Phytoextraction by harvesting dead leaves: cadmium accumulation associated with the leaf senescence in *Festuca arundinacea* Schreb

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Abstract
Phytoextraction strategy by harvesting dead leaves provides continuous phytoremediation and a great saving in disposal cost of hazardous plant residues. This strategy is entirely dependent upon the amount of cadmium (Cd) accumulated in dead leaves. However, it is unknown that whether the leaf Cd accumulation is associated with its senescence and how to regulate its Cd accumulation. This study showed that Cd was preferentially and consistently distributed to and accumulated in the senescent leaves with the new leaf emergence and the old leaf dieback under 75 μM of Cd stress in tall fescue (*Festuca arundinacea* Schreb.). Individual leaf monitoring from its emergence to senescence showed that Cd concentration increased exponentially with the leaf life cycle, while leaf biomass decreased gradually after 14 days of leaf emergence. The total amount of Cd accumulated in the leaf showed an exponential increase during leaf senescence, regardless of the leaf biomass loss. Our results demonstrated that leaf Cd accumulation was significantly associated with its senescence and the highest Cd accumulated in dead leaves could be contributed from the continuous Cd input during the leaf senescent process, indicating that further regulatory studies should be focused on the leaf senescence process to achieve higher Cd accumulation and phytoextraction efficiency by harvesting dead leaves.

Keywords Phytoextraction · Cadmium · Tall fescue · Leaf · Senescence

Introduction

Cadmium (Cd) is one of the most hazardous heavy metals in the environment (Larison et al. 2000), which induced gene mutation and serious diseases such as cardiovascular disease (Cosselman et al. 2015) and many kinds of cancers, even at low concentrations (Koedrith et al., 2013). Phytoextraction is a green technology using plants to remove soil Cd pollution (Benavides et al. 2021). Phytoextraction efficiency is mainly dependent upon the amount of Cd accumulated in the harvesting organs of plants (Adamidis et al. 2017; Yuan et al. 2019).

Current phytoextraction technology is to remove soil Cd pollution by harvesting plant shoots enriched with Cd (Hu et al. 2016; Luo et al. 2016). Most of the hyperaccumulators are annual plant species (Rascio and Navari-Izzo 2011; Sterckeman et al. 2019), which need to be replanted in their growing season after each harvesting to restore the phytoextraction process (Bidar et al. 2009; Pogrzeba et al. 2018). There is a period between harvesting and replanting, in which soil erosion could lead to a risk of Cd diffusion (Wang et al. 2019a, b; Kidd et al. 2015). Besides, the huge amount of harvesting plant residues is difficult and costly for their disposal (Ghosh and Singh 2005; Carrier et al. 2011; Chaney and Baklanov 2017). Sas-Nowosielska et al. (2004) estimated that the cost of plant residue incineration was 180–220 €/t.

Our previous studies found that tall fescue (*Festuca arundinacea* Schreb.) performed hypertolerance of soil Cd pollution by its avoidance mechanism (Xu and Wang 2013; Zuo et al. 2021). Most of the shoot Cd was accumulated in its senescent and dead leaves and little Cd was accumulated in its photosynthetic mesophyll tissues of the young and mature leaves (Dong et al. 2017; Fei et al. 2018). A novel strategy
of Cd phytoextraction by harvesting the dead leaves was proposed because the dead leaves accumulated 73.4–87.2% of the shoot Cd with only 12.6–16.3% of the shoot biomass (Wang et al. 2019a, b). This novel Cd phytoextraction strategy was also supported by Luo et al. (2019, 2020), in which Cd phytoextraction by harvesting the senescent and dead leaves of tall fescue was enhanced by the intercropping with *Cicer arietinum* L. and irrigation of the magnetized water.

Compared with the previous phytoextraction technologies, this new strategy has obvious advantages in saving the disposal cost of the harvesting plant residues and providing continuous and uninterrupted soil phytoextraction. However, the phytoextraction strategy by harvesting the dead leaf is entirely dependent upon the capacity of Cd accumulation in dead leaves. Dead leaves are the result of leaf senescence. It is of vital importance to know whether the leaf Cd accumulation is associated with its senescence and what happened during the process of leaf senescence in tall fescue.

Therefore, this study was designed to investigate the following: (1) how leaf Cd accumulated during its senescent process, and (2) whether the higher Cd concentration in the senescent leaf was from external Cd input or its biomass loss.

