polluted niches, potentially accelerating its invasion, while terrestrial pollution may inadvertently strengthen biotic resistance by favoring the native congener.

Invasive Advantage in Aquatic Environments: Mechanisms and Trait-Based Responses

Our second hypothesis—that the invasive *A. philoxeroides* would exhibit greater tolerance or benefit from microplastic exposure relative to the native *A. sessilis*—was strongly supported in aquatic habitats. The invader showed significant biomass gains under multiple treatments (Figs. 1, 3), maintained or increased its shoot-to-root ratio (Fig. 4), and exhibited positive relative effect sizes for both above- and belowground biomass (Figs. 5, 6). These responses reflect the acquisitive, stress-tolerant strategy characteristic of successful invaders (Davidson et al. 2011; Strayer 2010).

The trait-based responses observed in *A. philoxeroides* are consistent with adaptive phenotypic plasticity —a key predictor of invasion success. In aquatic treatments, microplastics increased or stabilized the invader's shoot-to-root ratio, suggesting opportunistic investment in aboveground light capture when belowground conditions change (Qi et al. 2018). This plastic allocation strategy is known to boost biomass accumulation under enriched or flooded conditions (Harms et al. 2023) and may partially explain why *A. philoxeroides* consistently outperformed *A. sessilis* under identical treatments (Figs. 1, 3).

Mechanistically, the polymer-specific responses we observed align with known differences in plastic behavior and contaminant interactions. Larger PE fragments may function as physical mulch or structural elements, improving gas exchange and reducing hypoxia at sediment—water interfaces—conditions that would favor fast-growing invasives. In contrast, smaller nylon fibers can entangle roots, alter boundary layers, and more strongly absorb or release chemicals, thereby disrupting nutrient uptake and allocation (Rochman et al. 2013; Koelmans et al. 2016). Recent studies have further shown that microplastic fibers can alter rhizosphere microbial communities and enzyme activities, creating feedbacks that differentially affect plant species (Zang et al. 2020; Zhao et al. 2021). Polymer type may also influence performance outcomes through allelopathy. Exposure to PE has been shown to increase plant biomass while enhancing chemical interference via changes in leaf metabolites (Yuan et al. 2024).

Terrestrial Reversal and Pollutant-Enhanced Biotic Resistance

In sharp contrast to aquatic results, terrestrial microplastics suppressed the invader while often promoting or having neutral effects on *A. sessilis* (Figs. 5–7). This reversal suggests a form of "pollutant-enhanced biotic resistance" (Ehrenfeld 2003), wherein soil degradation disproportionately constrains resource-intensive invaders while buffering native species that may be better adapted to suboptimal soil conditions..

The suppression of *A. philoxeroides* on land likely results from soil biophysical degradation. Microplastics, particularly fibers (nylon) and films (PE), can disrupt soil aggregation, reduce water holding capacity, and impede root penetration (de Souza Machado et al. 2018; Boots et al. 2019). Invasive species like *A. philoxeroides*, which typically require high resource fluxes to maintain rapid growth, may be more sensitive to these physical constraints than the stress-tolerant native *A. sessilis*. The native species' ability to maintain or increase biomass under these conditions implies a pre-adaptation to resource-poor or physically challenging substrates found in its native range.

Furthermore, particle size played a critical role in modulating these outcomes. We observed that smaller particles often induced different responses than larger ones (e.g., terrestrial *A. sessilis* inhibited by micro-nylon/PE but promoted by macro-nylon/PE, Fig. 5–7). This aligns with findings that nanoplastics and microplastics exert distinct toxicity profiles: smaller particles can block root pores and accumulate in tissues (Li et al. 2020), whereas larger fragments primarily act as physical barriers or channels (Lozano et al. 2021). The varying responses of the two species to these size-dependent stressors highlight the complexity of soil-plant-plastic interactions.

Our findings align with field-relevant studies showing similar habitat-dependent patterns. Low-density PE fragments increased aboveground biomass and shoot-to-root ratios of the invasive Solidago canadensis under moist conditions but had negligible or negative effects on native congeners (Li et al. 2024a). Community-level experiments have similarly demonstrated that fertilization can interact with microplastics to shift biomass gains toward natives rather than aliens (Rillig et al. 2019; Shi et al. 2024), and that PE residues may strengthen allelopathic suppression by native plants (Yuan et al. 2024).

Polymer Type and Particle Size: Modulators of Plant Response

Our third hypothesis—that polymer type and particle size further modulate microplastic effects—was supported by the significant interactions detected in our statistical models (Supplementary Tables S1–S2). Macro-sized PE and micro-sized BDP tended to favor *A. philoxeroides* in aquatic habitats, while *A. sessilis* responded differently as noted above in terrestrial habitats, highlighting species- and habitat-dependent effects of polymer type and particle size (Figs. 5–7).

The size-dependent effects observed in our study are consistent with emerging evidence that particle dimensions can flip the direction of plant responses. Nanoscale plastics often suppress early growth through cellular uptake and oxidative stress (Rillig et al. 2021; Lozano et al. 2021), while larger fragments may physically modify soil or sediment structure in ways that benefit certain growth strategies. Particle shape also matters: fibrous microplastics (like nylon) have been shown to have stronger negative effects on root development than fragment or spherical forms, likely due to entanglement and altered water flow patterns (Lozano and Rillig 2020).

