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How do initial concentrations, metal(loid)s types, and pH drive sustainable dendroremediation?

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Abstract

Woody plants have significant yet under evaluated potential for metal(loid)s (HMs) phytoremediation. The meta-analysis of 2,766 observations from 243 studies assessed 117 woody genera across 10 HMs (antimony (Sb), arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), manganese (Mn), nickel (Ni), titanium (Ti), and zinc (Zn)) across potted, hydroponic, field, and sterile conditions. HMs exposure reduced plant biomass by 18.7 − 34.2%, with roots most affected (-24.9%). Antioxidant enzymes (SOD, POD, CAT) activities were increased by 100–200% to mitigate oxidative stress. *Gardenia* and *Platycladus* tolerated HMs (TI > 1), *Cinnamomum* and *Ficus* accumulated them efficiently (BCF > 1), while *Albizia* and *Populus* excelled in HMs extraction (TF > 1). Targeted remediation candidates include *Ulmus* (Cd), *Platycladus* (Pb), *Tamarix* (Zn), and *Salix* (Zn, Cu, Sb). HMs accumulation correlated with pH, contamination levels, and speciation. Future research should focus on dynamic translocation metrics, field simulation, and biochar-microbe synergies for enhanced HMs immobilization. This framework supports precise species selection for sustainable dendroremediation for mining sites and brown field.

Introduction

Heavy metals or metal(loid)s (HMs) contamination of terrestrial and aquatic ecosystems presents a critical sustainability crisis, threatening environmental security and public health through bioaccumulation in agricultural systems and the human food chains [1, 2, 3]. The main contaminants, including arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and mercury (Hg), persist globally despite regulatory efforts in the 21st -century, with ecological degradation and the environmental issue now widely evident [4, 5]. Particularly alarming is the European Environment Agency's report that metallic elements constitute 60% of soil contaminants, representing the dominant pollution category in European terrestrial systems [6]. In comparison, Cd is the main HMs pollution in China, following other HMs like As, Cu, and Pb [7, 8]. African aquatic systems exhibit alarming HMs concentrations, with documented ranges including 20.3–249 μg L^{-1} Pb, 2.80–15.6 μg L^{-1} Cd, and 94.7–199 μg L^{-1} Cr - levels posing immediate risks to aquatic biodiversity and potable water supplies [9, 10]. The potential hazards of HMs have garnered global attention, underscoring the urgency of addressing and mitigating HMs pollution as a matter of immediate concern [11].

Phytoremediation offers a soil-conserving approach to HMs remediation, immobilizing contaminants while preserving topsoil fertility [12]. Woody plants emerge as cost-efficient bio-remediators due to their deep root systems, high biomass production, and multi-decadal lifespan, enabling effective HMs sequestration [13, 14, 15, 16]. Species such as *Eucalyptus camaldulensis* demonstrate rapid HMs uptake and phytoremediation potential, attributed to their accelerated growth rates [17]. The biomass of *Morus alba* has been shown to increase significantly with cultivation time in Cd-contaminated soil [18]. Genera such as *Populus* and *Salix* synergize contamination mitigation with economic returns through biomass valorization [19, 20, 21, 22]. Beyond HMs removal, these plants enhance ecosystem resilience by reducing erosion, boosting soil organic matter, and reactivating nutrient cycles [23, 24, 25]. These adaptive strategies

significantly mitigate secondary contamination risks compared to conventional physical and chemical approaches [13, 26]. A recent study showed that five years of remediation using *Quercus robur* and *Tilia cordata* significantly reduced soil arsenic by 71.8% [27], this integration of ecological restoration with circular resource recovery positions woody phytoremediation as a keystone strategy for sustainable land rehabilitation (possible dendrorestoration) [28].

Intrinsic genetic traits and environmental factors influence the phytoremediation capacity of woody plant. Species- and genotype-dependent variations in root architecture, physiology, and biomass production govern HMs uptake heterogeneity across taxa [21, 26, 29, 30, 31, 32]. Genetic diversity causes divergent Cd accumulation in *Salix* lineages [33, 34, 35, 36], while species like *Salix caprea* and hybrid poplar (*Populus tremula* × *P. alba*) demonstrate leaf-based Zn/Cd accumulation [37, 38]. Soil pH critically regulates HMs' bioavailability and the acidic conditions mobilize cation of HMs, whereas alkaline environments promote the precipitation of metal cation [22, 39, 40, 41, 42, 43]. Soil organic matter, nutrient availability, and microbial activity further influence HMs dynamics by altering metal speciation and plant uptake efficiency [44, 45]. HMs toxicity varies with concentration, as low doses may stimulate plant growth, whereas high doses are inhibitory or lethal [46]. These multifactorial controls underscore the need for mechanistic frameworks that link plant-environment-metal interactions to predict remediation outcomes.

Local-scale studies on phytoremediation using woody plants yield inconsistent results due to variable pre-growth conditions, element speciation/dosage, and environmental parameters [47, 48]. While meta-analyses can resolve species-specific remediation patterns, a global synthesis of the drivers of HMs accumulation across woody taxa remains lacking. Here, we address this gap through a systematic analysis of 243 international studies (Fig. 1, Supplementary Fig. 1 and Supplementary Table 1) covering 10 HMs: antimony (Sb), arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), manganese (Mn), nickel (Ni), titanium (Ti), and zinc (Zn). Specifically, our aims are to: (1) examine the growth and physiological responses of woody plants to HMs stress; (2) investigate inter-genus variations in HMs tolerance; and (3) identify the critical factors governing HMs accumulation. We hypothesized that: (1) The potential of woody plants to remediate HM pollution depends on plant functional group, HM type, and environmental pH, as HM toxicity varies with metal species and is strongly influenced by environmental pH, which in turn differentially affects woody plant growth; and (2) Variation in antioxidant enzyme activity plays a regulatory role in plant growth and HM accumulation, the extent of this regulation is influenced by the specific properties of the HMs (e.g., type and concentration) as well as experimental conditions. This work may advance the systematic understanding of the potential of woody plants for large-scale HMs remediation and provides insights for optimizing field-level contamination management strategies.

Results

Woody plants, HMs, and experimental conditions involved in the study

Our meta-analysis synthesized 2,766 data across 69 plant families, dominated by Salicaceae (n = 856), Fabaceae (n = 270), Myrtaceae (n = 198), Moraceae (n = 148), and Ginkgoaceae (n = 112) (Supplementary Table 2). The dataset encompassed 117 genera, including *Salix* (n = 480), *Populus* (n = 364), *Eucalyptus* (n = 182), and *Ginkgo* (n = 112), spanning 88 tree and 38 shrub species. Experimental designs comprised potted (n = 1586), hydroponic (n = 681), field (n = 412), and sterile medium (n = 87) trials. Ten metal(loid)s types with Cd (n = 1328), Pb (n = 535), Cu (n = 396), Zn (n = 305), Cr (n = 51), As (n = 47), Mn (n = 42), Sb (n = 30), Ni (n = 26), and Ti (n = 6) were included, reflecting predominant environmental burdens (Fig. 1 and Supplementary Table 2).

