

Combining grass and legume species with compost for assisted phytostabilization of contaminated soils

Questa è la versione Post print del seguente articolo:

Original

Combining grass and legume species with compost for assisted phytostabilization of contaminated soils / Garau, Matteo; Castaldi, Paola; Diquattro, Stefania; Pinna, Maria Vittoria; Senette, Caterina; Roggero, Pier Paolo; Garau, Giovanni. - In: ENVIRONMENTAL TECHNOLOGY & INNOVATION. - ISSN 2352-1864. - 22: 101387:(2021), pp. 1-13. [10.1016/j.eti.2021.101387]

Availability:

This version is available at: 11388/241581 since: 2024-09-20T10:12:17Z

Publisher:

Published

DOI:10.1016/j.eti.2021.101387

Terms of use:

Chiunque può accedere liberamente al full text dei lavori resi disponibili come "Open Access".

Publisher copyright

note finali coverpage

(Article begins on next page)

This is the Author's accepted manuscript version of the following contribution:

Combining grass and legume species with compost for assisted phytostabilization of contaminated soils / Garau, Matteo; Castaldi, Paola; Diquattro, Stefania; Pinna, Maria Vittoria; Senette, Caterina; Roggero, Pier Paolo; Garau, Giovanni. - In: ENVIRONMENTAL TECHNOLOGY & INNOVATION. - ISSN 2352-1864. - 22: 101387:(2021), pp. 1-13. [10.1016/j.eti.2021.101387]

The publisher's version is available at:

<https://dx.doi.org/10.1016/j.eti.2021.101387>

When citing, please refer to the published version.

Environmental Technology & Innovation

COMBINING GRASS AND LEGUME SPECIES WITH COMPOST FOR ASSISTED PHYTOSTABILIZATION OF CONTAMINATED SOILS

--Manuscript Draft--

Manuscript Number:	ETI-D-20-00614R1
Article Type:	Research Paper
Keywords:	potentially toxic elements; Gentle remediation options; organic amendments; PTE-uptake; Bioaccumulation factors
Corresponding Author:	Paola Castaldi ITALY
First Author:	Matteo Garau
Order of Authors:	Matteo Garau Paola Castaldi, Professor Stefania Diquattro, PhD Maria Vittoria Pinna, PhD Caterina Senette Pier Paolo Roggero, Professor Giovanni Garau, PhD
Abstract:	<p>Assisted phytoremediation, i.e. the combination of amendment and plant cultivation to remove potentially toxic elements (PTE) from soil, or to reduce their mobility and toxicity, can represent an effective gentle remediation option for the recovery of PTE-contaminated soils. The aim of this study was to evaluate the suitability of different grass and legume species, such as <i>Arundo donax</i> L., <i>Hordeum vulgare</i> L. and <i>Lupinus albus</i> L., in assisted phytoremediation programs of PTE-contaminated soils in combination with a municipal solid waste compost (MSWC) used at 2 and 4% rates. The soil was heavily contaminated by different PTE, i.e. Pb (15,383 mg·kg⁻¹), Zn (4,076 mg·kg⁻¹), Sb (109 mg·kg⁻¹), Cd (67 mg·kg⁻¹) and As (49 mg·kg⁻¹). The selected plant species were able to grow in the contaminated soil, and their biomass production was significantly influenced by the compost either positively (e.g. <i>A. donax</i>) or negatively (e.g. <i>H. vulgare</i> roots). Compost addition significantly decreased or did not influence the PTE uptake and bioaccumulation factors of <i>A. donax</i> and <i>H. vulgare</i> roots and shoots, while it increased those of <i>L. albus</i> (particularly in roots) with respect to As, Sb, Pb and Cu. Finally, MSWC increased the PTE removal efficiency of <i>A. donax</i> (and partially of <i>L. albus</i> but not by <i>H. vulgare</i>), i.e. its ability to bioaccumulate PTE in the below ground organs, especially when grown in soils amended with 4% MSWC. The results indicated that <i>A. donax</i>, and in selected cases <i>L. albus</i>, can be used in combination with MSWC for the phytostabilization of PTE-contaminated soils.</p>
Suggested Reviewers:	Meri Barbaferi meri.barbaferi@cnr.it Bruno Barbosa b.barbosa@campus.fct.unl.pt Giuseppe Bonanno bonanno.giuseppe@unict.it Susan Tandy s.tandy@bangor.ac.uk Zhaohui Guo

zhguo@csu.edu.cn

Opposed Reviewers:

Response to Reviewers:

Ms. Ref. No.: Ms. No. ETI-D-20-00614
Title: COMBINING GRASS AND LEGUME SPECIES WITH COMPOST FOR ASSISTED PHYTOSTABILIZATION OF CONTAMINATED SOILS

Journal: Environmental Technology & Innovation

Dear Prof. Ravi Naidu
Editor in chief
Environmental Technology & Innovation

below you will find our responses to the reviewers' comments and suggestions. As you will see, all the requested or recommended changes have been applied to the revised manuscript. We would like to thank the anonymous reviewers since we feel that their observations and suggestions, contributed significantly to improve the manuscript.

Reviewer #1

The revisions suggested by the Reviewer#1 have been incorporated in the revised version of the manuscript and shown as yellow text.

- The title clearly reflect the contents.
Thank you.

- The aims of the paper is poorly written. It must be improved accordingly.
As suggested by the review we improved the aims of the paper (Lines 20-21, 121-125).

- Introduction: in the present form the introduction is not enough described
This conflicts with the Reviewer#2, for which the Introduction is "interesting and quite well written, but too long". According with the Reviewer#2, we deleted some parts of the "Introduction" and we better explained the aim of the study (as also required by the Reviewer#1), as well as the novelty and the originality of the research (Lines 121-130).

- Material and methods: The methodology is well thought through. The description of materials and methods is informative to allow replication of the experiment.
Thank you.

- The originality and novelty of the paper need to be further clarified. What progress against the most recent state-of-the-art similar studies was made in this study?
As suggested by the Review#1 we better underlined the originality and novelty of the paper (Lines 125-130).

Reviewer #2

All the revisions suggested by the Reviewer#1 have been incorporated in the revised version of the manuscript and shown as green text.

The authors provide information about plant analyses, but data regarding soils and compost characteristics are only vaguely commented and referred to previous publications.

Data related to soil and compost characteristics (before plant growth) have been added in this revised version as supplementary material (i.e. Table S1). Moreover, an additional figure (Fig. S1), showing the mobility of PTE after soil incubation with compost (i.e. before plant growth), has been also added as supplementary material. Now the reader will be able to easily understand compost and soil features just before planting.

In fact, soil analysis seem to have been only performed in soils after the incubation period with the compost, but not after the development of the pot experiment and the growth of the plants in those. This, as the authors comment in the paper, may have

influenced the soluble fraction of the PTEs in the soils and cannot be omitted. This is possibly the main concern of this manuscript, which has been generally very well written, but may still be thoroughly revised to avoid repetition and vague/imprecise/speculative comments.

We thank the reviewer for this observation. We better explained in the "Material and methods" that the pot experiment started immediately after the incubation period (Lines 184). In addition, according with the Reviewer observation, we carried out a number of additional chemical analyses on soils collected after plant growth. In particular, we determined the main soil chemical parameters (Table S2) as well as the labile fraction of PTE (water-soluble and exchangeable) therein (Fig. S2). The respective materials and methods employed have been added in the revised text (Lines 199-212). Finally, the text has been revised accordingly and, hopefully, vague/imprecise/speculative comments have been significantly reduced (if not completely eliminated).

Abstract: the conclusion in the abstract is contradictory and a bit confusing, as the authors say that 'removal efficiency' of *A. donax* was increased and that this made it suitable for phytostabilizing PTEs in soils. This must be rewritten in a clearer way. We agree, we clarified this part, thank you (Lines 31-33).

Introduction: interesting and quite well written, but too long. In addition, the aim of the work may better reflect the novelty of the results and the originality of the research performed.

We thank the reviewer for his comment, we deleted some parts of the Introduction, in addition we better explained the aim, novelty and originality of the research carried out (Lines 68, 80, 82, 121-130).

Materials and Methods: a complete description of the characteristics of the original materials would be of interest, even if only in the supplementary information of the manuscript.

As required, we added as Supplementary Materials a table (Table S1) and one figures (Fig. S1) reporting soil and compost characteristics and PTE mobility after the incubation period and before plant growth. In addition, we added in Table S2 and Fig. S2 selected chemical parameters and labile PTE in soils collected after plant growth (Lines 199-212).

The interest of the different rations included in the plant analysis part is frequently arguable. A precise description of the data used for their calculation (e.g., which soil data were used, or if plant and soil concentrations and amounts were expressed or used in a per pot basis) would provide this data some robustness.