The contrasting effects of biodegradable plastics (BDP) deserve particular attention. Although BDP is often promoted as an environmentally friendly alternative, our results show that its effects on plant growth are not uniformly benign and can be either positive or negative depending on particle size and habitat (Figs. 5–8). This aligns with growing evidence that BDP degradation products—including organic acids and oligomers—may have distinct phytotoxic properties compared to conventional polymers (Qi et al. 2018, 2020). These findings caution against assuming that biodegradable materials pose fewer ecological risks.

Implications for Ecosystem Management and Future Perspectives

The demonstration that microplastics can fundamentally reverse performance outcomes—shifting from facilitation in aquatic environments to suppression in terrestrial soils—necessitates a more nuanced, habitat-specific approach to ecosystem management. Our findings challenge the "one-size-fits-all" assumption in current ecological risk assessments, suggesting instead that management strategies must be tailored to the hydrological context.

In aquatic ecosystems, riparian zones accumulating microplastics should be reclassified as high-priority sentinel sites for biosecurity. Our data indicate that these sediment sinks, particularly when polluted with polyethylene fragments, effectively act as invasion nurseries. Consequently, managers should target microplastic accumulation zones—such as slow-flowing river bends or dam reservoirs—as potential "bridgeheads" where plastic pollution and invasive species may generate self-reinforcing cycles of ecosystem degradation (Li et al. 2024b). Early removal of plastic debris in these hotspots could deliver a "double dividend" by simultaneously reducing pollutant load and mitigating invasion pressure. Conversely, in terrestrial soils, while microplastics may not directly trigger invasion, they function as a selective filter. Conservation efforts here should focus on the resilience of native communities, as pollution-induced stress could subtly restructure species composition by filtering out sensitive taxa even in the absence of dominant invaders.

While this study establishes a clear baseline using pristine polymers to isolate specific physical and chemical mechanisms, real-world scenarios involve complex interactions with weathered particles and environmental vectors. Moving forward, extending this framework to include aged microplastics and broader trophic dynamics—such as herbivory and pollination—will be essential to fully predict community trajectories in the field. Such integrative research will further refine our ability to forecast how the pervasive footprint of plastic pollution intersects with biological invasions to shape future ecosystems.

Conclusions

In summary, microplastics are not merely passive contaminants but active drivers of plant community reorganization. By integrating raw growth data with absolute and relative effect sizes, we demonstrated that microplastics facilitate the invasive *A. philoxeroides* in aquatic environments—likely through habitat structural modification and nutrient interactions—while impeding it in terrestrial soils. These findings highlight the urgent need to incorporate habitat heterogeneity and species identity into the global assessment of microplastic impacts, moving beyond simple toxicity tests to understand how plastic pollution reshapes the invasion dynamics of our changing ecosystems.

Declarations

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Jialiang Zhang designed the experiments. Bilin Xu, Jun Fu and Yu Zhou did the work. Jialiang Zhang performed data analyses and plotted graphs. All authors contributing to the writing of the manuscript.

