Erschienen in: Biological Invasions. Springer. 2024, 26(8), S. 2595-2606
https://doi.org/10.1007/s10530-024-03332-3

Biochar produced from diverse invasive species improves remediation of cadmium-contaminated soils

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Abstract Biodiversity commonly contributes to ecosystem functioning and provides ecosystem services. Biochar application is frequently used to remediate soils contaminated with heavy metals. As many invasive plant species can quickly form huge amounts of biomass, they are potentially useful for producing biochar for remediating contaminated soils. However, it remains untested whether invasive species richness contributes to biochar-mediated soil remediation. We applied single biochar made from each of six invasive plant species and biochar mixtures (i.e., mixtures of biochar derived from 2, 3, and 6 invasive plant species) to soils contaminated with cadmium (Cd), with no biochar application as the control. We then grew native plant communities on these soils. Compared to the control, biochar application significantly decreased Cd bioavailability (−34% averaged across the three richness treatments) in the soils, and this effect increased with increasing invasive species richness involved in the biochar mixtures (from −22 to −38%). Biochar application significantly increased both the concentration (+126%) and pool size (+59%) of Cd in roots of the native plant community, although it significantly decreased its biomass (−25%). Thus, invasive species diversity can contribute to biochar-mediated remediation of soils contaminated with Cd. Our findings indicate a novel biodiversity-mediated ecosystem service, i.e., the use of multiple invasive plant species for the production of biochar. As harvesting of invasive species for biochar production may also contribute to their management, this might mitigate the two ecological problems at once.

Keywords Biochar diversity · Cd · Exotic plants · Heavy metal · Phytoremediation

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Introduction

Biological invasions have become a world-wide problem and attracted much attention (Wang et al. 2017; Pyšek et al. 2020; Zhang et al. 2023; Dong et al. 2024). Efficient control and prevention of biological invasions is the ultimate purpose of invasion biology (Sala et al. 2000; Pearson et al. 2016). Although plenty of efforts have been spent, cases of successful control of invasive species are still rare (Kuebbing and Nuñez 2014; Seastedt 2015). One potential way of invasive species control is to find the way to make better use of invasive species (Yan et al. 2017). Using biochar made from materials of invasive plant species for soil remediation could be a promising way (Liu et al. 2022; Yang et al. 2022).

Increasing industrial activities, e.g., mining, milling and smelting, have aggravated the extent of heavy metal pollution in soils (Khan et al. 2017; Mazurek et al. 2017), which is detrimental to plants and animals through groundwater and food chains (Cortad et al. 2018; Palansooriya et al. 2020). Among various heavy metals, cadmium (Cd) is considered one of the most serious pollutants due to its high toxicity and mobility, and thus easiness to pass into the food chain (Reimann et al. 2019; Adomako et al. 2020; Haider et al. 2021; Adomako and Yu 2023). According to the National General Survey Report on soil contamination, announced by former Chinese Ministry of Environment Protection (MEP) and Ministry of Land and Resources (MLR), environmental pollution by Cd has ranked the first among that by heavy metals in China (MEP and MLR 2014).

Many techniques have been proposed to remediate soils contaminated with heavy metals (Khalid et al. 2017). One technique is based on the use of biochar, a charcoal-like substance produced through the pyrolysis of organic material. Biochar can immobilize heavy metals in soils due to its specific physico-chemical properties (Godlewska et al. 2017; Guo et al. 2020), which is considered as a cost-effective and environmental-friendly approach to in situ remediate contaminated soils (Kamran et al. 2019; Wang et al. 2020). Recently, invasive plant species have been considered as excellent materials to make biochar (Nguyen et al. 2021; Simmons et al. 2021; Liu et al. 2022), which is potentially a promising measure for invasive plant management.

In non-native ranges, invasive alien plants frequently displace native plants due to their rapid growth and high competitive ability (van Kleunen et al. 2018; Pyšek et al. 2020). Thus, they sometimes form monocultures with a huge amount of biomass (Hooper et al. 2005; Kuebbing et al. 2015; Wang et al. 2022a). These properties give invasive plant species great potential to be used as raw materials for biochar production (Yang et al. 2022). The few studies on the roles of biochar derived from invasive plant species in remediating soils indicate that application of single biochar (i.e., derived from single invasive plant species) could potentially reduce bioavailable Cd in soils (Cai et al. 2020; Lian et al. 2020; Wang et al. 2021). However, the effect of biochar mixtures derived from diverse invasive plant species on remediation of heavy metal-contaminated soils is still unknown.