Tree-based experiments predominantly assessed Cd (n = 1078, 0–1,400 mg kg^{-1}), Pb (n = 424, 0–20,000 mg kg^{-1}), Cu (n = 342, 0–9,767 mg kg^{-1}), and Zn (n = 260, 0–7,290 mg kg^{-1}) impacts, with hydroponic trials averaging 53 days versus 180 days for soil/sterilized media systems (Supplementary Figs. S2 and S3). Shrub studies focused on Cd (0–453 mg kg^{-1}), Pb (0–6,000 mg kg^{-1}), Cu (0–453 mg kg^{-1}), and Zn (0–2,000 mg kg^{-1}), showing shorter experimental durations (38 days for hydroponic; 110 days for soil / sterile medium) (Supplementary Fig. 3). Geographically, 22 countries contributed data, with China dominating the research landscape (1,838), followed by India (230), Iran and Pakistan (105 each), Poland (85), and Italy (73) (Supplementary Fig. 4).

Biomass response and tolerance index of woody plants to HMs

HMs stress reduced whole plant biomass by 23.8%, with reductions at extreme (-28.9%), high (-23.9%), middle (-17.0%), and low (-24.2%) levels (Fig. 2a, Supplementary Fig. 5a and Fig. 6). Biomass declined in underground (-24.9%), leaf (

-18.6%), and aboveground parts (-24.2%) (Figs. 2a–d and Supplementary Fig. 5a). Both aboveground and underground showed similar reductions across HMs levels, with the greatest decreases at extreme (-40.2% and − 41.7%, respectively) and high (-30.5% and − 27.9%, respectively) levels (Figs. 2b and 2d). Leaves biomass decreased significantly with increasing HMs concentration ($p < 0.001$) (Fig. 2c and Supplementary Fig. 5a). Trees and shrubs exhibited significant biomass reductions of 24.3% and 21.2%, respectively ($p < 0.05$) under HMs stress for three and six months, respectively ($p < 0.05$) (Fig. 2).

Genus-specific responses included significant biomass reductions under Cd (*Hubiscus*, *Shepherdia*, *Amygdalus*; $p < 0.01$), Pb (*Ginkgo*, *Amygdalus*, *Ulmus*; $p < 0.01$), and Zn, Cu, Sb stress (*Prosopis*, *Populus*, *Broussonetia*; $p < 0.01$) (Figs. 3a–e). Interestingly, *Platycladus* and *Tamarix* showed biomass increases under Pb and Zn stress, respectively ($p < 0.01$) (Figs. 3b and 3c). The root-shoot ratio (R/S) of *Eucalyptus* improved in hydroponics under Pb stress (Supplementary Figs. 7a and Fig. 8a). The tolerance index (TI) of *Gardenia*, *Platycladus*, *Styphnolobium*, and *Osmanthus* was > 1 in soil or sterile media, *Tamarix* showed

TI > 1 under Zn stress, *Albizia* and *Populus* exhibited TI > 1 under Cd stress in hydroponics conditions (Supplementary Figs. 9a and 10a).

HMs accumulation and translocation in woody plants

HMs concentration in the whole plant increased by 565.9%, with specific increases at extreme (1837.8%), high (1334.1%), middle (504.2%), and low (168.7%) levels of HMs (Fig. 2e, Supplementary Fig. 5b and Fig. 11). HMs concentration in aboveground, and underground tissues increased by 1270.6%, and 1681.6%, respectively ($p < 0.05$) (Supplementary Fig. 5b). In acidic environments, HMs concentration in the underground parts was significantly higher than those in alkaline or neutral conditions ($p < 0.01$) (Fig. 2g). Furthermore, whole plant HMs concentration increased significantly under extreme and high HMs stress, with enhanced bioavailability in acidic environments ($p < 0.05$) (Fig. 2e).

The bioconcentration factor (BCF) and translocation factor (TF) of HMs in woody plants varied greatly among genus (Supplementary Figs. 9b and 9c). The BCF values of Cd in *Ficus* and *Ligustrum*, and Cu in *Cinnamomum*, were higher than 1. *Albizia* and *Populus* exhibited TF values greater than 1. For Cd, the highest leaf and stem BCF were observed in *Amygdalus* (> 5) and *Salix* (> 1), respectively (Supplementary Figs. 10 and 12).

Physiological responses of woody plants to HMs

Under HMs stress, malondialdehyde (MDA) levels in leaves exhibited significant increase across cultivation systems, with hydroponic (24.1%) and solid media (25.8%) showing comparable increases ($p < 0.05$) (Supplementary Fig. 13d). This oxidative damage intensified with increasing HMs concentration surpassing controls by 25.8–32.8% ($p < 0.001$) (Supplementary Fig. 13d and 14d). Notably, non-neutral pH conditions amplified MDA accumulation in all experimental configurations, particularly affecting shrubs versus trees in hydroponic systems ($p < 0.05$) (Supplementary Fig. 13d).

The superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) activities in leaves exhibited significant enhancement under HMs stress compared to control conditions ($p < 0.05$) (Supplementary Figs. 13 and 14). Specifically, CAT activity demonstrated a dramatic increase by 32.8% under high HMs exposure, while POD showed substantial elevations of 25.2% and 39.0% under high and low HMs concentration, respectively (Supplementary Figs. 13a and 13b). Extreme HMs stress-induced CAT activity that was significantly surpassed those observed under other contamination levels ($p < 0.05$) (Supplementary Fig. 13c).

Hydroponic cultivation induced remarkable increases in antioxidant enzyme activities, with SOD, POD, and CAT in leaves showing elevations of 34.5%, 56.9%, and 981.4%, respectively. Significant interspecific variation was observed between shrubs and trees, particularly in SOD and CAT responses ($p < 0.05$) (Supplementary Fig. 13c). Furthermore, comparative analysis of propagation methods revealed

seedlings maintained superior SOD and POD activities relative to cuttings and transplanted specimens (Supplementary Figs. 13a and 13b).

Driving factors for woody plants to mitigate HMs toxicity

A significant positive relationship was observed between the natural log response ratios of HMs concentration in aboveground tissue and environmental pH ($p < 0.001$) (Fig. 4f). The activities of SOD and CAT, and MDA content in leaves demonstrated significant increases in response to rising environmental pH (Figs. 4i and 9k–l). Conversely, HMs accumulation in the leaves, underground organs, and whole plants exhibited marked reductions with elevated pH ($p < 0.001$) (Fig. 4g–h). Enhanced foliar HMs levels triggered significant upregulation of CAT and POD ($p < 0.05$) (Fig. 4n–o).