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Figures

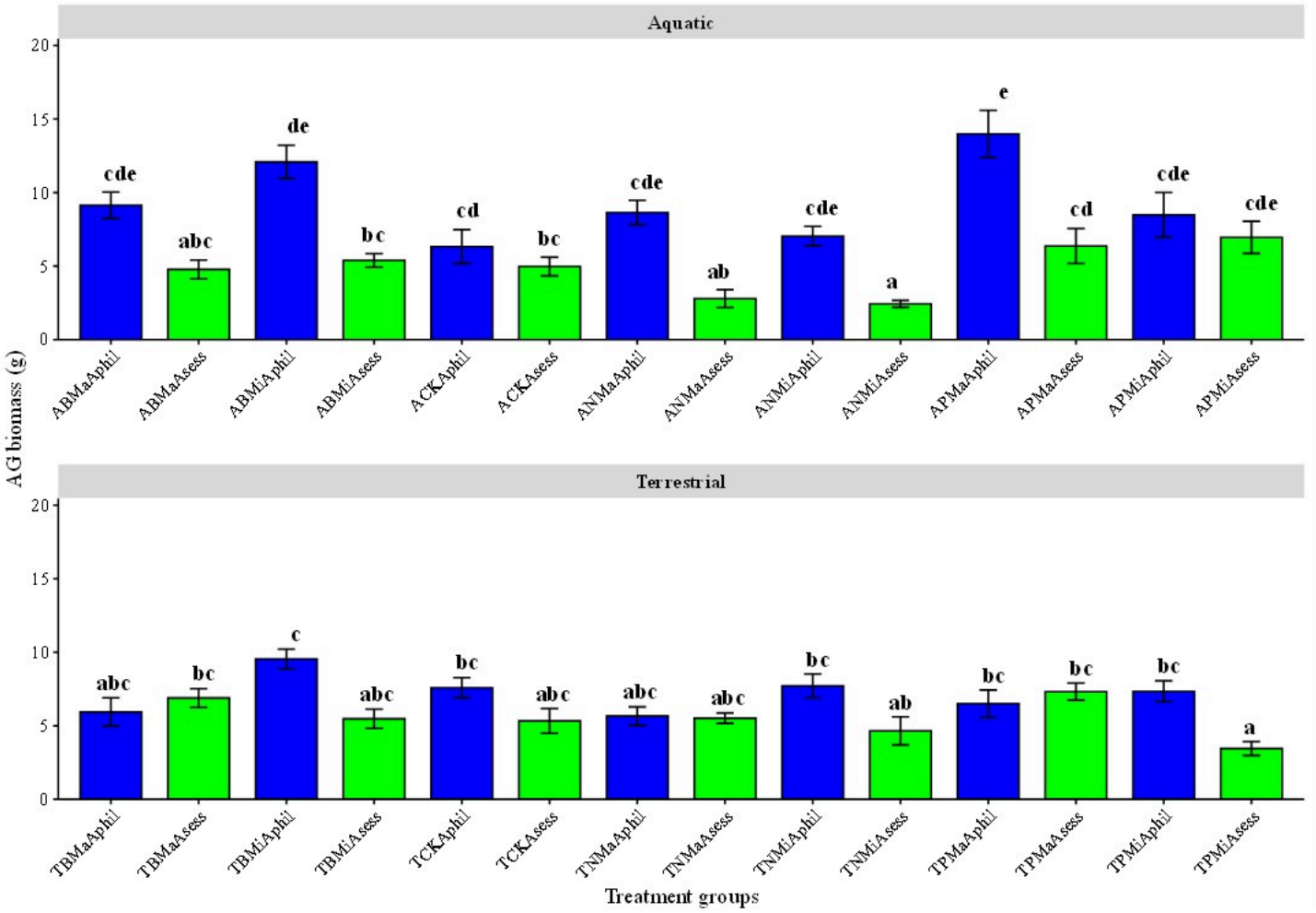

Figure 1

Effects of microplastics on aboveground biomass of *Alternanthera philoxeroides*and *A. sessilis*

Group named by following meanings: A-Aquatic,T- Terrestrial, CK-control, Ma-Macro, Mi-Micro, B-biodegradable plastic, N-nylon, P-polyethylene, group labels are consistent across Figs. 1-8.

A. philoxeroides is represented by blue bars, *A. sessilis*by green bars; Bar sharing a common letter are not significantly different (P 0.05). The same annotation is used in Figs. 1-8.