**Materials and methods**

**Plant growth and experiment design**

Tall fescue (*Festuca arundinacea* Schreb.) cultivar “jaguar 4G” was used in this study. One seed of tall fescue was placed in the filter paper saturated with distilled water and incubated in the dark at 25 °C. When the seed germinated and roots appeared from the filter paper at 7 days, seedlings were transplanted into plastic tanks (25 seedlings per tank) containing 2.4 L of the half-strength Hoagland’s solution. The growth condition was the same as our previous hydroponic experiments (25/20 ± 2 °C of day/night temperatures, 50 ± 2% of relative humidity, 14 h of photoperiod, and 400 μmol m⁻² s⁻¹ of canopy photosynthetically active radiation).

A completely random design was used in this experiment with four replicates in each treatment. Half of the experimental tanks were exposed to Cd stress when the 4th leaf was emerging from the main shoot and the other half as the non-Cd control. Cd stress was at 75 μM Cd²⁺ concentration by adding CdCl₂•2.5H₂O into the 1/2 Hoagland’s solution. The nutrient solution was maintained at 6.5 pH and replaced freshly every week. All leaves grown from the plants were recorded and labeled throughout the whole experimental period. Plants were sampled every 7 days for the following measurements.

**Measurements**

**Plant growth parameters**

Plant height and root length of tall fescue were measured according to Zuo et al. (2021). Ten plants in each pot were selected randomly and their average was used as the treatment mean. Plant samples were separated into shoots and roots based on a single tiller, then oven-dried to a constant weight, and recorded as their biomasses.

**Cd analyses**

Each leaf was separated and sampled for Cd analyses. To avoid the dead leaves from being contaminated by Cd in the nutrient solution, the bottom leaf was cut off before it drooped. Therefore, the leaves in this experiment were only defined as the emerging, mature, and senescent leaves and no dead leaves appeared. Cd analyses followed the procedures of our previous studies (Xu and Wang 2013) and were determined using inductively coupled plasma spectroscopy (ICP Optima 8000, PerkinElmer, America). Quality control of the analyses was verified by co-analyzing certified reference samples for every 12 experimental samples. A blank was used to check interference and cross-contamination for every 15 samples. The Cd recovery rate was 95~103%.

Data analysis was followed by the same method as previously described (Xu and Wang 2014; Wang et al. 2017). Statistical analysis was performed by analysis of variance (ANOVA) with the software SAS (version 9.1, SAS Institute Inc., Cary, NC). Asterisk and the different letters in the figures indicate statistically significant differences separated by Duncan’s multiple tests at a significant level of *p* < 0.05.

**Results**

**Plant growth**

Cd stress significantly inhibited the plant growth of tall fescue (Fig. 1). Plant vertical growth was stopped by the Cd stress as indicated by no significant changes of plant height during the whole experimental period, which was significantly lower than the non-Cd control after 21 days of treatment (Fig. 1A). Shoot biomass per tiller was not as sensitive as plant height in response to the Cd stress and it still stably increased under the Cd stress until 49 days of treatment, which only showed significantly lower than the non-Cd control after 28 days of treatment (Fig. 1B). Root length and root biomass per tiller also showed steady increases under the Cd stress until 28 days of treatment and only showed
their decline after 49 days of treatment (Fig. 1C, D). When compared with the non-Cd control, root length was significantly shorter during the whole experimental period, but root biomass per tiller only showed a significantly lower after 21 days of treatment.

**Cd accumulation in roots and shoots**

Root accumulated a significantly higher Cd than shoot until 49 days after Cd stress (Fig. 2). Root Cd accumulation shows a sharp increase before the 35 days but remains at a relatively stable level after 42 days of Cd stress, which meet an equation: $y = -3.2 + 3.9x - 0.08x^2 + 0.0006x^3$, while $y$ is the root Cd accumulation (μg/plant) and $x$ is the days under the Cd stress. $R^2 = 0.96$ ** ($p < 0.01$). Shoot Cd accumulation shows a sharp increase throughout the whole experimental period, which meets an exponential curve: $y = 6.0e0.04x$, while $y$ is the shoot Cd accumulation (μg/plant) and $x$ is the days under the Cd stress. $R^2 = 0.95$ ** ($p < 0.01$). At 56 days of Cd stress, no significant difference in Cd accumulation was noticed between root and shoot.

**Cd distribution in different leaves**

The main shoot maintained 5~6 living leaves during the experimental period, with one emerging leaf, one senescent
leaf, and three mature leaves before 28 days or four mature leaves after 35 days of Cd stress. The first leaf showed senescent symptoms (yellowing) at 7 days and 14 days and completely dead before 21 days of Cd stress. As the young leaves continuously emerged from the top, the bottom leaf was gradually getting senescent. At 56 days of Cd stress, the 11th leaf was emerging, and the 6th leaf was getting senescent. In all eight periodical samplings, Cd distribution among the leaves showed a consistent pattern with the highest Cd concentration in the senescent leaf, the lowest Cd in the emerging leaf, and gradually Cd increases with the lower leaf position among the mature leaves (Fig. 3).