Biodiversity plays an important role in ecosystem functioning (Hooper et al. 2005; Tilman et al. 2014; Isbell et al. 2018). However, studies on biodiversity-ecosystem functioning relationships have focused mostly on the roles of native species diversity (Duffy et al. 2017; Jactel et al. 2018; Adomako et al. 2019; Xue et al. 2022; Huang et al. 2023). By contrast, the potential roles of invasive species diversity have been little considered (but see Wang et al. 2022a; Wang et al. 2022b). Because biodiversity can contribute to ecosystem functioning, we hypothesize that invasive species richness can contribute to biochar-mediated remediation of contaminated soils. In other words, compared to biochar made from single invasive plant species, a mixture of biochar made from a high number of invasive plant species promotes the ability of biochar to remediate contaminated soils. One potential mechanism is that biochar derived from different plant species varies in its properties and may consequently have synergistic effects that promote the phytoremediation ability of biochar mixtures.

To test the role of invasive species diversity, we applied biochar derived from each of six invasive plant species (*Bidens frondosa*, *Bidens pilosa*, *Conyza canadensis*, *Sesbania cannabina*, *Solidago canadensis,* and *Symphyotrichum subulatum*), and biochar mixtures made from 2, 3 and 6 invasive plant species to soils contaminated with Cd. We also had a control treatment without biochar application. We then constructed a native plant community in these soils to absorb available Cd, aiming to reduce bioavailable Cd in soils. Specifically, we tested three hypotheses:

(1) increasing the number of invasive plant species involved in biochar will reduce bioavailable Cd in the soils due to synergistic interactions among biochar of different invasive species (Hypothesis I); (2) due to decreased bioavailable Cd in the soils, productivity (biomass) of the native plant community will increase with increasing the number of invasive plant species involved in biochar production (Hypothesis II); (3) due to greater productivity, plant communities grown in the soils with biochar made from a higher number of invasive plant species will store and thus stabilize more Cd in their tissues, leading to a larger Cd pool size in plants (Hypothesis III).

Materials and methods

Invasive species, and biochar production and characterization

Six invasive plant species, i.e., *Bidens frondosa* L. (Asteraceae), *Bidens pilosa* L. (Asteraceae), *Conyza canadensis* (L.) Cronq. (Asteraceae), *Sesbania cannabina* (Retz.) Poir. (Fabaceae), *Solidago canadensis* L. (Asteraceae) and *Symphyotrichum subulatum* (Michx.) G.L. Nesom (Asteraceae), were used to produce biochar. These invasive plant species all have large biomass and are commonly found in Taizhou, Zhejiang Province, China (Table S1). *B. frondosa*, *B. pilosa*, *C. canadensis*, *S. cannabina* and *S. subulatum* are annals and *S. canadensis* is perennial. *S. canadensis* is capable of clonal growth, and the other five species are non-clonal plants. All six species have invaded many provinces in China (Qin et al. 2024).

In November 2020, aboveground parts of the six invasive plant species were harvested, oven-dried, and ground. Then, the ground materials of the six invasive species were individually pyrolyzed in a muffle furnace (Nabertherm LT5/11, Germany) at 450 °C for 2 h at a heating rate of 10 °C min^{-1}, as done in previous studies (e.g., Cai et al. 2020; Jain et al. 2020). The biochar products were ground into powder and then passed through 0.2 mm mesh.

The characteristics of biochar, i.e., yield, ash content, cation exchange capacity (CEC), carbon (C) and nitrogen (N) concentrations, pH, specific surface area (S_{BET}) and total pore volume (V_{total}), of each of the six invasive species are shown in Table S2. A scanning electron microscope (Phenom Pro, Thermo Fisher Scientific, USA) was used to observe the surface morphology of biochar (Fig. S1). A Fourier transform infrared spectroscope (IS10, Thermo Fisher Scientific, USA) was used to determine the chemical functional groups of biochar in the range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1} (Fig. S2).

Native species and seedling preparation

The native plant community consisted of two grasses (*Arthraxon hispidus* (Thunb.) Makino and *Cynodon dactylon* (L.) Pers.), one forb (*Plantago asiatica* L.) and one legume (*Astragalus sinicus* L.). These species are common herbs distributed in Taizhou (Table S1). The seeds of *A. hispidus* were collected in the campus of Taizhou University, whereas seeds of the other three native plants (*C. dactylon*, *P. asiatica* and *A. sinicus*) were purchased from a local supplier in Taizhou. On 22 March 2021, the seeds were sown in plastic pots (54 cm in length × 28 cm in width × 5 cm in depth) filled with peat in a greenhouse (temperature, 25 °C; relative humidity, 80%) at Taizhou University. One month later, for each species, seedlings of similar size were chosen for the experiment described below.

Experimental design

A pot experiment was carried out in the same greenhouse used for seed germination and seedling cultivation. We filled 66 pots (3L) with soil mixture (field soil: river sand = 1:1, v/v). Both field soil and river sand were collected in Taizhou. The field soil contained 0.39 ± 0.01 (mean ± SE) g kg^{-1} total N, 0.64 ± 0.04 g kg^{-1} total phosphorus (P), and 10.04 ± 1.03 g kg^{-1} organic carbon, with CEC of 11.69 ± 1.78 cmol kg^{-1} and pH of 6.45 ± 0.98. To simulate Cd-contaminated soil, 10 mg kg^{-1} Cd in the form of $CdCl_2$ was added to the soil in each pot. Then, the soil was watered and stirred every day to make sure that Cd was distributed evenly. The Cd-contaminated soil was allowed to stabilize for two months before use (Zhang et al. 2019). The amount of Cd added is close to the Cd concentration in some contaminated soils in Taizhou (Wu et al. 2019).