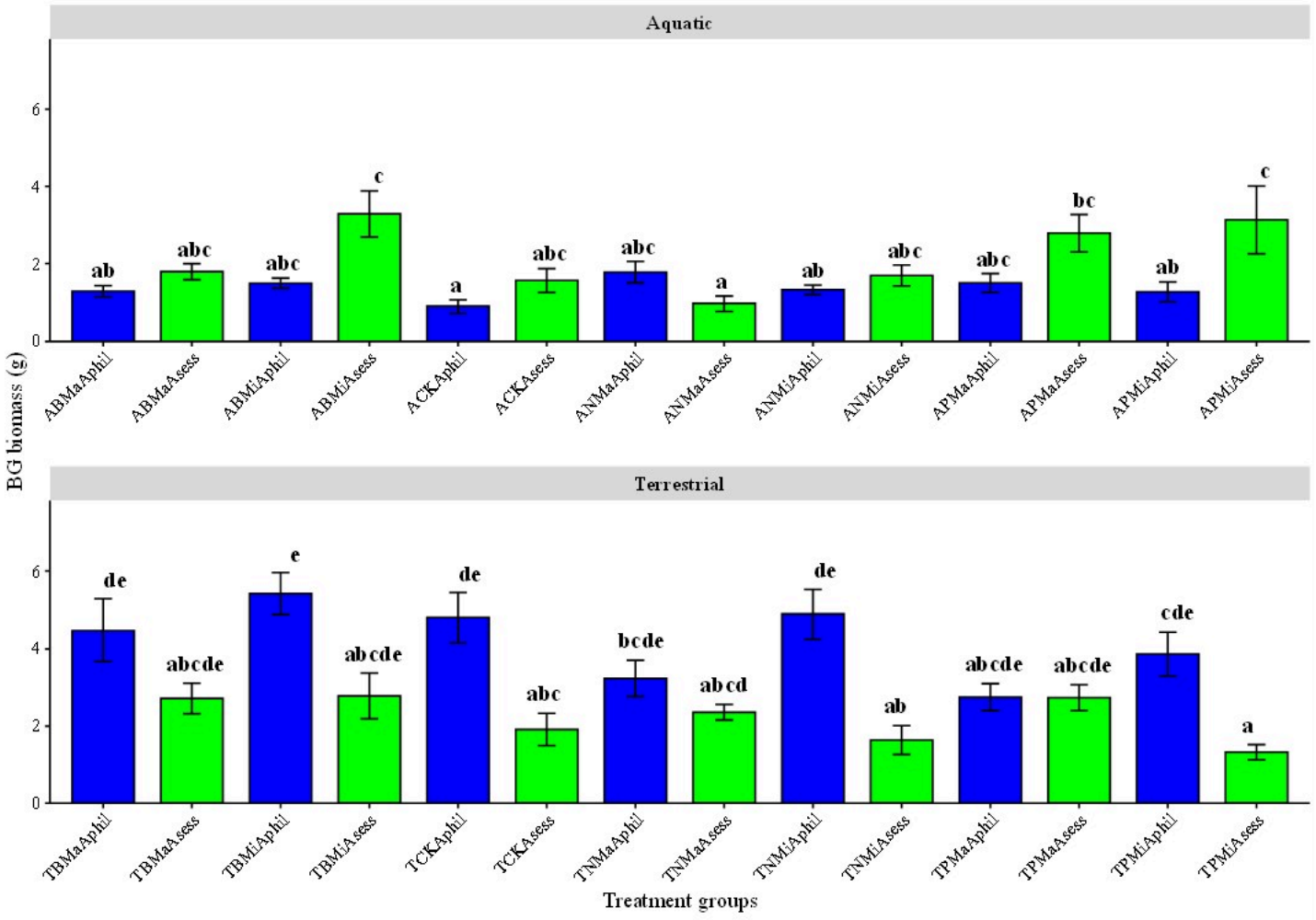

Figure 2

Effects of microplastics on belowground biomass of *A. philoxeroides* and *A. sessilis*

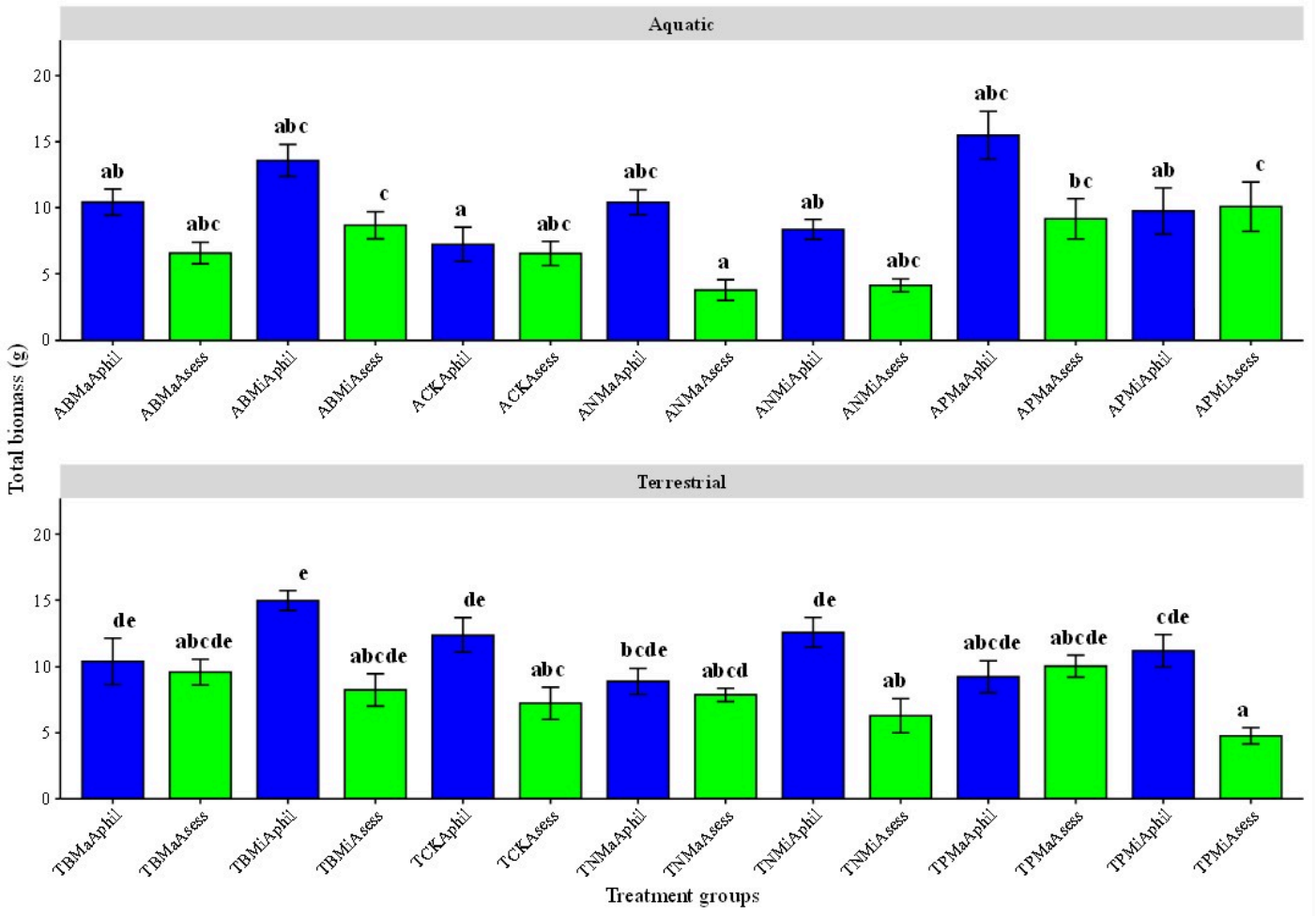

Figure 3

Effects of microplastics on total biomass of *A. philoxeroides* and *A. sessilis*