A strong positive relationship ($p < 0.01$) between POD activity and environmental pH was revealed in soil and sterile medium (Supplementary Fig. 16). In soil or sterile medium under Pb stress, the activities of SOD, CAT, and POD increased with increasing HMs concentration in leaves ($p < 0.05$) (Supplementary Fig. 17). In contrast, Cd stress induced significant negative correlations between foliar HMs concentration and all three antioxidant enzymes ($p < 0.05$) (Supplementary Fig. 17). Additionally, leaves HMs showed a strong positive association with MDA content but a negative correlation with CAT activity under Cu exposure ($p < 0.05$) (Supplementary Fig. 17).

In addition, plant genus, and HMs levels are the important predictors of leaf BCF (Figs, 5a and 5d), plant genus, HMs levels, and functional group have greater impact on plant TF (Figs, 5b and 5e). For plant TI, HM types, environmental pH, and plant genus are key predictors (Figs, 5c and 5f). Overall, plant genus, HMs types, levels, and environmental pH are the key predictors of phytoremediation capacity for HMs using woody plants (Fig. 5).

Discussion

Responses in biomass of woody plants to HMs

HMs stress inhibited the growth of woody plants, significantly reduced total biomass by 23.8%. Specifically, the biomass of the underground, leaves, and aboveground components decreased by 24.9%, 18.6%, and 24.2%, respectively. Firstly, HMs suppression of cyclin-B proteins arresting root apical meristem division, reducing primary root, lateral root formation, and sparse root hairs [29]; Secondly, HMs such as As, Cd, Pb, and Zn inhibit the expression of genes associated with cell expansion [26, 49, 50, 51], decreasing leaf cell volume and leaf area, restricts stomatal opening, decreases CO_2 absorption, impairs photosynthesis, and ultimately reduces carbon fixation in plants[39, 50, 52]. Consequently, the biomass of the plant declines under HMs stress.

The root-to-shoot ratio (R/S) reflects the distribution of plant photosynthetic products, revealing divergent adaptive strategies under HMs stress. *Eucalyptus* and *Liquidambar* exhibited root proliferation

to counterbalance nutrient uptake inhibition [53]. In contrast, the root-to-shoot ratio of other species did not significantly change under HMs treatment, reflecting species-specific adaptation strategies, variations in nutrient absorption capacity, and differences in metal bioavailability [54]. *Salix* and *Populus* displayed low R/S values (< 1), a hallmark of hypertolerance achieved through vacuolar HM sequestration [55].

Tolerance index (TI) is typically calculated as the ratio of plant biomass under stress conditions to that under control conditions [56, 57]. A higher TI indicates greater tolerance, reflecting the plant's ability to sustain growth and function despite adverse conditions [56]. Four genera (*Gardenia*, *Platycladus*, *Styphnolobium*, *Osmanthus*) exhibited TI > 1 in contaminated substrates, and *Salix* and *Populus* showed the TI values above 0.6, indicating these species excellence in adaptation to HMs stress conditions.

Physiological responses of woody plants to HMs

HMs exposure triggers a redox crisis in plants, generating cytotoxic ROS that induce MDA content [58] and genomic instability through vesicle transport disruption and DNA strand breaks [59]. To counter this oxidative onslaught, plants activate a tripartite enzymatic defense system, such as SOD catalyzes O_2^- conversion to H_2O_2, and CAT or POD detoxify H_2O_2 into H_2O/O_2 [60, 61, 62]. Under extreme HMs levels stress environment, plant leaf SOD activity significantly increased by 31.8%, which is consistent with previous studies [32, 63, 64]. The present study observed a significant positive relationship between environmental HMs and leaf POD activity, there POD plays a larger role in clearing H_2O_2 from the leaves of woody plants [65]. A negative relationship between pH and enzyme activity was also observed in the current study, which is ascribed to the boosted function and activity in neutral or slightly alkaline environments while the inhibited structure and function in the acid environment of the enzyme [43]. A recent study showed that the optimum pH values for the activities of SOD, POD, and CAT are 7.0 [30]. High environmental pH may promote the availability of certain essential metal ions (such as Ca, Mg, etc.) [66], which are cofactors for many enzymes and help maintaining enzyme activity.

Phytoremediation capacity of woody plants to HMs

Phytoremediation capacity is primarily determined by factors such as total plant biomass, and HM concentration in plant [22, 56, 67]. Our study identified 69 plant families and 117 genera that exhibit notable HM accumulation in polluted environments, and phytoremediation capacity of HMs is species-specific. *Platycladus orientalis* exhibited greater resistance to HM pollution compared to *Sabina chinensis* [65, 68, 69]; *Cinnamomum*, *Ficus*, and *Ligustrum* demonstrated greater HM enrichment capacity. Furthermore, *Albizia*, Populus, *Khaya*, and *Salix* exhibited stronger HM extraction capabilities. *Salix*, *Ficus*, *Ligustrum*, and *Cinnamomum* exhibited BCFs greater than 1, particularly under Cd, Pb, and Cu stress (Supplementary Fig. 15). *Salix* demonstrated exceptional potential for remediating combined HMs contamination, with evidence supporting their critical role in HM enrichment [22, 70, 71, 72]. *Albizia* and *Populus* exhibited higher

transfer factor values, while most other species had transfer factor values less than 1. This indicates that *Albizia* and *Populus* are suitable for the extraction of environmental HMs, while most other plants are more suited for the fixation of environmental HMs. This result is consistent with previous studies [73, 74].

Slow-growing or precious species exhibit higher metal tolerance and stable accumulation over time, which is essential for long-term remediation [75]. According to the years of field experiments, Li et al. [75] proposed a comprehensive evaluation method for the accumulation of multiple HMs in plants, combining plant biomass and HM concentrations into the thorough bioaccumulation index (CBAI). This method provides a foundation for the comprehensive evaluation of the ability of *Quercus* species to accumulate multiple HMs [75, 76]. Further evaluation approach on phytoremediation potential using woody plants is still needed. For example, evidence on the HM bioaccumulation capabilities of genera such as *Buddleja*, *Amygdalus*, *Leucaena*, and *Melia* remains limited [77, 78, 79, 80].

Key environmental regulators of phytoremediation for HMs by woody plants

Environmental pH critically modulates HMs biogeochemical cycling [81], with our data revealing acidification amplifies plant HM accumulation by 523.8% (leaves), 1922.4% (aboveground), and 3274.7% (underground) versus neutral conditions, far exceeding alkaline environment impacts (315.4%, 459.5%, and 1077.7%, respectively). Meanwhile, environmental pH is important predictor of woody phytoremediation potential (Fig. 5). The pH-dependent bioavailability stems from proton-driven dissolution of metal oxides/sulfides, increasing Cd^{2+}, Pb^{2+}, and Zn^{2+} mobility [82, 83]. In addition to pH, substrate cultures, which provide richer nutrients and water, further facilitate plant growth and HMs accumulation [41, 84]. Over time, the accumulation of dry matter supports this process [85]. Prolonged exposure (6 months) further enhanced HMs uptake and accumulate by plants. However, this increase is not indefinite; a threshold exists beyond which the positive correlation between exposure time and tissue HMs accumulation becomes non-significant [35].