The experiment consisted of one control (no biochar added to the Cd-contaminated soil) and four levels of biochar diversity, i.e., application of biochar made from 1, 2, 3 or 6 invasive plant species

(Table S3). For the 1-species treatment, biochar of each of the six invasive plant species was applied to the soils in three pots, resulting in 18 pots. For the 2-species treatment, 12 different 2-species biochar mixtures were randomly chosen and applied to 12 pots. Similarly, for the 3-species treatment, 12 different 3-species biochar mixtures were randomly chosen and applied to 12 pots. The 2- and 3-species biochar mixtures were selected according to the criterion that biochar from each species was used the same number of times, similar to the design of many biodiversity experiments (Naeem et al. 1996; Hector et al. 1999; Wang et al. 2022a). For the 6-species treatment, the biochar mixture of the six invasive species was applied to 12 pots. As there were only 6 invasive species in total, the 6-species treatment was not replicated at the species composition level. For the treatment without biochar, 12 replicates (pots) were used. For all treatments with biochar, the same amount of biochar, i.e. 30 g per pot [equivalent to a total weight of 1% (w/w)], was added into the soil mixture (Jain et al. 2020). Thus, for the 1-, 2-, 3- and 6-species treatments, we added 30, 15, 10 and 5 g biochar of each species, respectively, to the soil in each pot.

One week after biochar application, on 22 April 2021, each of the 54 pots with biochar application and the 12 pots without biochar application were planted with eight seedlings, consisting of two seedlings of each of the four native plant species. During the first two weeks after transplantation, the dead seedlings were replaced immediately. All pots were watered every two days. No additional fertilizer was applied during the experiment.

Harvest

On 22 August 2021, we harvested shoots (the aboveground parts) and roots of the plant community in each pot. Both shoots and roots were oven-dried, weighed, and then ground into powder. The powder was used to measure concentrations of total Cd, total N and total P. A soil sample (30 g) was collected from each pot for the analysis of Cd, N, P, organic C and pH in the soil.

Soil chemical properties

Bioavailable Cd in the soil was extracted using diethylenetriamine pentaacetic acid according to the method of Lindsay and Norvell (1978), and then its concentration was measured by ICP-MS (NexION 2000B, Perkinelmer, America). Soil total N and P concentrations were measured with Auto Analyzer 3 (Bran & Luebbe, Norderstedt, Germany) after digestion with a mixture of sulfuric and perchloric acid at a ratio of 10:1. Soil organic carbon (SOC) concentration was measured by dichromate oxidation in sulfuric acid solution (Sims and Haby 1971). Soil pH was measured with a soil to water ratio of 1:2.5 (w/v; g/ml).

Plant Cd, N and P concentrations

The tissue Cd concentration was measured by ICP-MS (NexION 2000B, Perkinelmer, America) after digestion with a mixture of sulfuric and perchloric acid (10:1). The N and P concentrations in plants were measured with Auto Analyzer 3 (Bran & Luebbe, Norderstedt, Germany) after digestion with a mixture of sulfuric and perchloric acid at a ratio of 10:1.

Data analysis

All analyses were performed using R version 4.1.0 (www.r-project.org). Linear mixed models were used to test for the effects of biochar treatment (0, 1, 2, 3 and 6 invasive species) on the concentrations of soil bioavailable Cd, SOC, total N and total P, soil pH, shoot biomass, root biomass and total biomass of the native plant communities, and the concentrations and pool sizes (concentration multiplied by biomass) of Cd, N and P in both shoots and roots of the plant communities. In these models, biochar treatment was included as a fixed factor and species composition as a random factor. One-way ANOVAs were used to test for the effects of species identity (i.e., biochar derived from each of the six invasive species) on these variables. Linear regression was used to examine the relationships of soil bioavailable Cd with soil pH, SOC, total N and total P. Tukey's test was used for multiple comparisons. Residuals of all variables were checked for homoscedasticity and normality. The data on the Cd concentration in shoots, and the pool sizes of P in both shoots and the whole plants of the native plant community were log-transformed before analysis.

A significant effect of biochar diversity could be because increasing the number of invasive species

involved in the biochar mixtures increases the likelihood of including biochar made of an invasive plant species with a strong and dominant effect. It could also be driven by interactions among biochar made of different invasive species, which could be specific to certain invasive species combinations or be a general effect. To disentangle these two potential mechanisms (identity vs. interaction effects) underlying the significant biochar diversity effect on soil bioavailable Cd, the hierarchical diversity-interaction modeling framework of Kirwan et al. (2009) was applied. Five hierarchical models for soil bioavailable Cd were run to specify different assumptions, which focused on the contributions of biochar made of individual invasive plant species and their interactions to the Cd-immobilization effect. Then, these models were compared using likelihood-ratio tests (see Methods S1 for details).