Cd accumulation with leaf development

The higher Cd concentration in the senescent leaf could have resulted from the loss of leaf biomass during the process of leaf senescence or Cd preferential distribution and accumulation associated with leaf senescence. In our experiment, leaves 4 (L4), 5 (L5), and 6 (L6) were continuously monitored for the changes of leaf biomass, Cd concentration, and accumulation from their emergence to senescence. The senescent symptom (yellowing) only occurred in 49 days after leaf emerging in all three leaves. In 14 days after emerging, leaf biomass increased with leaf emerging and development. However, leaf biomass decreased steadily after 21 days of emerging in all L4, L5, and L6, showing that leaf senescent started much earlier than its symptom appeared.

Cd concentrations in all three leaves showed the sharp increase with the leaf development and meet the exponential curve (Fig. 4). The leaf 4 (L4) was as follows: $y = 33.0 e^{0.05x}$, $R^2 = 0.99 ** (p < 0.01)$. The leaf 5 (L5) was as follows: $y = 37.7 e^{0.04x}$, $R^2 = 0.95 ** (p < 0.01)$. The leaf 6 (L6) was as follows: $y = 28.8 e^{0.06x}$, $R^2 = 0.93 ** (p < 0.01)$, while $y$ is the Cd concentration (mg/kg) in the leaf and $x$ is the days after its emergence.

Cd amount accumulated in all three leaves also showed the sharp increase with the leaf development and meet the exponential curve. The leaf 4 (L4) was as follows: $y = 0.6 e^{0.03x}$, $R^2 = 0.75 * (p < 0.05)$. The leaf 5 (L5) was as
Fig. 4 Leaf Cd accumulation during its development under the Cd stress. L4, L5, and L6 are the 4, 5, and 6 leaves that emerged from the main stem of tall fescue (from the base). (A) Leaf Cd concentration changes after its emergence. Cd concentrations in all three leaves showed the sharp increase with the leaf development and meet the exponential curve. The leaf 4 (L4) was as follows: $y = 33.0e^{0.05x}, R^2 = 0.99 \ (p < 0.01, n=24)$. The leaf 5 (L5) was as follows: $y = 37.7e^{0.04x}, R^2 = 0.95 \ (p < 0.01, n=24)$. The leaf 6 (L6) was as follows: $y = 28.8e^{0.06x}, R^2 = 0.93 \ (p < 0.01, n=24)$, while $y$ is the Cd concentration (mg/kg) in the leaf and $x$ is the days after its emergence. (B) Leaf biomass changes after its emergence. (C) Leaf Cd accumulation changes after its emergence. Cd accumulations in all three leaves showed the sharp increase with the leaf development and meet the exponential curve. The leaf 4 (L4) was as follows: $y = 0.6e^{0.03x}, R^2 = 0.75 \ (p < 0.05, n=24)$. The leaf 5 (L5) was as follows: $y = 0.75e^{0.04x}, R^2 = 0.87 \ (p < 0.01, n=24)$. The leaf 6 (L6) was as follows: $y = 1.0e^{0.04x}, R^2 = 0.87 \ (p < 0.01, n=24)$, while $y$ is the Cd concentration (mg/kg) in the leaf and $x$ is the days after its emergence.
follows: \( y = 0.75 \times e^{0.04x} \), \( R^2 = 0.87 ** (p < 0.01) \). The leaf 6 (L6) was as follows: \( y = 1.0 \times e^{0.04x} \), \( R^2 = 0.87 ** (p < 0.01) \), while \( y \) is the Cd concentration (mg/kg) in the leaf and \( x \) is the days after its emergence.

A correlation analysis showed that leaf Cd accumulations were significantly increased during the leaf senescence process (after 21 days of leaf emerging) despite the decline of leaf biomass in all three monitored leaves (Fig. 5). The exponential curves to describe the relationships of leaf Cd accumulation and leaf biomass decline are as follows: \( y = 12.2 \times e^{-0.1x} \), \( R^2 = 0.45 ** (p < 0.01) \) for L4; \( y = 8.1 \times e^{-0.05x} \), \( R^2 = 0.61 ** (p < 0.01) \) for L5; and \( y = 24.3 \times e^{-0.08x} \), \( R^2 = 0.79 ** (p < 0.01) \) for L6, respectively.