The type and concentration of HMs play a decisive role in plants' adsorption and fixation (Fig. 4 and Fig. 5). For instance, the concentration of Cu in plants is significantly higher than that of Cd, Zn, and Pb, which can be attributed to the differential toxicity of these metals to plants [86]. High concentrations of HMs in the environment result in higher HMs accumulation in plants compared to low concentrations. These findings highlight that the toxicity of HMs to plants is determined by both their types and concentrations, while environmental pH directly modulates their bioavailability. For the effective phytoremediation of HMs, three external factors must be carefully considered, such as initial HMs concentration, types, and environmental pH. These factors collectively influence the bioavailability, uptake, and accumulation of HMs in plants, ultimately determining the success of phytoremediation efforts.

The limitations and prospects of dendroremediation

This study systematically summarized the phytoremediation potential of woody plants and its influencing factors (Fig. 6), while the dendroremediation presents a sustainable nature-based solution, four critical knowledge gaps must be addressed to scale its real-world application. (1) Current evidence derives from only 117 genera, the selection of woody plant materials is still limited in terms of climatic zones, HM types, concentrations, and soil types, constraining the evidence. (2) Current research relies heavily on controlled indoor experiments (85.1%) rather than field trials (14.9%), making it difficult to apply findings to real-world contaminated sites. (3) Most studies focus on single-element stress and suitable environments, neglecting the combined effects of multiple environmental factors (e.g., flooding, increased temperature, drought, nitrogen deposition) and HMs stress [87]. Considering the possibility of competition between different species, especially closely related species with potentially highly overlapping ecological niches [88], the accumulation of HMs may be overestimated. (4) There is a lack of comprehensive understanding of the underlying mechanisms, such as ecological stoichiometry, homeostasis, and molecular regulatory mechanisms affecting HMs absorption and detoxification.

To advance the field of dendroremediation study, the following actions are recommended. (1) Expand research to identify effective indicators and adaptable species for various climates, HMs types, and soil conditions. The existing indicators (TI, BCF, and TF) are less operational in woody plants, it is necessary to extend the study and screen the main indicators for evaluating the phytoremediation capacity of woody plants like CABI. Such efforts can significantly enhance the existing pool of plant materials and technological systems. (2) Pay more attention to field trials and establish diverse plant communities to investigate community-level phytoremediation capabilities. (3) Considering the multi-factor interactions to understand how multiple plant species respond to various stresses. (4) Improve soil conditions using techniques like amendments application to reduce HMs bioavailability and toxicity. Additionally, research should focus on the relation among plant functional traits, photosynthetic efficiency, and molecular mechanisms to provide a deeper understanding of plant responses to HMs stress and enhance phytoremediation strategies.

Methods

Systematic literature survey

The systematic literature survey was conducted using two databases, the Web of Science Core Collection (WoS: https://clarivate.com.cn/solutions/web-of-science/), and China National Knowledge Infrastructure (CNKI: https://www.cnki.net/) databases. Three separate searches were performed with keywords related to HMs, metalloids, trees, shrubs, and dendroremediation. The first search, conducted on August 31, 2021, covered studies from 1986 to 2020 (WoS). The second search, conducted on April 14, 2022, and the third search, conducted on October 16, 2024, included studies from 2022 to 2024 (WoS). The search string was detailed in Supplementary Table 3 to query titles, abstracts, and keywords. The methodology for the meta-analysis is outlined in the PRISMA checklist (Supplementary Fig. 1). Ultimately, 2766 data points from 243 publications were analyzed, focusing on plant growth responses—

such as biomass, HMs concentration, and physiological parameters under HMs stress. For the literature selection process and effect size calculation, see Supplementary Method 1.

In the selected publications, we manually extracted the mean values, replicates, and standard deviation (or standard errors where available) for biomass, HMs concentration, and physiological parameters, along with the related information from tables and texts, or indirectly extracted data from figures using the online tool Getdata (https://getdata.sourceforge.net/). The relation information included location (latitude, longitude), climate (mean annual temperature (MAT); mean annual precipitation (MAP)) and environmental characters (soil organic carbon content, pH, nitrogen content, and the soil clay content, bulk density) of each observation were also collected. For studies where the latitude and longitude of the experiment were not provided, we approximated these coordinates by geocoding the location names in Google Earth (the free version) [89]. For the missing climate records in articles, we extracted MAT or MAP from WorldClim dataset (https://www.worldclim.org/) with 10 arcminute resolution based on latitude and longitude. Soil organic carbon content, pH, nitrogen content, and the soil clay content, bulk density of the surface soils (0–15 cm) was provided based on the World Soil Information Service (WoSIS) soilGrids (https://soilgrids.org/) products with a 250 × 250 m spatial resolution [90].

Multi-level meta-analysis models

To examine variation in effect sizes and address the non-independence of observations, we employed multi-level meta-analytical models, equivalent to linear mixed-effects models. We explained the effect sizes by incorporating random (nesting) factors (Supplementary Table 4). We first constructed null models with only random effects to estimate the overall effect of HMs on plant growth. We then compared these null models with models including nested random terms: (1) publication unique identifier, (2) country where the study was conducted, (3) plant family, and (4) plant genus. Additionally, we included a unique identifier per effect size/data row in all tested null models as a random term to estimate residual heterogeneity. The goodness of fit for candidate random structures was assessed using the Akaike information criterion (AIC) (Supplementary Table 4). The optimal random structure identified included the unique publication identifier.

To explain heterogeneity in effect sizes, we incorporated moderators as fixed effects in the models using the optimal random effect structure identified in the previous step. The moderators assessed included: (1) plant material (cutting, plant, and seedling); (2) functional group (tree and shrub); (3) experimental method (potted, sterile medium, hydroponics, and field); (4) stress period (three months, six months, and more than six months); (5) plant age (one year, two years, and more than two years); (6) pH (< 6.5: acidic, 6.5–7.5: neutral, > 7.5: alkaline); and (7) HMs levels (Supplementary Table 5) [42, 91]. We then tested the significance of variation in effect sizes attributed to each moderator variable using *Q*-statistics ($p < 0.05$). We estimated mean effect sizes and variances in the best-fitting models using restricted maximum likelihood (REML). To visualize the model results, we presented the overall mean effect with 95%

confidence intervals (CIs) expressed as a percentage change (%). All analyses were conducted using the *rma.mv* function in the metafor package [92] within the R software (version 4.2.0) [93].