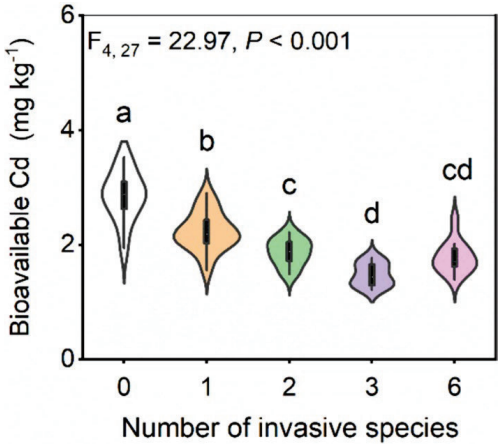

Fig. 1 The violin plot of the bioavailable Cd concentration in the soil without biochar (0) or with biochar of 1, 2, 3 and 6 invasive species. F-values and *P* values of the linear mixed model are given. Different letters indicate significant differences among the biochar treatments

Results

Characterization of biochar

Biochar derived from the six invasive species differed in ash content, pH, CEC, C and N concentrations, S_{BET}, V_{total}, surface functional groups and surface morphology (Table S2; Figs. S1 and S2). pH of biochar derived from *S. cannabina* and *S. subulatum* were significantly lower than that of biochar derived from the other four invasive species (Table S2). CEC of biochar derived from *B. pilosa* was the highest, while that of biochar from *S. cannabina* was the lowest (Table S2). Among biochar of the six invasive species, relatively high values of S_{BET} and V_{total} were obtained for biochar derived from *S. canadensis* (Table S2). Biochar from *B. pilosa* had a more porous structure than biochar from the other five invasive species (Fig. S1).

Effects of biochar application and diversity on soil parameters

Compared to the control (no biochar application), biochar application significantly decreased the concentration of soil bioavailable Cd, and this decrease became more pronounced with increasing biochar diversity (Table S4; Fig. 1, $P < 0.001$). In the hierarchical diversity-interaction modeling, the model incorporating separate-pairwise interactions showed the best fit for soil bioavailable Cd (Table 1), suggesting that the biochar diversity effect on soil bioavailable Cd was mainly driven by specific pairwise interactions.

Compared to the soil mixed with biochar, the soil without biochar had lower pH, SOC and total N, but higher total P (Fig. 2). With increasing biochar diversity from one to six species, soil pH first increased, reached the highest value in the 2-species treatment and then decreased (Fig. 2a, $P < 0.001$). SOC showed the opposite patten (Fig. 2b, $P < 0.001$). Neither soil total N nor soil total P was influenced by biochar diversity (Fig. 2c, d). Soil bioavailable Cd and soil pH (Fig. S3a–b) varied among the six 1-species treatments. SOC, soil total N and soil total P did not vary significantly among the 1-species treatments (Fig. S3c–e).

Soil bioavailable Cd showed a negative correlation with soil pH (Fig. 3a, $P = 0.002$), SOC (Fig. 3b, $P < 0.001$) and soil total N (Fig. 3c, $P < 0.001$). However, it showed a positive relationship with soil total P (Fig. 3d, $P < 0.001$).

Effects of biochar application and diversity on plant community productivity

Neither biochar application nor biochar diversity influenced shoot biomass ($P = 0.073$) or root biomass ($P = 0.078$) of the native plant community (Table S4;

Table 1 Contributions of invasive plant species (IPS) identity and interactions to the biochar-diversity effect on soil bioavailable Cd

Model (reference model number)	Df	AIC	logLik	χ^2	*P*
1. Null	–	44.45	− 18.23	–	–
2. Invasive plant species (IPS) identity (1)	5	54.74	− 18.37	0.29	0.998
3. Separate-pairwise IPS interactions (4)	14	**24.58**	**11.71**	**48.57**	**< 0.001**
4. Average IPS interaction (2)	1	45.14	− 12.57	11.60	< 0.001
5. Additive IPS-specific interaction contributions (3)	9	44.05	− 7.03	37.48	< 0.001

Comparison of the hierarchical diversity interaction models (Methods S1) based on log-likelihood ratio tests to assess individual IPS and IPS-interaction contributions to the biochar diversity effect on soil bioavailable Cd. The statistics (AIC, logLik, χ^2 and *P*) of the best fitting models are highlighted in bold