**Discussion**

Cd is one of the most toxic and serious heavy metals in soil pollution. Approximately 7% of investigated soil samples were contaminated by Cd according to the National Soil Pollution Investigation of China (MEP and MLR 2014). Cd in the soil can be adsorbed and desorbed in the soil buffers, but it will never degrade and eliminate (Chaudhary et al. 2011). Cd toxicity will always exist once the soil is polluted (Sato et al. 2010). Phytoextraction is an economic and ecological way to eliminate Cd toxicity and remediate soil. Soil Cd can be removed permanently by root uptake, root-to-shoot translocation, and plant harvesting. Myrna (1997) compared the cost-efficiency of phytoremediation to in situ and ex situ remediation methods. Phytoremediation may cost as little as 0.05/m³, which is only 0.05–0.5% of that by in situ remediation. Li et al. (2012) estimated the phytoremediation efficiency of 11 plant species (including 4 hyperaccumulators and 7 non-hyperaccumulators); they need 15 years of phytoextraction period to remove 50% of the total soil Cd by plants, assuming that no change of the Cd removal percentage over time. The phytoextraction duration to remove 50% of the total soil Cd could be shortened to 3.91 years by tall fescue, showing an attractive prospect in soil Cd remediation (Wang et al. 2019a, b).

Our previous research measured Cd accumulation in common turfgrass species (Xu et al. 2014). Tall fescue (F. arundinacea) is the only turfgrass species that can accumulate a large amount of Cd in dead leaves, which has also been confirmed by research by Luo’s laboratory (Luo et al. 2019, 2020). This characteristic provides a novel Cd phytoextraction strategy by harvesting dead leaves. This unique trait has not been found in other plant species according to the literature search.

Tall fescue is a perennial turfgrass species that can provide soil phytoremediation for many years once it is established (Banuelos et al. 1996; Adamidis et al. 2017). The phytoextraction strategy by harvesting the dead leaves in tall fescue has many advantages over current phytoextraction methods: (1) it provides continuous year-round phytoextraction. Harvesting the dead leaves does not affect the normal growth of tall fescue plants (Wang et al. 2019a, b). (2) It
likely to distribute and accumulate in the active young and mature leaves than in the senescent and dead leaves (Perron-net et al. 2003; Cao et al. 2014), which could be explained by the difference in transpirational pulling.

Most nutrients can be reused in plants, and they can be decomposed and transported out to the active plant parts for their reuse when the leaves get into senescence (Avila-Ospina et al. 2014; Maillard et al. 2015; Have et al. 2017). Most decomposed nutrients are transported and redistributed via the phloem pathway (Achat et al. 2018; Ding et al. 2019). Only a few non-reusable mineral nutrients cannot be transported out from the senescent leaves and resulted in a higher accumulation in the senescent leaves than that in the younger leaves (Chen et al. 2016; Shao et al. 2018).

Cd is very toxic to plant tissues (Choppala et al. 2014). Currently, no evidence showed that Cd could be redistributed and transported out when leaves get senescence (Ismael et al. 2019). The partition of transpiration flow could explain the higher Cd accumulation in the young and mature leaves via the xylem pathway in most plant species. Some previous studies reported that the older leaves accumulated double Cd concentrations than the younger leaves in Schinus molle L. (Pereira et al. 2017), Brassica juncea L. (Ru et al. 2004), and Brassica napus L. (Wang and Su 2005). Their double Cd concentrations in the older leaves could be contributed by leaf biomass loss or Cd redistribution during the leaf senescence process. Mendoza-Cozatl et al. (2008) found that Cd could be transported as PC–Cd and GSH–Cd complexes via phloem from source to sink in B. napus. Fujimaki et al. (2010) also reported that Cd was transferred from the xylem to phloem in the basal nodes and then transported to the grains at the grain-filling stage in rice. Our previous study found that Cd fluorescence was only located in the xylem part of vascular bundles and no Cd fluorescence was observed in the phloem part of tall fescue (Dong et al. 2017), indicating that Cd accumulation in the leaf of tall fescue was a one-way process. Cd could be only pumped in via the xylem pathway, not redistributed out via the phloem pathway.