Publication bias

To assess publication bias in our dataset, we employed two methods in the meta-analysis. Firstly, we visually inspected funnel plots. Secondly, we applied Egger's regression method with an effective sample size to test for publication bias in the Ln*RR*, providing a test for funnel plot asymmetry and accounting for dependence on effect sizes. Thirdly, Rosenthal's fail-safe number (FSN) was calculated to estimate the number of insignificant, unpublished, or missing studies that would need to be added to negate the overall effect size [94]. According to Rosenberg [94], if the FSN exceeds 5n + 10 (where n is the number of observations), the results are considered robust. The quality of this meta-analysis was evaluated based on the quality criteria checklist (Supplementary Figs. 19–21 and Supplementary Table 6) proposed by Koricheva and Gurevitch [95]. In our meta-analysis, responses in plant biomass, HMs concentration, and physiological reactions to Cd, Cu, Zn, Sb, and As stress were found to be asymmetrical (Supplementary Figs. 19–21 and Supplementary Table 6). However, the FSN for metal stress was significantly higher than the critical threshold of 5 n + 10 (Supplementary Table 6), suggesting that publication bias is unlikely to affect our results.

Key predictors of HMs phytoremediation

In order to explore the key factors affecting the potential of phytoremediation, we first constructed several linear regression models, which mainly included the relationship between environmental pH and plant growth, physiology and HM concentrations provided by the study of included, as well as the relationship between plant HM concentrations and physiological parameters. Secondly, we used the random forest model and Shapley Additive Explanation (SHAP) models to analyze the influence of variables such as plant family, genus, functional group, trees age, HMs levels, types, climate factors, and soil properties on bioconcentration factor, translocation factor and tolerance factor. In the random forest model, the number of trees (ntree) and the number of variables at each node (mtry) were chosen based on the reduction in error rates and robust results, respectively. A tenfold cross-validation was conducted to evaluate the parameters of random forest model, with 80% of the data used as training data and the rest of the data used for validation [96]. The ‘randomForest’ [97] and ‘fastshap’ [98] package were used to predict importance and the absolute value of target variables in R software, respectively.

Declarations

Data and Code availability

The data and R code used in this study have been deposited on the GitHub digital repository under https://github.com/ZhongYu-Du/Meta-HMs/tree/main.

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Declaration of competing interest

The authors declare no competing interests.

Contributions

G.C. Chen and Z.Y. Du conceived the study.

Z.Y. Du and Y. Jiang performed the literature search and extracted effect sizes.

Z.Y. Du analysed the data.

Z.Y. Du, S.F. Wang, S. Budzyńska and G.C. Chen wrote and revised the manuscript. All authors discussed the results and contributed to the final draft.

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Ethics declarations

Competing interests

The authors declare no competing interests.

Supplementary information

Supplementary Figs. 1–21, Methods 1, Tables 1–8 and References.

Source data

Statistical source all data.

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Figures

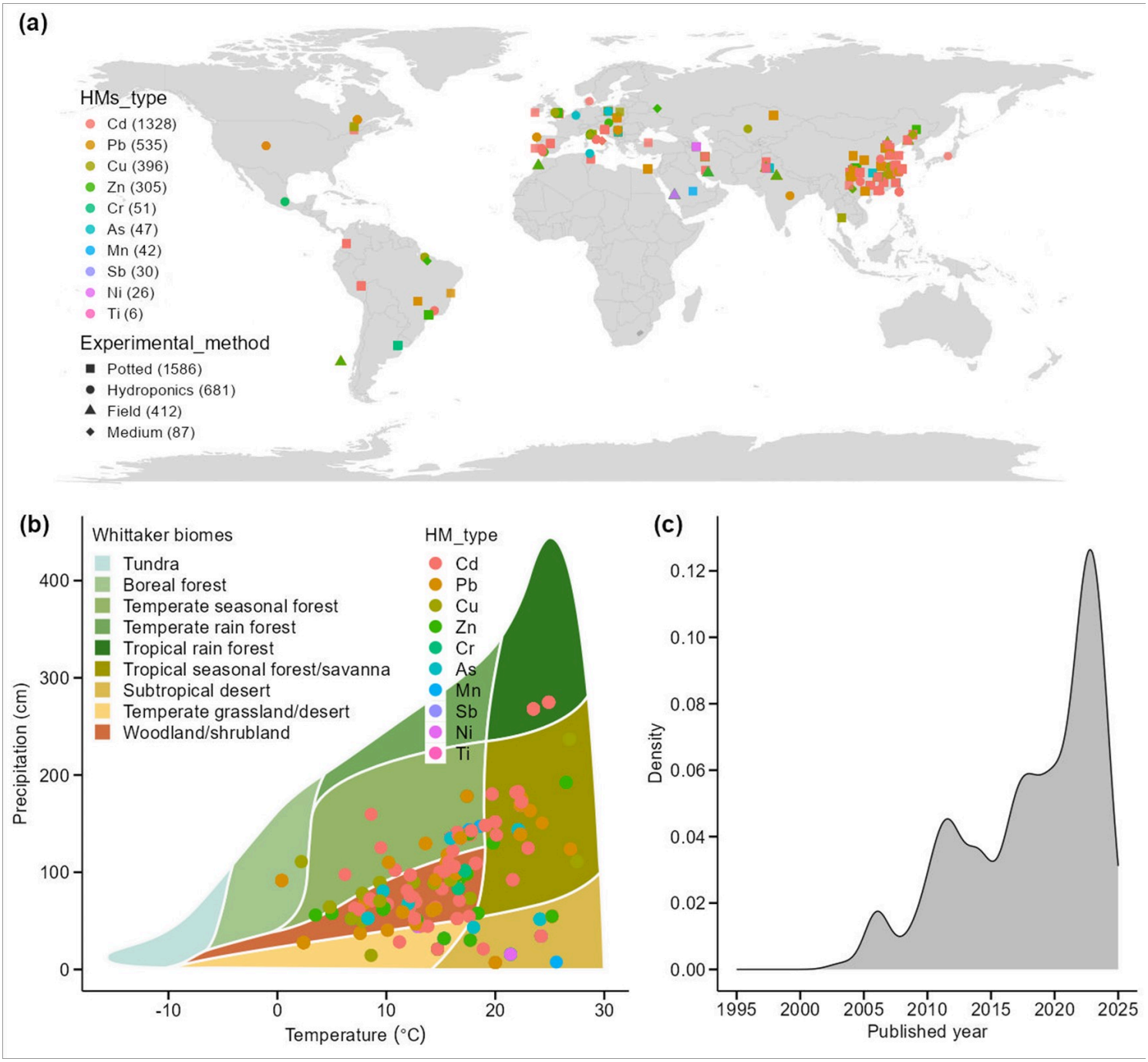


Figure 1

Distribution of experimental sites in the meta-analysis of woody plant responses to heavy metals or metal(loid)s (HMs). (a) Geographical distribution of experimental sites with metal(loid)s enrichment in plants. The values in parentheses represent the sample size for each site included in this study. (b) Distribution of sites classified according to Whittaker's biomes. (c) Temporal distribution showing the density of published studies included in the analysis.