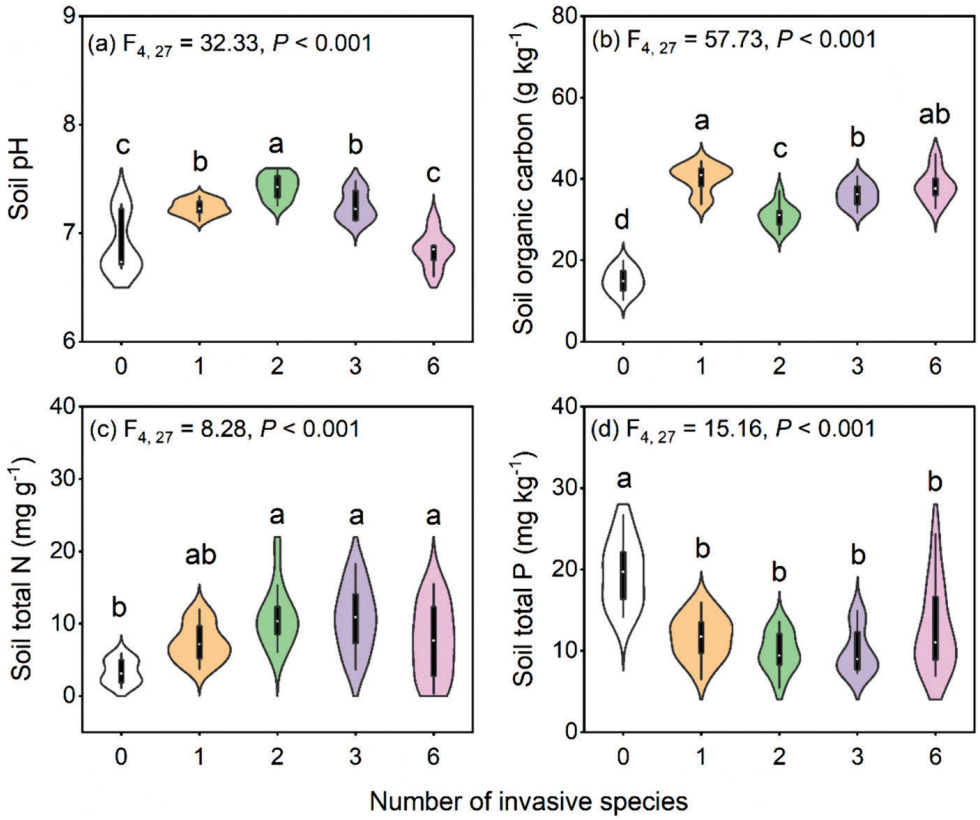

Fig. 2 Violin plots of pH (**a**), organic carbon (**b**), total N (**c**) and total P (**d**) in the soil without biochar (0) or with biochar of 1, 2, 3 and 6 invasive species. F-values and *P* values of the linear mixed models are given. Different letters indicate significant differences among the biochar treatments

Fig. 4). However, total biomass was significantly higher in the control than in the 6-species treatment ($P = 0.027$, Table S4; Fig. 4). Biomass of the plant community did not vary significantly among the six 1-species treatments (Fig. S4).

Effects of biochar application and diversity on plant Cd, N and P

Both the concentration (Table S4; Fig. 5a, b, $P < 0.001$) and pool size (Table S4; Fig. 6a, b, $P < 0.001$) of Cd were much lower in shoots than in roots of the native plant community. Biochar application tended to decrease Cd (both in concentration and in pool size) in shoots (Figs. 5a and 6a), but only the 6-species treatment decreased it significantly (Figs. 5a and 6a). By contrast, biochar application significantly increased Cd concentrations (Fig. 5b) and pool sizes (Fig. 6b) in roots, both of which, however, varied little from the 1-species to the 6-species treatments (Figs. 5b and 6b). Only the 1-species treatment significantly increased the Cd pool size in the whole plant (Fig. 6c).