In tall fescue, the senescent and dead leaves accumulated over ten times of Cd concentration than that in the emerging leaves (Fei et al. 2018; Wang et al. 2019a, b). In this paper, we found that both Cd concentration and amount were exponentially increased with the leaf aging, despite the decreases of the leaf biomass during the process of leaf senescence (Fig. 4). The exponential increases of leaf Cd amount in all three monitored leaves demonstrated that leaf Cd accumulation was significantly associated with its senescence process. Our data elucidated the dynamics of leaf Cd accumulation during its senescence in tall fescue. Leaf Cd was actively accumulated and the external Cd was continuously inputted to the senescent leaves during their senescence process, which well explained why the highest Cd accumulation was found in the dead leaves (Fei et al. 2018; Luo et al. 2019; Wang et al. 2019a, b; Luo et al. 2020). Further researches should...
focus on the regulatory mechanism of Cd accumulation in the process of leaf senescence. Phytorextraction efficiency by harvesting dead leaves could achieve by encouraging more Cd input during leaf senescence and higher Cd accumulation in dead leaves in tall fescue.

Conclusion

The tall fescue plant maintained normal growth under 75 μM of Cd stress. Cd was preferentially and consistently accumulated in the older leaves throughout the whole experimental period. Individual leaf monitoring showed that leaf Cd was exponentially increased during the leaf senescent process, despite the leaf biomass loss. Our results indicated that leaf Cd accumulation was significantly associated with the leaf senescence in tall fescue. The highest Cd accumulated in the dead leaves was contributed by the continuous Cd input during their senescent processes. These results provide insights into the relationship between Cd accumulation and leaf senescence and lay a foundation for the regulatory mechanism to improve the phytorextraction efficiency by harvesting dead leaves in tall fescue.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-21104-1.

Data availability

All data generated or analyzed during this study are included in this published article.

Author contribution

Ling Fei: investigation, formal analysis, writing—original draft. ShaoFan Zuo: investigation, formal analysis. JiaXin Zhang: investigation, formal analysis. ZhaoLong Wang: conceptualization, methodology, supervision, writing—review and editing.

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Declarations

Ethics approval

Not applicable

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

References

Achat DL, Pousse N, Nicolas M, Augusto L (2018) Nutrient remobilization in tree foliage as affected by soil nutrients and leaf life span. Ecol. Monogr. 88:408–428. https://doi.org/10.1002/ecm.1300

Adamidis GC, Aloupis M, Masteras P, Papadaki MI, Dimitrakopoulos PG (2017) Is annual or perennial harvesting more efficient in Ni phytoextraction? Plant Soil 418:205–218. https://doi.org/10.1007/s11104-017-3287-9

Avila-Ospina L, Moison M, Yoshimoto K, Masclaux-Daubresse C (2014) Autophagy, plant senescence, and nutrient recycling. J. Exp. Bot. 65, 3799–3811. SI: DOI: https://doi.org/10.1093/jxb/eru039

Baneulos GS, Zayed A, Terry N, Wu L, Akohoue S, Zambruzski S (1996) Accumulation of selenium by different plant species grown under increasing sodium and calcium chloride salinity. Plant Soil 183:49–59. https://doi.org/10.1007/BF02185564

Benavides BJ, Drohan PJ, Spargo JT, Maximova SN, Guitlittin MA, Miller DA (2021) Cadmium phytorextraction by Helianthus annuus (sunflower), Brassica napus cv Wichita (rapeseed), and Chrysopogon zizanioides (vetiver). Chemosphere 265:129086. https://doi.org/10.1016/j.chemosphere.2020.129086

Bidar G, Pruvot C, Garcon G, Verdin A, Shirali P, Douay F (2015) Seasonal and annual variations of metal uptake, bioaccumulation, and toxicity in Trifolium repens and Lolium perenne growing in a heavy metal-contaminated field. Environ. Sci. Pollut. Res. 16:42–53. https://doi.org/10.1007/s11356-008-0021-4

Broschat TK, Elliott ML (2004) Nutrient distribution and sampling for leaf analysis in St. Augustinegrass. Commun. Soil Sci. Plant Anal. 35:2357–2367. https://doi.org/10.1080/00122450490537627

Cao D, Zhang H, Yang Y, Zheng L (2014) Accumulation and distribution characteristics of zinc and cadmium in the hyperaccumulator plant Sedum plumbeicocula. Bull. Environ. Contam. Toxicol. 93(2):171–176. https://doi.org/10.1007/s00128-014-1284-8

Carrier M, Loppinet-Serani A, Absalon C, Marias F, Aymonier C, Mench M (2011) Conversion of fern (Pteris vitata L.) biomass from a phytoremediation trial in sub and supercritical water conditions. Biomass. Bioenergy. 35(2):872–883. https://doi.org/10.1016/j.biombioe.2010.11.007