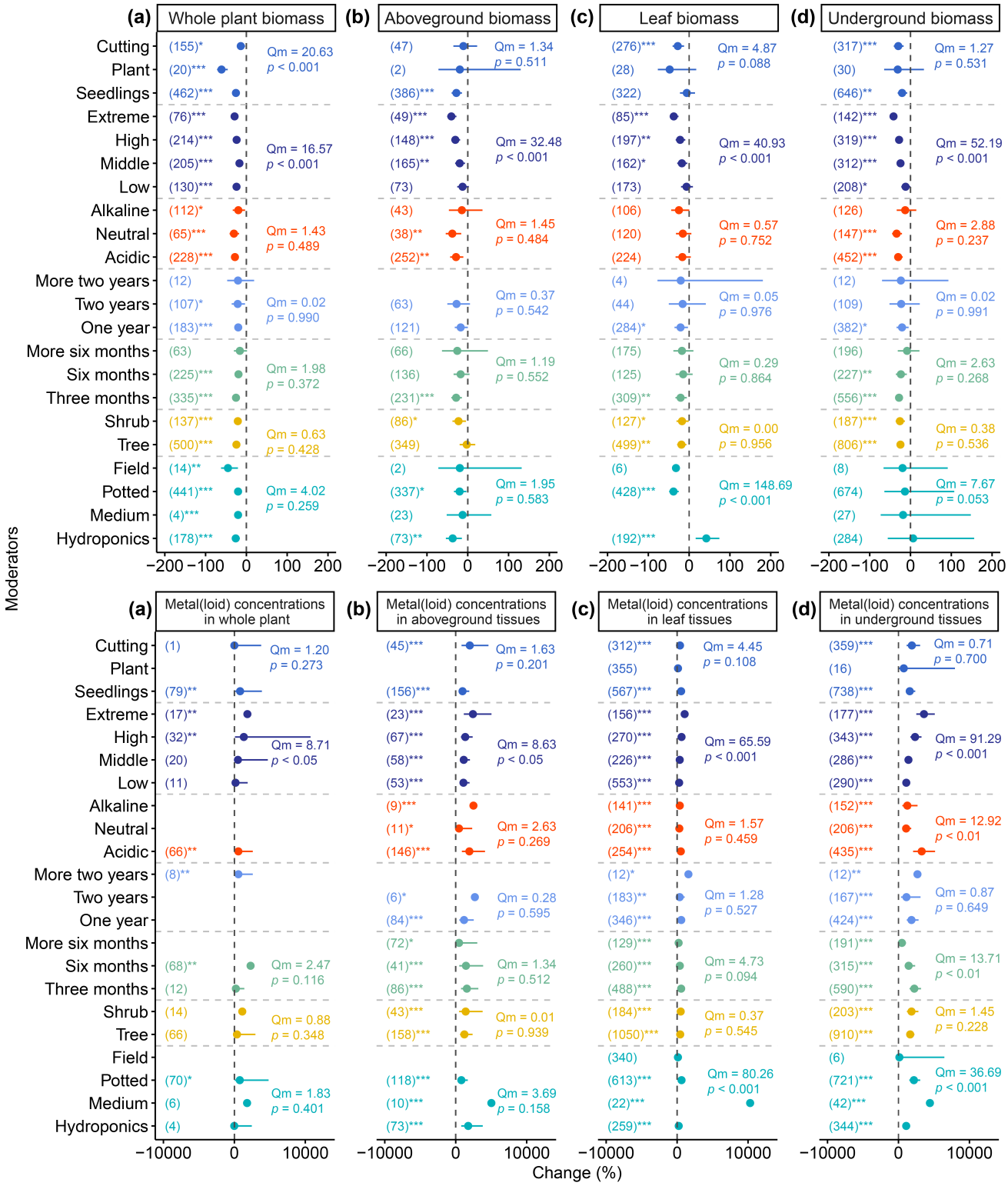


Figure 2

Biomass and metal accumulation in woody plants under HMs stress. (a) whole plant biomass, (b) aboveground biomass, (c) leaf biomass, (d) underground biomass; (e) HMs concentration in whole plant; (b) HMs concentration in aboveground part; (c) HMs concentration in leaf; (d) HMs concentration in underground part. Values in parentheses denote sample sizes (n); points represent standardized effect sizes with error bands showing ±95% CIs. Effects are significant when CIs exclude zero; asterisks

indicate significance levels (***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$). Qm and p-values quantify between-group heterogeneity and moderator effects.