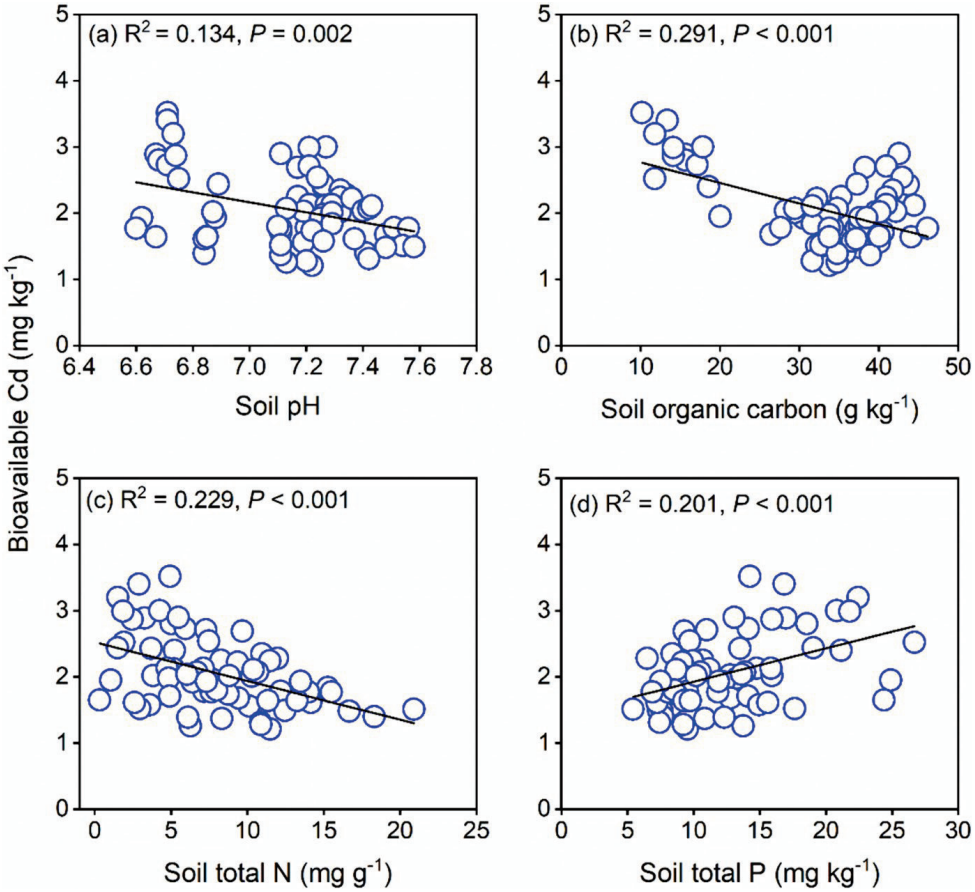

Fig. 3 Relationships of the concentration of bioavailable Cd in the soil with soil pH (**a**), soil organic carbon (**b**), soil total N concentration (**c**) and soil total P concentration (**d**)

Neither biochar application nor biochar diversity significantly affected the concentrations (Table S5; Fig. S5) or the pool sizes (Table S5; Fig. S6) of N and P in the tissues of the native plant community. Except for a little variation in the Cd pool size in shoots (Fig. S8a), the concentrations and pool sizes of Cd, N and P in the native plant community did not vary among the six 1-species treatments (Figs. S7 and S8).

Discussion

The fast growth and the huge amount of biomass produced by some invasive plant species make them potentially useful to manufacture biochar for soil remediation, and harvesting invasive plants for this purpose can contribute to their management (Cai et al. 2020; Lian et al. 2020). Our results indeed found that application of biochar made of invasive plant species significantly decreased soil bioavailable Cd and that this effect increased with increasing diversity of invasive species involved in biochar. These results suggest that invasive species diversity can contribute to the process of biochar-mediated soil remediation. Surprisingly, however, productivity of native plant species did not increase with increasing biochar diversity of invasive species despite the decrease in bioavailable Cd in the soils.

Bioavailability of Cd determines its toxicity in soils and the potential risk of entering food chains (Reimann et al. 2019; Haider et al. 2021). We found that the bioavailable Cd concentration in the soils decreased with application of biochar made from invasive plant species. This effect of biochar has also been observed for biochar derived from non-invasive plant species (Mohamed et al. 2015; Kamran et al. 2019; Hamid et al. 2020). Previous studies have reported that application of biochar promoted the immobilization of Cd in soils (Li et al. 2019a; Tu et al. 2020). Decreased Cd bioavailability may be caused by the intrinsic properties of biochar, e.g., the highly porous structure, high pH, CEC and number of chemical functional groups (Ahmad et al. 2014). Soil pH can regulate the mobility of Cd in soils via

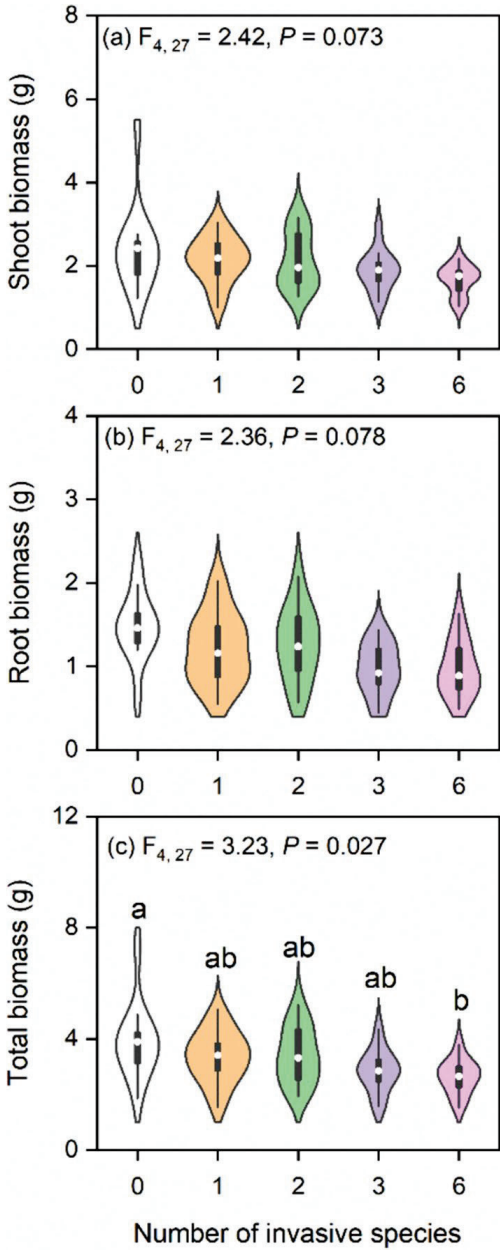

Fig. 4 Violin plots of shoot (**a**), root (**b**) and total biomass (**c**) of the native plant communities grown in the soil without biochar (0) or with biochar of 1, 2, 3 and 6 invasive species. F-values and *P* values of the linear mixed models are given