Chaney RL, Bakanov IA (2017) Phytoremediation and phytomining: status and promise. In: Cuypers, A., Vagronsveld, J. (Eds.), Phytoremediation. Adv. Bot. Res. 83, pp. 189–221. DOI: https://doi.org/10.1016/bs.abr.2016.12.006

Chaudhary M, Mobbs HJ, Almås ÅR, Singh BR (2011) Assessing long-term changes in cadmium availability from Cd-enriched fertilizers at different pH by isotopic dilution. Nutr. Cycl. Agroecosyst. 91:109. https://doi.org/10.1007/s10705-011-9446-0

Che QW, Mu XH, Chen FJ, Yuan LX, Mi GH (2016) Dynamic change of mineral nutrient content in different plant organs during the grain filling stage in maize grown under contrasting nitrogen supply. Eur. J. Agron. 80:137–153. https://doi.org/10.1016/j.eja.2016.08.002

Choppala G, Saifullah, Bolan N, Bibi S, Iqbal M, Rengel Z, Kunhirikshanan A, Ashwath N, Ok YS (2014) Cellular mechanisms in higher plants governing tolerance to cadmium toxicity. Crit. Rev. Plant Sci. 33:374–391. https://doi.org/10.1080/07352689.2014.903747

Cosselman KE, Navas-Acien A, Kaufman JD (2015) Environmental factors in cardiovascular disease. Nat. Rev. Cardiol. 12:627–642. https://doi.org/10.1038/nrcardio.2015.152

Ding GD, Lei GJ, Yamaji N, Yokosho K, Mitani-Ueno N, Huang S, Ma JF (2019) Vascular cambium-localized AtSPDT mediates xylem-to-phloem transfer of phosphorus for its preferential distribution in Arabidopsis. Mol. Plant. https://doi.org/10.1093/molp/moz009.10.002

Dong Q, Xu PX, Wang ZL (2017) Differential cadmium distribution and translocation in roots and shoots related to hyper-tolerance between tall fescue and Kentucky bluegrass. Front. Plant Sci. 8:113. https://doi.org/10.3389/fpls.2017.00113

Fei L, Xu PX, Dong Q, Mo Q, Wang ZL (2018) Young leaf protection from cadmium accumulation and regulation of nitritotriacidic acid
in tall fescue (*Festuca arundinacea*) and Kentucky bluegrass (*Poa pratensis*). Chemosphere 212:124–132. https://doi.org/10.1016/j.chemosphere.2018.08.072

Fujimaki S, Suzuki N, Ishioka NS, Kawachi N, Ito S, Chino M, Nakamura S (2010) Tracing cadmium from culture to spikelet: Non-invasive imaging and quantitative characterization of absorption, transport, and accumulation of cadmium in an intact rice plant. Plant Physiol. 152:1796–1806. https://doi.org/10.1104/pp. 151035

Ghosh M, Singh SP (2005) A review on phytoremediation of heavy metals and utilization of its by-products. Asian J. Energ. Environ. 6(04):214–231

Have M, Marmagne A, Chardon F, Masclaux-Daubresse C (2017) Nitrogen remobilization during leaf senescence: lessons from Arabidopsis to crops. J. Exp. Bot. 68, 2513–2529. SI DOI: https://doi.org/10.1093/jxb/erw365

Hu YN, Cheng HF, Tao S (2016) The challenges and solutions for cadmium-contaminated rice in China: a critical review. Environ. Int. 92-93:515–532. https://doi.org/10.1016/j.envint.2016.04.042

Ismael MA, Elyamine AM, Moussa MG, Cai MM, Zhao XH, Hu CX (2019) Cadmium in plants: uptake, toxicity, and its interactions with selenium fertilizers. Metallomics 11:255–277. https://doi.org/10.1039/c8mt00247a

Kidd P, Mench M, Alvarez-Lopez V, Bert V, Dimitriou I, Fries-Hanl W, Herzog R, Janssen JO, Kolbas A, Muller I, Neu S, Renella G, Ruttens A, Vangronsveld J, Puschenreiter M (2015) Agronomic practices for improving gentle remediation of trace element-contaminated soils. Int. J. Phytoremediat. 17:1005–1037. https://doi.org/10.1080/15226514.2014.1003788

Larison JR, Likens GE, Fitzpatrick JW, Crock JG (2000) Cadmium toxicity among wildlife in the Colorado Rocky Mountains. Nature 406(6792):181–183. https://doi.org/10.1038/s350180