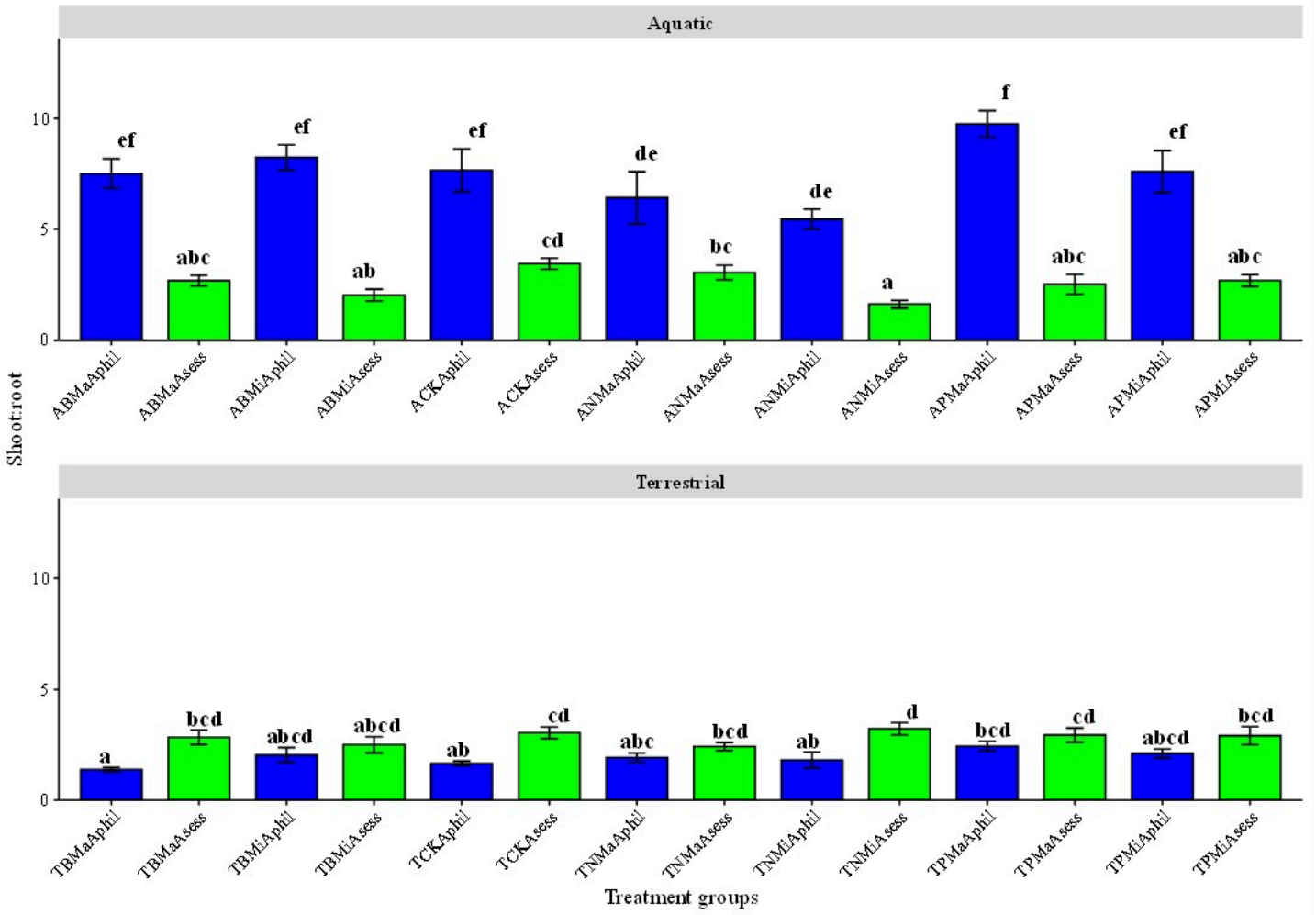

Figure 4

Effects of microplastics on Shoot:root of *A. philoxeroides* and *A. sessilis*

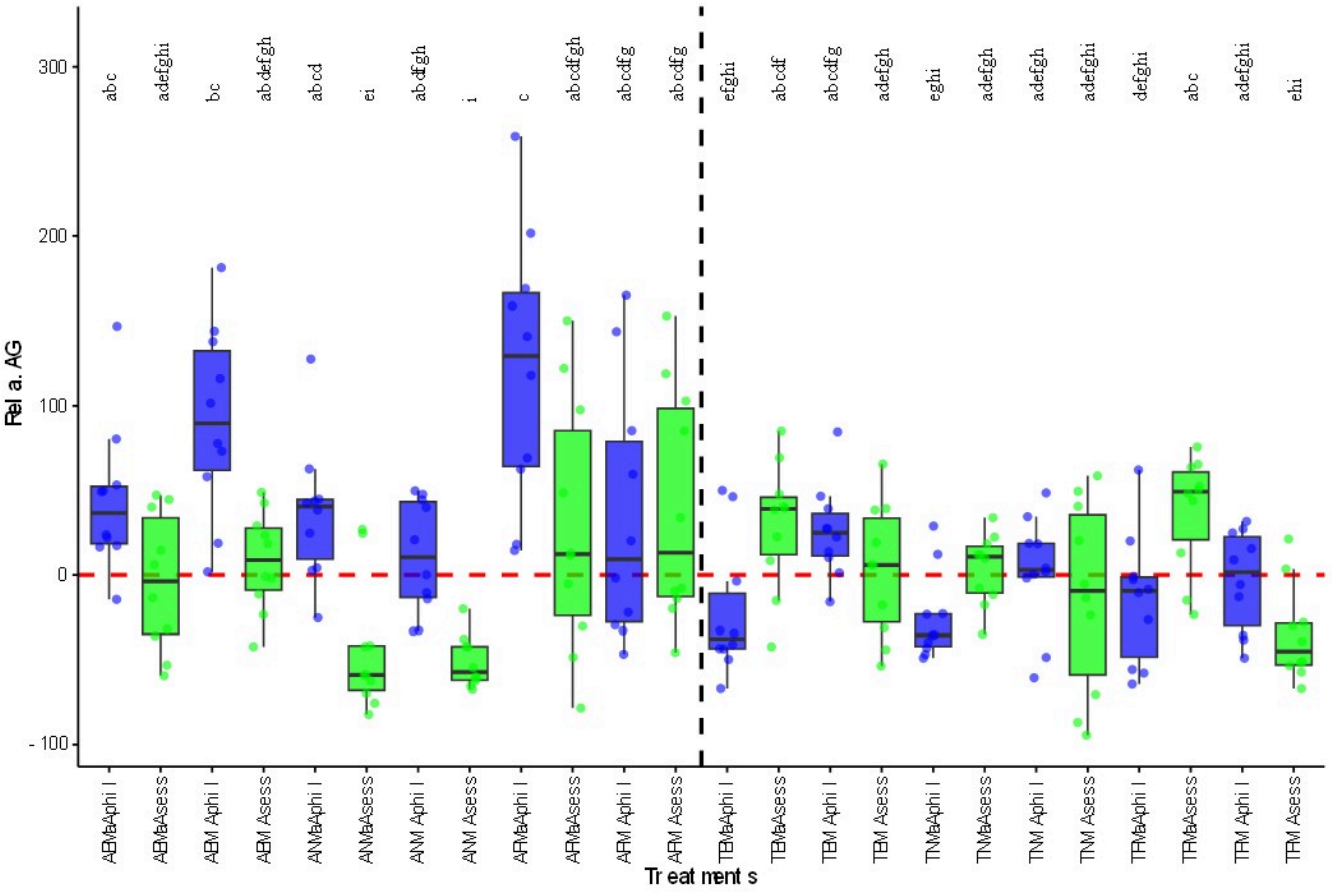

Figure 5

Relative effects of microplastics on abovegroud biomass of *A. philoxeroides* and *A. sessilis*

The black dashed line separates habitats, with the aquatic habitat on the left and terrestrial habitat on the right. The red dashed line denotes the zero-effect baseline; *A. philoxeroides* is represented by blue bars and points, *A. sessilis* by green bars and points.