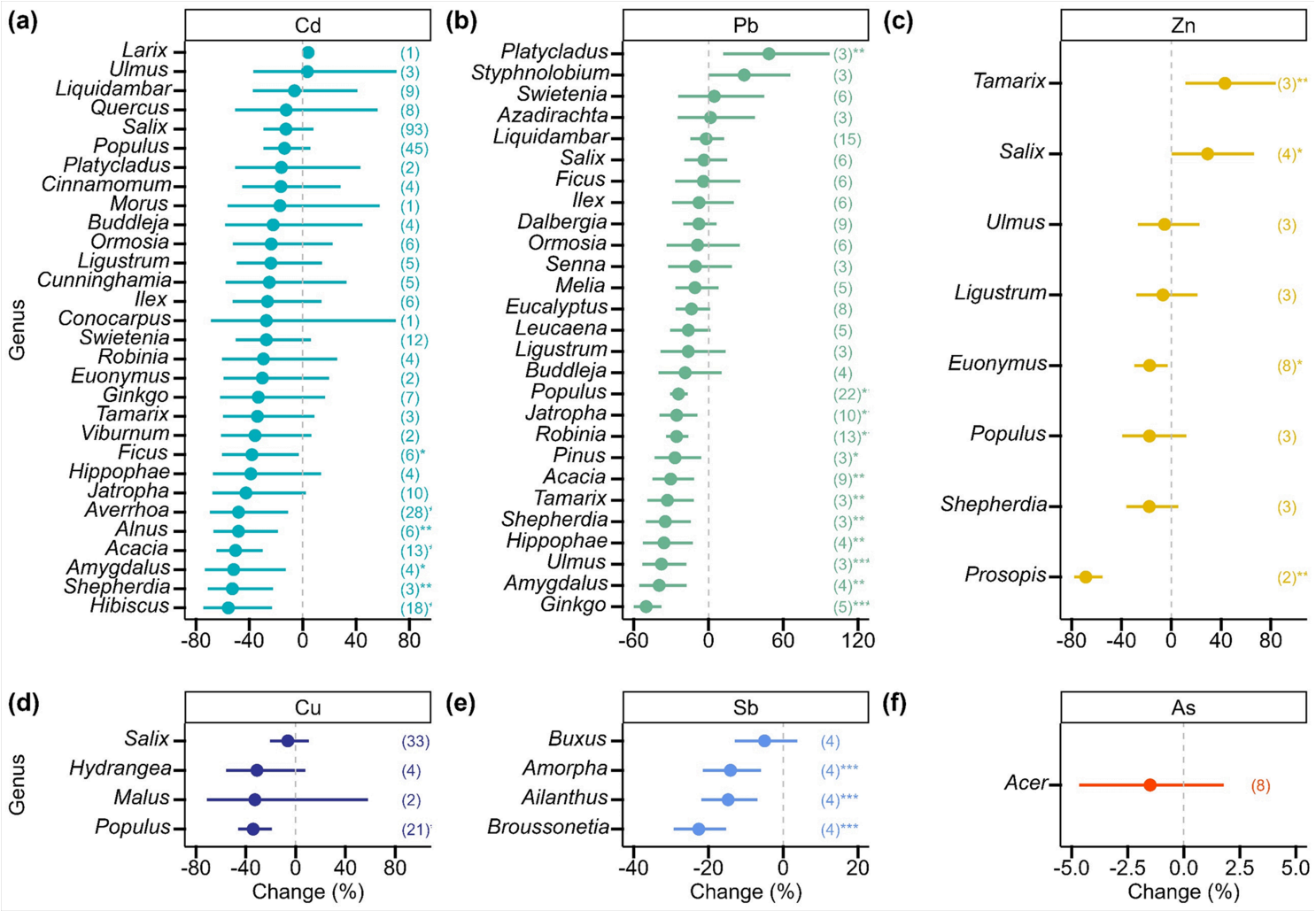


Figure 3

The whole plant biomass in different genera responses to HMs stress. (a) Cd; (b), Pb; (c), Zn; (d), Cu; (e), Sb; (f), As. Dots and error bars represent the mean effect size and the 95% confidence intervals (CIs). Numbers beside CIs indicate the sample size. ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$.

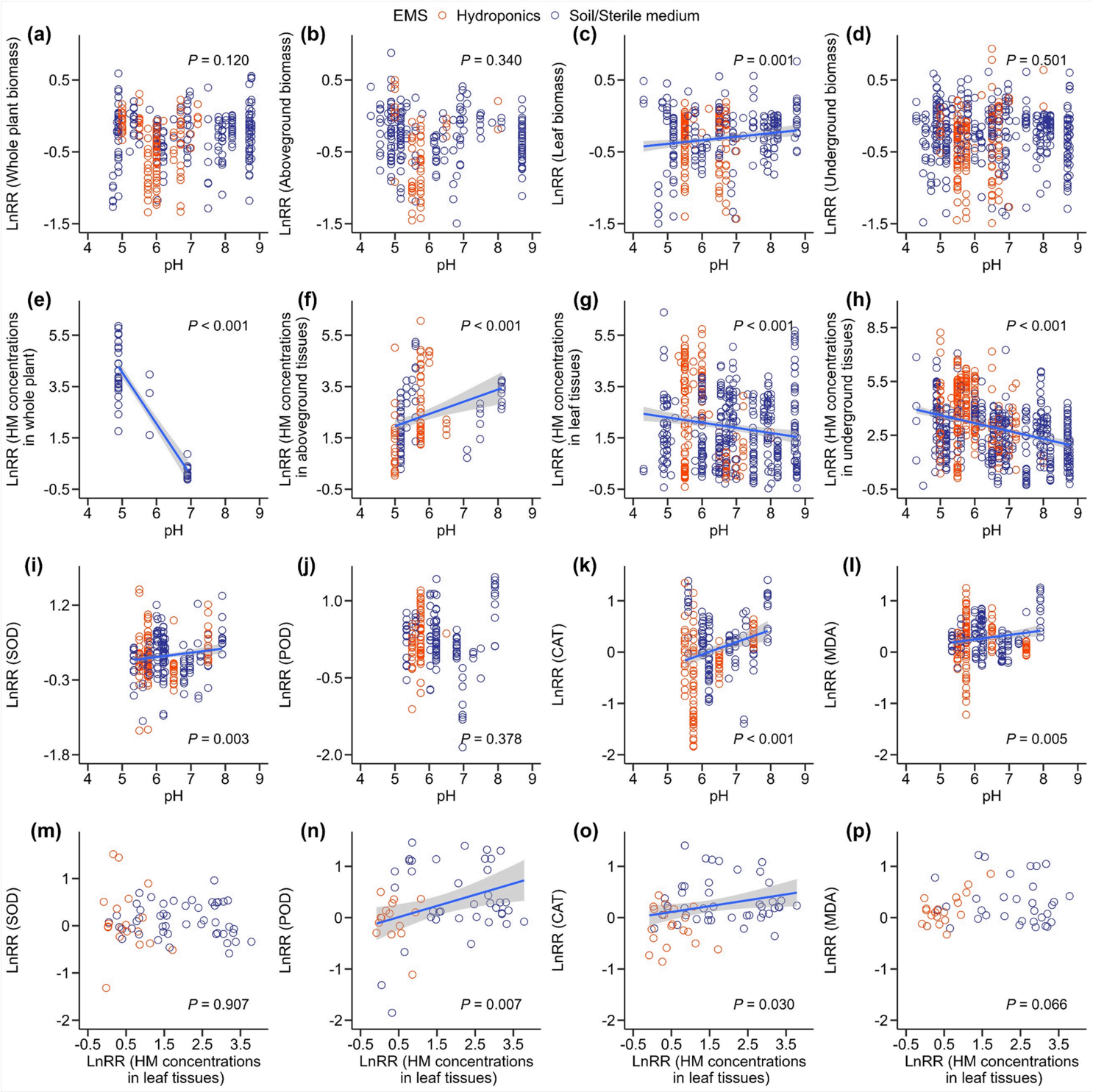


Figure 4

Relationship between pH and plant traits, physiological parameters and HMs concentration.(a) whole plant biomass, (b) aboveground biomass, (c) leaf biomass, (d) underground biomass, (e) HMs concentration in whole plant, (f) HMs concentration in plant aboveground part, (g) metal(loid)s concentration in plant leaf, (h) HMs concentration in plant underground part, (i) SOD, (j) POD, (k) CAT, (l) MDA. Correlations between (m) SOD, (n) POD, (o) CAT, (p) MDA, and HMs concentration in plant leaf.