adsorption and desorption through the exchange between H^+ and Cd^{2+}, and a high pH could facilitate Cd immobilization in soils by increasing the negative surface charge of soil particles (Dong et al. 2009). Biochar can be used as a liming material, thereby ameliorating soil acidity and reducing the toxicity of potential toxic elements (Bolan et al. 2023). Partly in agreement with this view, we found that decreased Cd bioavailability induced by biochar might largely be due to higher soil pH (Figs. 2a and 3a). Biochar might also decrease bioavailable Cd in soils by increasing the amount of SOC as high SOC can promote the immobilization of Cd in soils (Mansoor et al. 2021; Yao et al. 2021). Indeed, in this study, biochar application caused an increase in SOC, and bioavailable Cd decreased with increasing SOC (Figs. 2b and 3b). All these results suggest that the biochar effects on soil Cd immobilization may have resulted from the direct Cd absorption due to its physical properties on the one hand, and from the changed soil properties on the other hand (Palansooriya et al. 2020).

In line with our hypothesis I, bioavailable Cd in soils significantly decreased with increasing biochar diversity of invasive plant species (Fig. 1). This result suggests that biochar derived from a higher number of invasive plant species could lead to a higher potential of immobilizing Cd from soils. Because biochar produced from different invasive plant species differed greatly in many characters such as pH, CEC, C and N concentrations, S_{BET}, V_{total}, surface functional groups and surface morphology (Table S2; Figs. S1 and S2), and the biochar diversity effect was very likely caused by synergistic interactions among biochar of different invasive species. This explanation is supported by the results of the hierarchical diversity-interaction modeling showing that specific interactions among biochar of different invasive plant species contributed to the biochar diversity effect on soil bioavailable Cd (Table 1). Thus, the use of biochar mixtures, particularly derived from three different invasive plant species (Fig. 1), could be an efficient approach to help remediate soils contaminated with heavy metals and possible also other pollutants.

As bioavailable Cd in soils decreased with the increase in biochar diversity of invasive species, it is reasonable to expect a promoted growth of the native plant communities growing in these soils (hypothesis II). Also, biochar application, due to its benefits such as increased nutrient supply, water conservation and microbial activity (Sohi et al. 2010; Liu et al. 2013), is generally considered to increase plant growth (Houben et al. 2013; Li et al. 2019b). Surprisingly, however, our results showed that biochar application did not promote plant growth (Fig. 4c). Furthermore, biochar application did not affect the N and P concentrations in plant tissues (Fig. S5), although it increased the N concentration and decreased the P

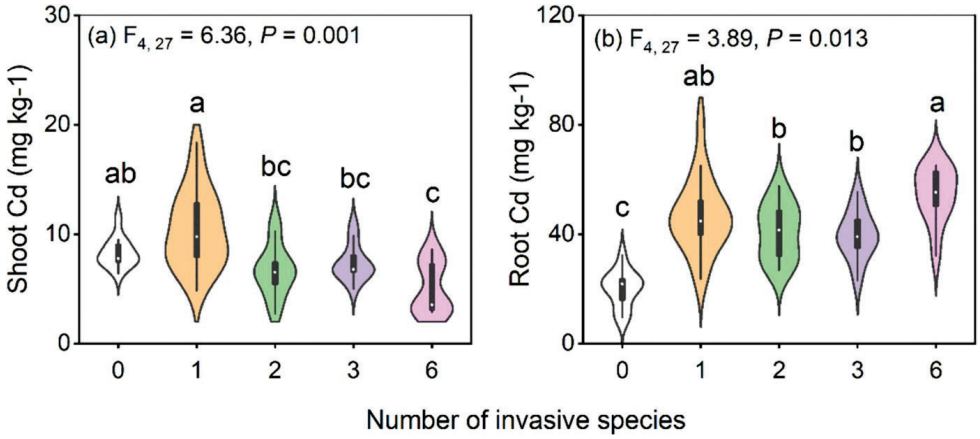

Fig. 5 Violin plots of the Cd concentration in shoots (**a**) and roots (**b**) of the native plant communities grown in the soil without biochar (0) or with biochar of 1, 2, 3 and 6 invasive species. F-values and *P* values of the linear mixed models are given. Different letters indicate significant differences among the biochar treatments

concentration in the soil. Possibly, an overall shortage of nutrients in the soils might have contributed to the decreased growth of the plant community following the application of biochar, as no extra nutrients were applied during the experiment. This has been evidenced by many studies on soil fertility, crop production and remediation, in which biochar application showed neutral or even negative effects, unless fertilizers were added (Asai et al. 2009; Scheer et al. 2011; Kuppusamy et al. 2016). Decreased biomass of the plant community, may also be attributed to higher Cd concentrations in roots in conjunction with unchanged N and P in both aboveground parts and roots (Fig. S5).