Li JT, Baker AJM, Ye ZH, Wang HB, Shu WS (2012) Phytoextraction of Cd contaminated soils: current status and future challenges. Crit. Rev. Environ. Sci. Technol. 42:2113–2152. https://doi.org/10.1080/10406339.2011.574105

Luo J, He WX, Rinklebe J, Igalavithana AD, Tack FMG, Ok YS (2019) Distribution characteristics of Cd in different types of leaves of *Festuca arundinacea* intercropped with *Cicer arietinum* L.: a new strategy to remove pollutants by harvesting senescent and dead leaves. Environ. Res. 179:108801. https://doi.org/10. 1016/j.envres.2019.108801

Luo J, He WX, Qi SH, Wu J, Gu XWS (2020) A novel phytoremediation method assisted by magnetized water to decontaminate soil Cd based on harvesting senescent and dead leaves of *Festuca arundinacea*. J. Hazard. Mater. 383:121115. https://doi.org/10. 1016/j.jhazmat.2019.121115

Luo J, Qi SH, Gu XWS, Wang JJ, Xie XM (2016) Evaluation of the phytoremediation effect and environmental risk in remediation processes under different cultivation systems. J. Clean. Prod. 119:25–31. https://doi.org/10.1016/j.jclepro.2016.01.043

Maillard A, Diquelou S, Billard V, Laine P, Garnica M, Prudent M, Garcia-Mina JM, Yvin JC, Ourry A (2015) Leaf mineral nutrient remobilization during leaf senescence and modulation by nutrient deficiency. Front. Plant Sci. 6:317. https://doi.org/10. 3389/fpls.2015.00317

MEP and MLR, 2014. http://english.mee.gov.cn/News_service/ news_release/201404/20140428_271088.shtml

Mendoza-Cozatl DG, Butko E, Springer F, Torpey JW, Komives EA, Kehr J, Schroeder JJ (2008) Identification of high levels of phytochelatins, glutathione and cadmium in the phloem sap of *Brassica napus*. A role for thiol-peptides in the long-distance transport of cadmium and the effect of cadmium on iron translocation. Plant J. 54:249–259. https://doi.org/10.1111/j.1365-313X.2008.03410.x

Myrna EW (1997) Phytoremediation on the brink of commercialization. Environ. Sci. Technol. 31:182–186. https://doi.org/10.1021/es972219s

Pereira MP, Correa FF, de Castro EM, de Oliveira JPV, Pereira FJ (2017) Leaf ontogeny of *Schinus molle* L. plants under cadmium contamination: the meristematic origin of leaf structural changes. Protoplasma 254:2117–2126. https://doi.org/10.1007/ s00709-017-1103-2

Perronnet K, Schwartz C, Morel JL (2003) Distribution of cadmium and zinc in the hyperaccumulator *Thlaspi caerulescens* grown on multicontaminated soil - distribution of metals in *Thlaspi caerulescens*. Plant Soil 249(1):19–25. https://doi.org/10. 1023/A:1022560711597

Pogrzeba M, Rusinowski S, Krzyzak J, (2018) Macroelements and heavy metals content in energy crops cultivated on contaminated soil under different fertilization-case studies on autumn harvest. Environ. Sci. Pollut. Res. 25, 2096-12106. SI DOI: https://doi.org/10.1007/s11356-018-1490-8

Qu G, Tong Y, Gao P, Zhao Z, Song X, Ji P (2013) Phytoremediation potential of *Solanum nigrum* L. under different cultivation protocols. Bull. Environ. Contam. Toxicol. 91:306–309. https://doi.org/10.1007/s00128-013-1046-z

Rascio N, Navari-Izzo F (2011) Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting? Plant Sci. 180:169–181. https://doi.org/10.1016/j.plantsci.2010.08.016

Ru SH, Wang JQ, Su DC (2004) Characteristics of Cd uptake and accumulation in two Cd accumulator oilseed rape species. J. Environ. Sci. 16:594–598

Sas-Nowsielska A, Kucharski R, Malkowski E, Pogrzeba M, Kuperberg JM, Krynski K (2004) Phytoextraction crop disposal - an unsolved problem. Environ. Pollut. 128(3):373–379. https://doi.org/10.1016/j.envpol.2003.09.012

Sato A, Takeda H, Oyanagi W, Nishihara E, Murakami M (2010) Reduction of cadmium uptake in spinach (*Spinacia oleracea* L.) by soil amendment with animal waste compost. J. Hazard. Mater. 181:298–304. https://doi.org/10.1016/j.jhazardmat.2010.05.011