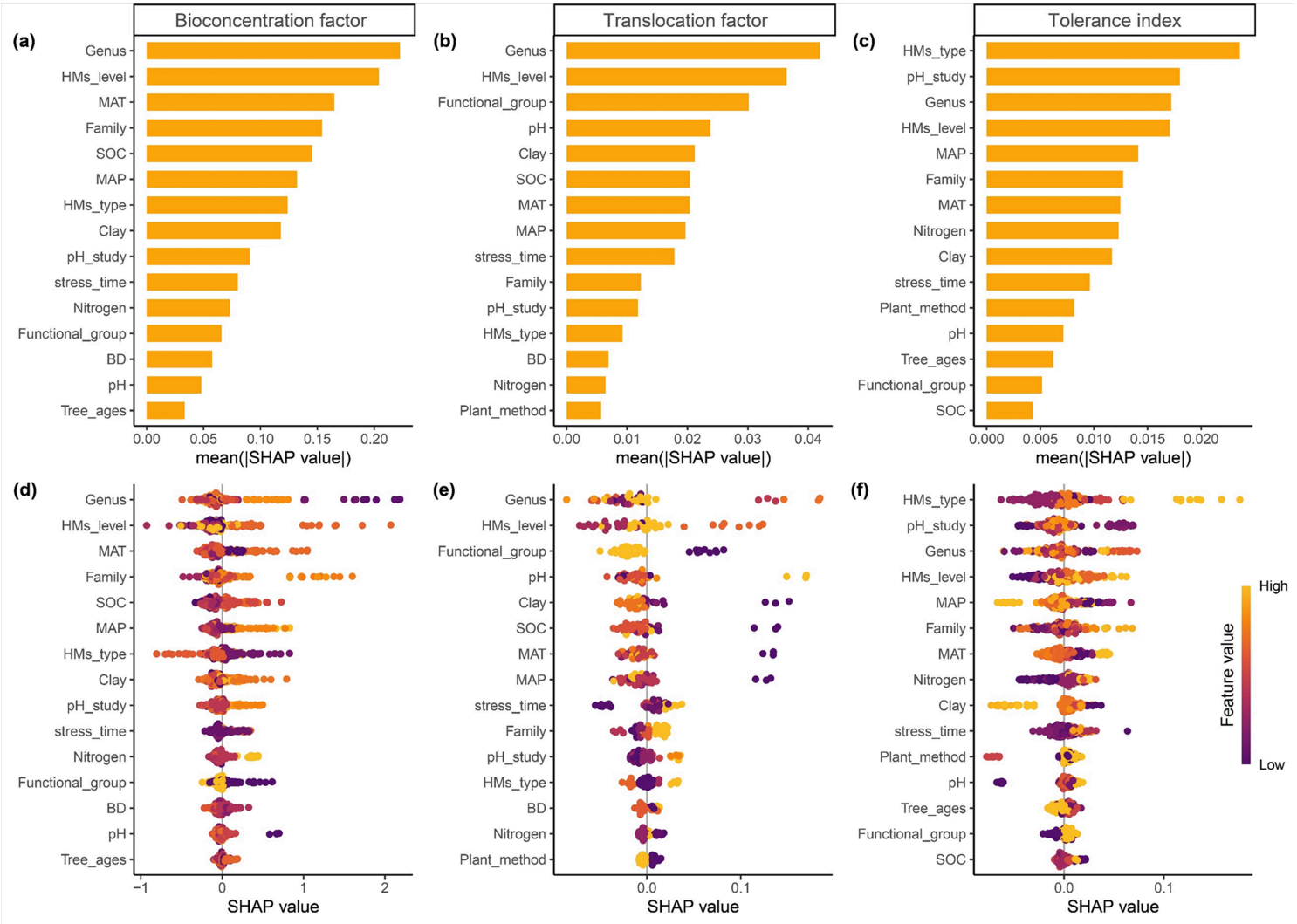


Figure 5

Dependence of leaf bioconcentration factor, translocation factor and tolerance factor on potential drivers. Importance ranking of drivers affecting leaf BCF (a, d), TF (b, e) and TF (c, f). The variable importance is assessed with its mean |SHAP| value, and all SHAP values.

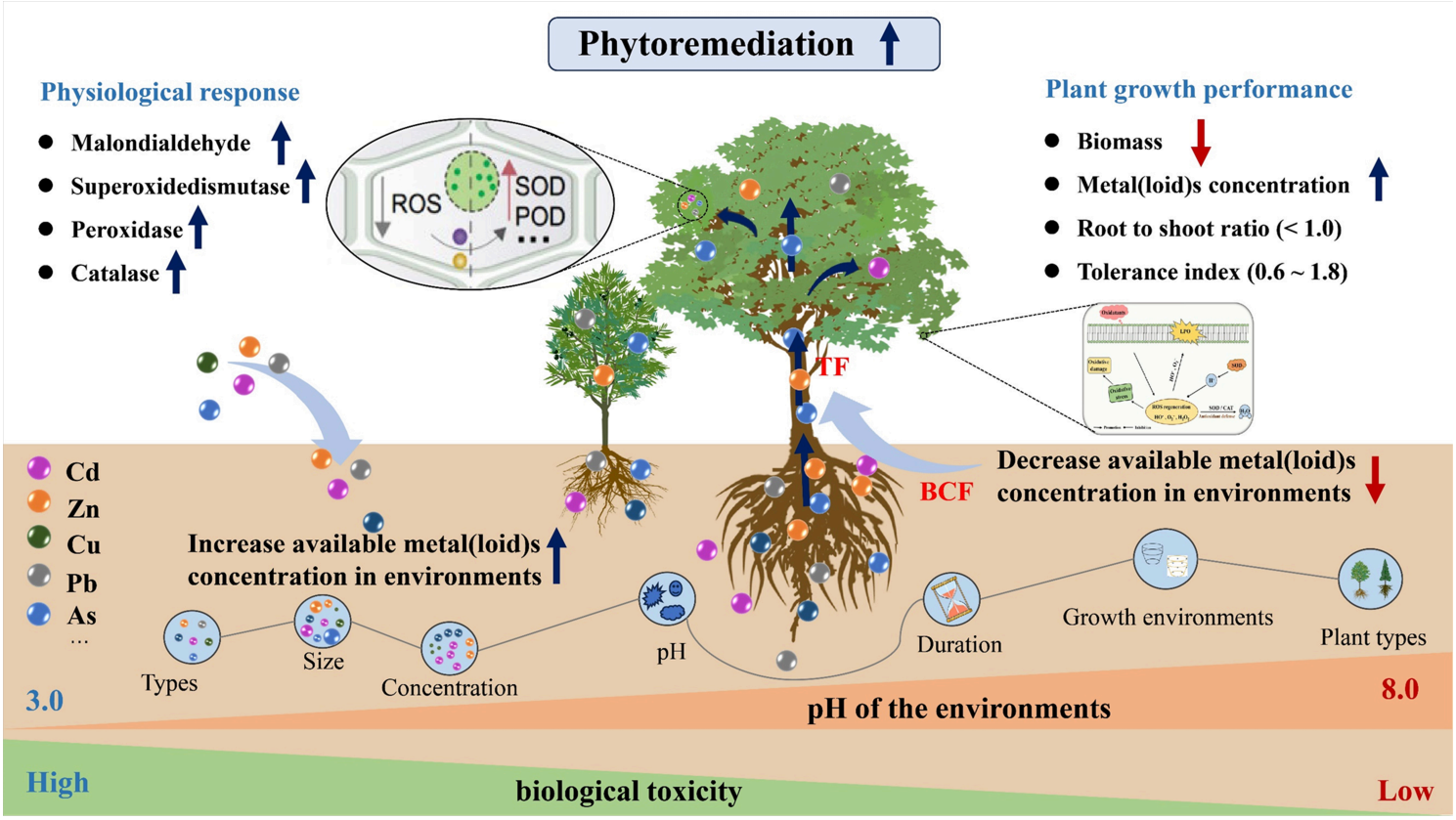


Figure 6

Phytoremediation of woody plants to HMs contamination based on a hierarchical meta-analysis.

Supplementary Files

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