We found that biochar application increased both the Cd concentration and the pool size in roots, but only decreased those in shoots in the 6-species treatment (Figs. 5a, b and 6a–c). However, the plant community did not store more Cd in tissues with increasing the number of invasive species involved in biochar mixtures, which does not support our hypothesis III. When absorbing soil nutrients and water, roots will inevitably absorb Cd^{2+} from the soil. However, high Cd concentrations in roots accompanied by low Cd concentrations in shoots suggest that Cd was not effectively translocated between plant tissues. This indicates, similar to previous studies (Moon et al. 2013; Khan et al. 2021), that biochar application promoted in situ immobilization of Cd belowground without Cd accumulation in aboveground biomass.

One caveat is that the highest diversity level of the biochar mixtures (6-species treatment) was not replicated at the species composition level as there were only six species available, and thus the impact of the 6-species treatment could be only due to the specific species composition. This may be the reason that increasing biochar diversity from three to six species did not increase further the efficiency of soil remediation (Fig. 1). Despite this limitation, we clearly found that the increase of biochar diversity from one to three invasive plant species significantly increased the soil remediation effect, suggesting that the increase of invasive plant species richness can promote the efficiency of contaminated soil remediation.

We conclude that biochar diversity of invasive plant species can improve remediation of Cd-contaminated soils. Our findings thus indicate a novel biodiversity-mediated ecosystem service, i.e., the use of multiple invasive plant species for the production of biochar. As harvesting of invasive species for biochar production may also contribute to their management, this might mitigate the two ecological problems at once. Our findings highlight the potential use of invasive plant species for phytoremediation of contaminated soils, and provide new insights into invasive plant management and the novel roles of biodiversity in ecosystem functioning. We suggest further studies for the roles of invasive species diversity in other aspects of ecosystem functions and services.

Author contributions XW and FHY conceived the ideas and designed the experiments. XW, WLZ, HMY performed the experiments. XW analyzed the data and prepared the manuscript. MHL, MvK and FHY improved the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Funding We thank two anonymous reviewers for their valuable comments. This study was supported by the National Key R&D program (2023YFE0124900), Taizhou Scientific and Technological Project (23nya19; 22gya05) and Natural Science Foundation of China (32071527).

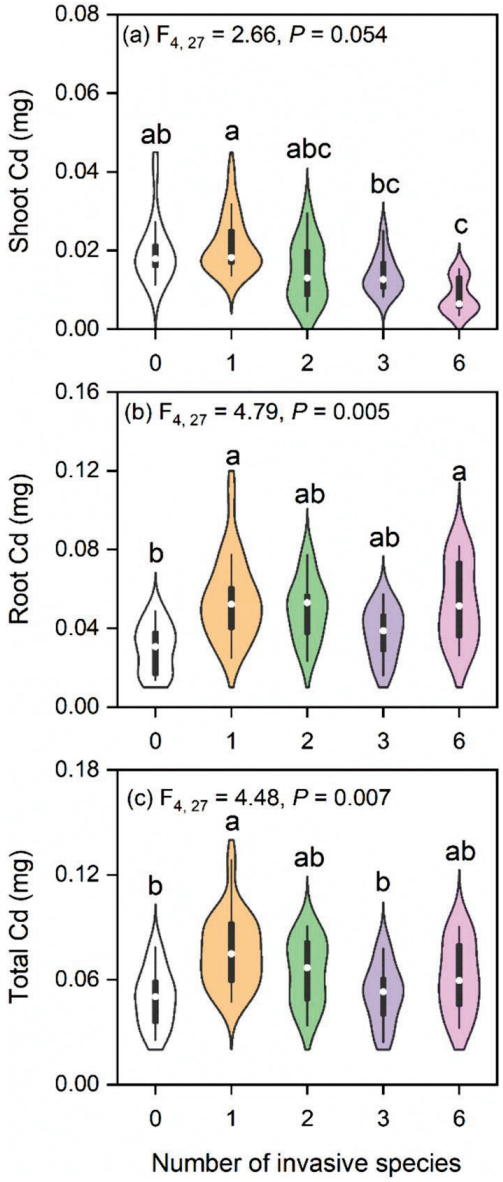

Fig. 6 Violin plots of the Cd pool size in shoots (**a**), roots (**b**) and whole plants (**c**) of the native communities grown in the soil without biochar (0) or with biochar of 1, 2, 3 and 6 invasive species. F-values and *P* values of the linear mixed models are given. Different letters indicate significant differences among the biochar treatments

Data availability Data will be made available on request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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