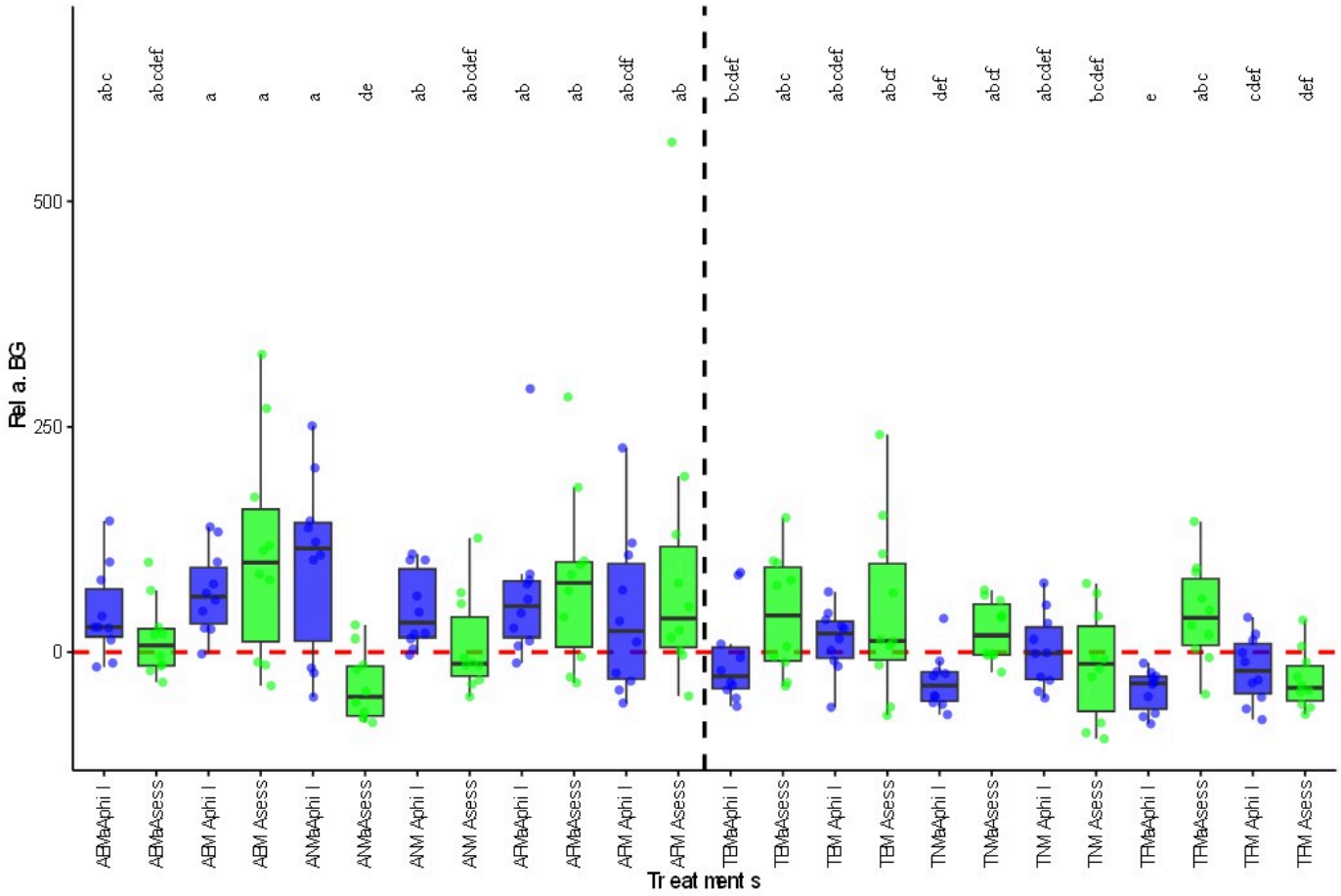

Figure 6

Relative effects of microplastics on belowgroud biomass of *A. philoxeroides* and *A. sessilis*