Shao JF, Yamaji N, Liu XW, Yokosho K, Shen RF, Ma JF (2018) Preferential distribution of boron to developing tissues is mediated by the intrinsic protein OsNIP3. Plant Physiol. 176:1739–1750. https://doi.org/10.1104/pp.17.01641

Siebrecht S, Herdel K, Schurr U, Tischner R (2003) Nutrient translocation in the xylem of poplar - diurnal variations and spatial distribution along the shoot axis. Planta 217:783–793. https://doi.org/10.1007/s00425-003-1041-4

Song Y, Jin L, Wang XJ (2017) Cadmium absorption and transportation pathways in plants. Int. J. Phytoremediat. 19:133–141. https://doi.org/10.1080/15226514.2016.1207598

Sterckeman T, Gossiaux L, Guimont S, Sirguey C (2019) How could phytoextraction reduce Cd content in soils under annual crops? Simulations in the French context. Sci. Total Environ. 654:751–762. https://doi.org/10.1016/j.scitotenv.2018.11.173

Tao Q, Jupa R, Luo JP, Lux A, Kovac J, Wen Y, Zhou YM, Jan J, Liang YC, Li TQ (2017) The apoplastic pathway via the root apex and lateral roots contributes to Cd hyperaccumulation in the hyperaccumulator *Sedum alfredii*. J. Exp. Bot. 68:739–751. https://doi.org/10.1093/jxb/erw453

Uraguchi S, Nakamura M, Kawasaki A, Ishikawa T, Murakami K, Matsumaru K, Ishikawa N (2011) Leaf ontogeny of *Sedum alfredii* and *Kentucky bluegrass* (*Poa pratensis*) grown on cadmium contaminated soil - distribution of metals in the hyperaccumulator *Sedum alfredii*. J. Exp. Bot. 62:3501–3509. https://doi.org/10.1093/jxb/erq330

Wang JQ, Su DC (2005) Distribution of cadmium in oilseed rape and Indian mustard grown on cadmium contaminated soil. J. Environ. Sci. 17:572–575
Wang, L.W., Hou, D.Y., Shen, Z.T., Zhu, J., Jia, X.Y., Ok, Y.S., Tack, F.M.G., Rinklebe, J., 2019a. Field trials of phytomining and phytoremediation: a critical review of influencing factors and effects of additives. Crit. Rew. Environ. Sci. Technol. 1547-6537 (Online). DOI: https://doi.org/10.1080/10643389.2019.1705724

Wang ST, Dong Q, Wang ZL (2017) Differential effects of citric acid on cadmium uptake and accumulation between tall fescue and Kentucky bluegrass. Ecotox. Environ. Safe. 145:200–206. https://doi.org/10.1016/j.ecoenv.2017.07.034

Wang Y, Meng DP, Fei L, Dong Q, Wang ZL (2019b) A novel phytoremediation strategy based on harvesting the dead leaves: cadmium distribution and chelator regulations among leaves of tall fescue. Sci. Total Environ. 650:3041–3047. https://doi.org/10.1016/j.scitotenv.2018.10.072

Xu PX, Fei L, Chen XB, Wang ZL (2014) Cadmium tolerance and accumulation in four cool-season turfgrasses. Acta Prataculturae Sinica 23(6):176–188

Xu PX, Wang ZL (2013) Physiological mechanism of hypertolerance of cadmium in Kentucky bluegrass and tall fescue: chemical forms and tissue distribution. Environ. Exp. Bot 96:35–42. https://doi.org/10.1016/j.envexpbot.2013.09.001

Xu PX, Wang ZL (2014) A comparison study in cadmium tolerance and accumulation in two cool-season turfgrasses and Solanum nigrum L. Water Air Soil Pollut. 225:1938. https://doi.org/10.1007/s11270-014-1938-5

Yingjajaval S (2013) Transpiration: venue for nutrients delivery. VII International Symposium on Mineral Nutrition of Fruit Crops. in Poovarodom, S., and Yingjajaval, S. Ed. Acta Horticulturae 984:25–35

Yuan XZ, Xiong T, Yao S, Liu C, Yin YN, Li HC, Li NS (2019) A real filed phytoremediation of multi-metals contaminated soils by selected hybrid sweet sorghum with high biomass and high accumulation ability. Chemosphere 237:UNSP 124536. https://doi.org/10.1016/j.chemosphere.2019.124536

Zuo SF, Hu S, Rao IL, Dong Q, Wang ZL (2021) Zinc promotes cadmium leaf excretion and translocation in tall fescue (Festuca arundinacea). Chemosphere 276:130186. https://doi.org/10.1016/j.chemosphere.2021.130186

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