We tried to make clearer the calculation of the different indexes mentioned in the text (Lines 236-239). Moreover, we would like to say that these indexes (i.e. BAF, TF, RF, mineralomasses) are widely used in phytoremediation studies since they provide useful information on a plant suitability for PTE stabilization or extraction.

Results and discussion: this section must be thoroughly revised and corrected, as at the moment is a bit repetitive and focuses mainly on qualitative results (if values were higher or lower for a species or another, with or without compost, etc.). The real interest of the results comes from their quantitative analysis, as this would really provide useful and contrastable information to other readers. For instance, discussion about BAF (and most of TF and RF) simply mirror the discussion of PTE concentrations in the different plant parts and is therefore of little relevance. What is really relevant from those ratios etc. is their value, if those values can be considered to be appropriate for stabilization or extraction, etc. Otherwise the discussion can result a bit ambiguous.

In principle, we understand the reviewer comment and we applied some revisions in this sense (Lines 413-417, 433-436, 447-450, 470-471, 481-484). However, we would like to say that quantitative information can be abundantly found in tables, figures and supplementary materials and that mentioning those values also in the text would not provide additional information (which is already there) nor improve the manuscript. We also believe that text reading should be accompanied by that of tables and figures and that readers can now benefit of both quantitative and qualitative information. Moreover, the aim of our study was to evaluate the suitability of three different plant species, in combination with MSWC, for the recovery of a soil contaminated by different PTE. In this sense, values higher or lower for a species or another, with or without compost, is

what we were interested. Finally, and most importantly, we would like to say that BAF and TF cannot be used in any way to identify plants suitable for PTE stabilization or extraction as they only highlight the attitude (or potential) of a given plant to concentrate PTE from soil to plant tissues (BAF) and to transfer them from roots to shoots. Plant growth, PTE uptake and mineralomasses (and therefore RF) are certainly most relevant in this sense as highlighted in the text.

In addition, part of the discussion can be considered to be somewhat speculative and not fully based on the results presented in the manuscript nor supported by appropriate close studies (e.g., lines 265-274, 318-319, 335-336, 348-349, 360-361, 365-373, 377-378, 451-453, 461-463, 479-480, 481-483).

As suggested by the reviewer we deleted some parts of the discussion (Lines 281, 372, 481, 487), and we better explained some aspects (which appeared rather speculative), following the results obtained of soil analyses carried out after plant growth (i.e. Table S2 and Fig. S3) (Lines 325-328, 341-343, 356-361, 376-378, 385-388, 421-423, 432-433, 447-450, 453-455, 470-471, 481, 483-484).

Also, the fact that *A. donax* is a well known invasive species and in that way has many detractors may be considered/mentioned in the text.

We mentioned this aspect in the text, thank you (Lines 94-97).

SPECIFIC COMMENTS

Delete too general comments in lines 90-91 and 427-434.

Done (Lines 82, 442).

Line 223: what 'soil mass' was used for this calculations? Per pot? How can that values be compared with results from other experiments?

For the calculation of RF, the weight of soil in the pot (kg) was used (i.e. 3 kg d.m. for *A. Donax* and 1 kg for lupin and barley), as reported by Moameri and Khalaki (2019). In this way it is possible to compare the results obtained in one pot with those of the other pots. We better explained what "soil mass" means in the manuscript (Lines 236-239).

Lines 258-259: soil values after incubation or after the pot experiment?

We better specified this point (Lines 272).

Lines 318-319 and 335-336: labile PTE concentrations in the soils from the pots were not measured or at least are not shown or described in the manuscript.

As suggested by the reviewer, labile PTE concentrations in soils before and after the pot experiment were reported as supplementary material (Fig. S1-S2; Lines 325-328, 341-343).

Lines 348-349: how was this determined?

(Lines 356-361) As suggested by the reviewer we determined the concentration of labile PTE (i.e. the PTE fraction extracted with $(\text{NH}_4)_2\text{SO}_4$) and we reported the results in the Supplementary Figure 3. We described in the "Materials and methods" section how the labile fraction of PTE after the plant growth was determined (Lines 199-212).

Lines 365-366: Cu and, especially, Pb concentrations were very high in this soils, which makes this comment unexpected.

We revised the text. In particular, we mentioned some results which have been added in Fig. S1 and are related to PTE mobility in soil before plating. Fig. S1 clearly shows that most Cu and Pb in soil (before planting) was extracted with EDTA (Lines 378-380).