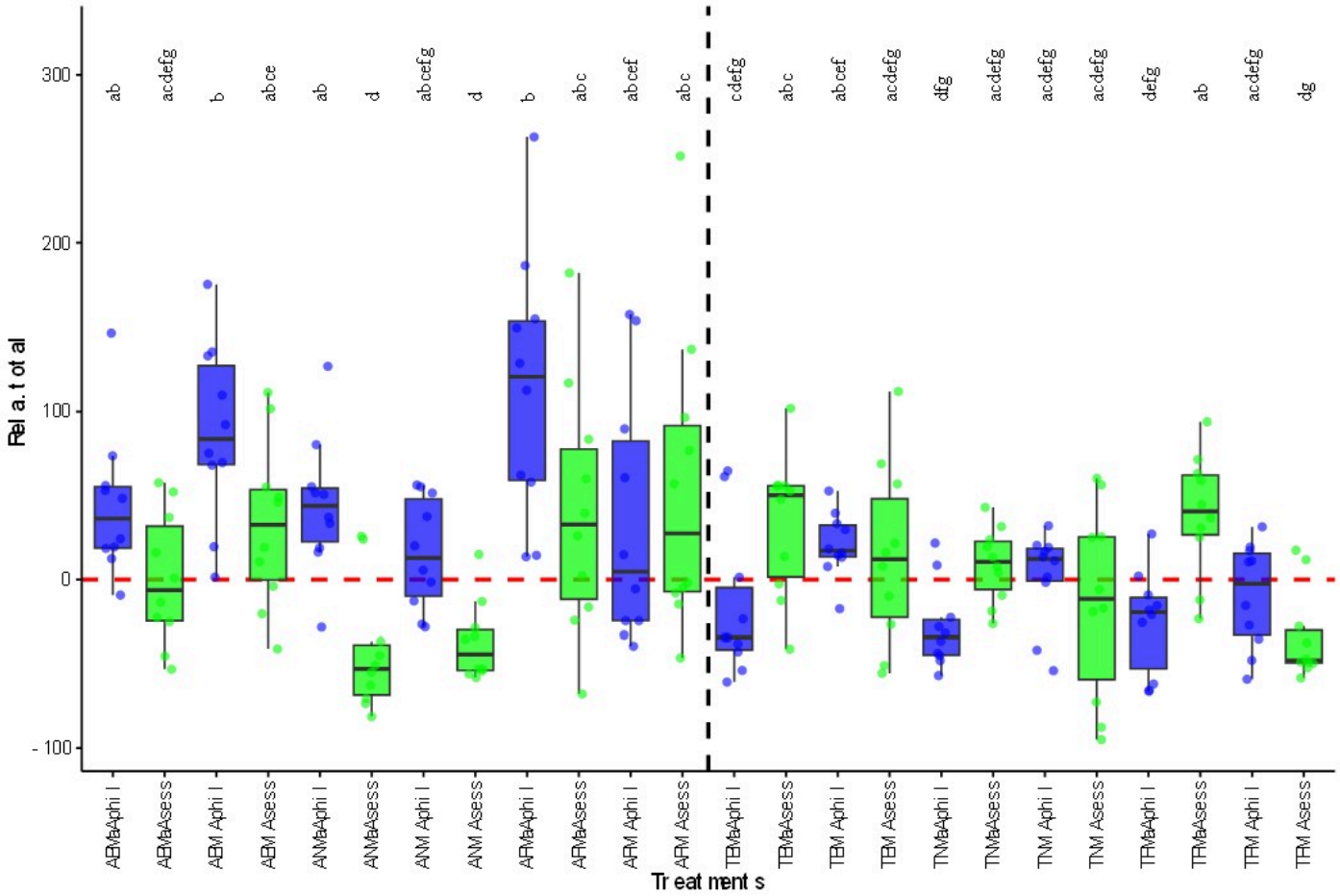

Figure 7

Relative effects of microplastics on total biomass of *A. philoxeroides* and *A. sessilis*

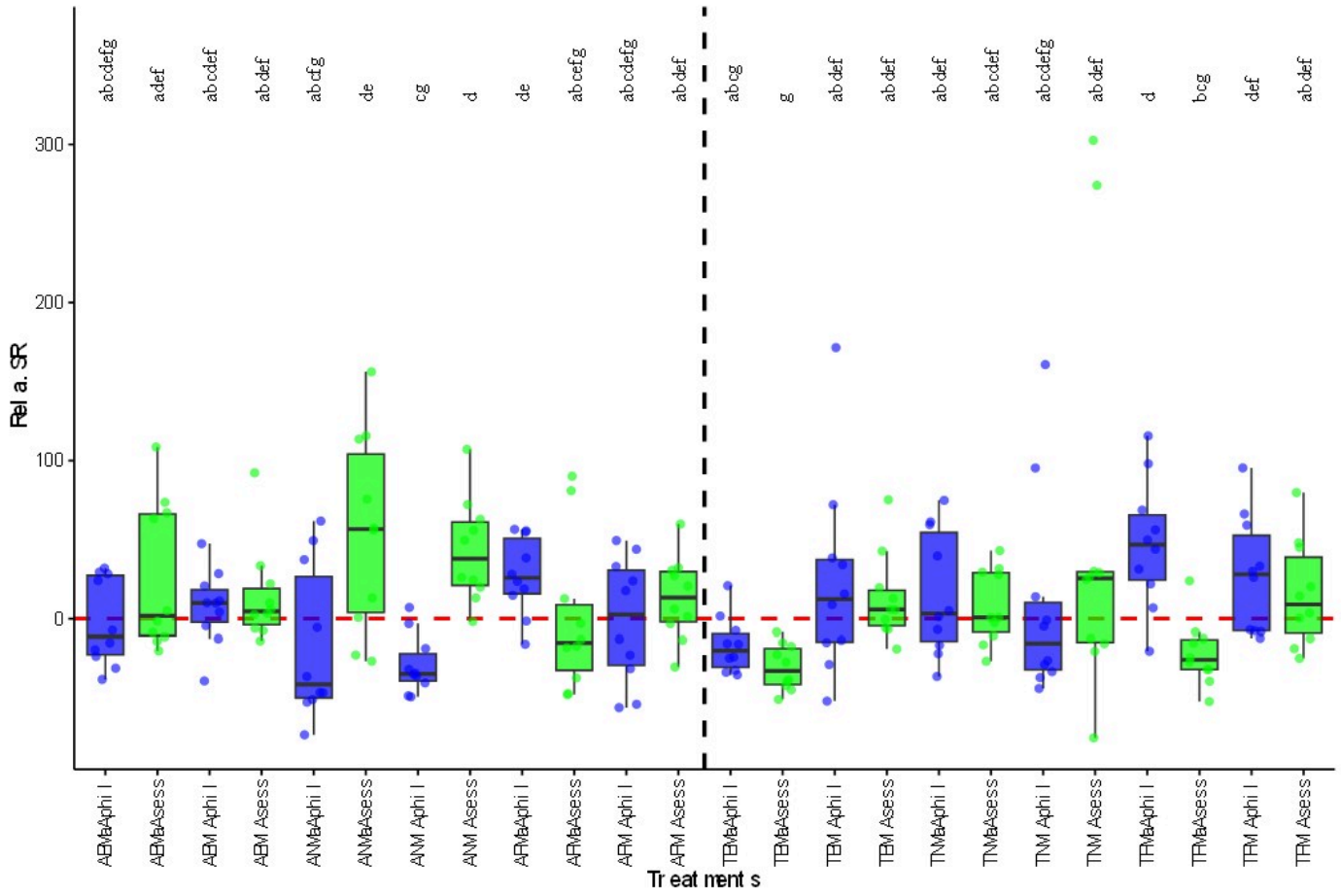

Figure 8

Relative effects of microplastics on shoot:root of *A. philoxeroides* and *A. sessilis*

Supplementary Files

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- SupplementfileaboutAbsoluteEffectSizes.docx
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