Lines 377-378: that is quite unlikely (quantitatively) and those data were not determined/shown in the manuscript.

Our statement is now supported by the PTE mobility data determined after plant growth, lupin in this case (Fig. S2). (Lines 392-393).

Lines 402-404: an example of repeated information.

We deleted the sentence, thank you (Lines 418).

Lines 481-483: that is possibly just a consequence of a dilution effect (higher biomass with the same accumulation capacity).

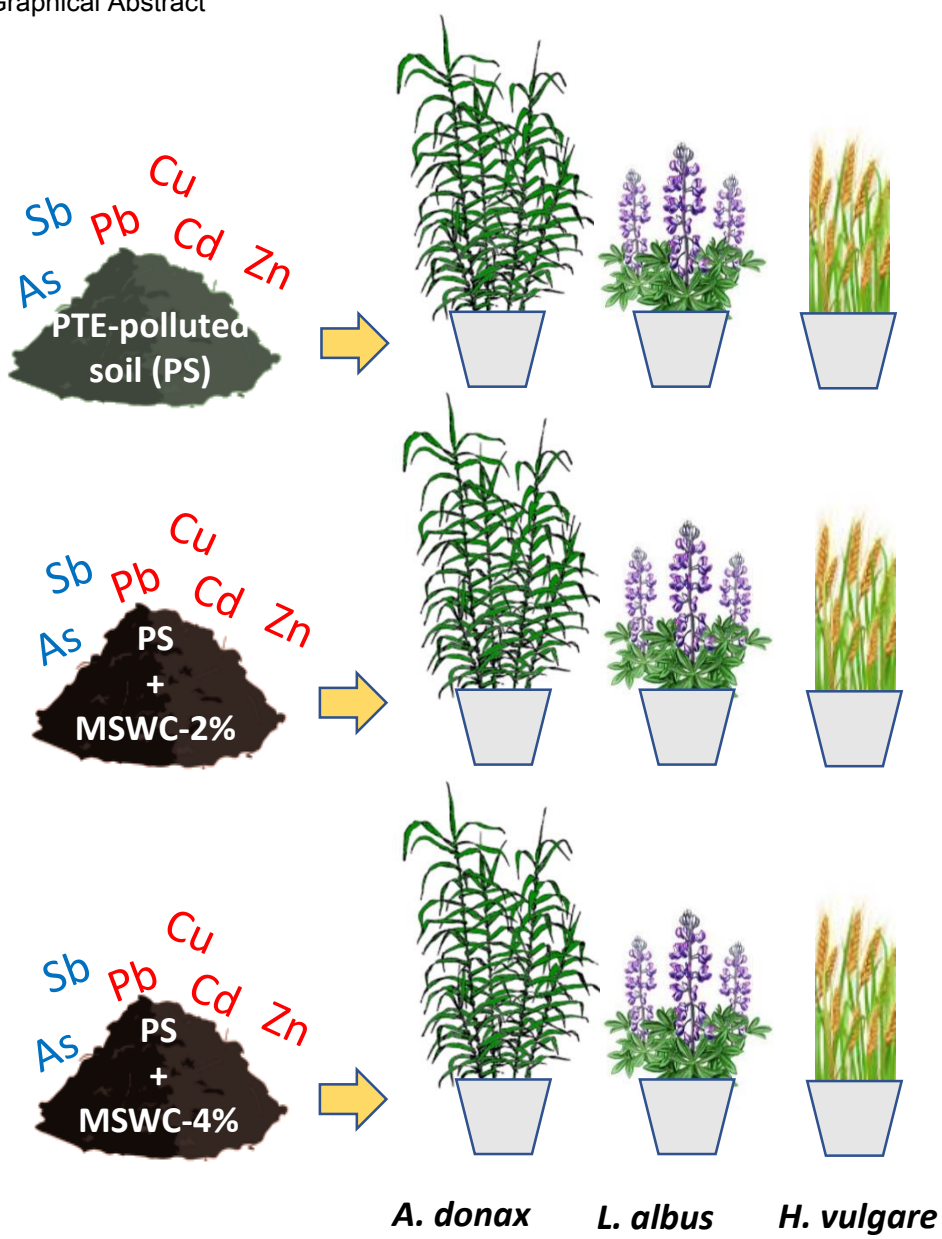
We mentioned this possibility in the revised manuscript, thank you (Lines 490-492).

Figure 1: are those data per pot? Please clarify this.

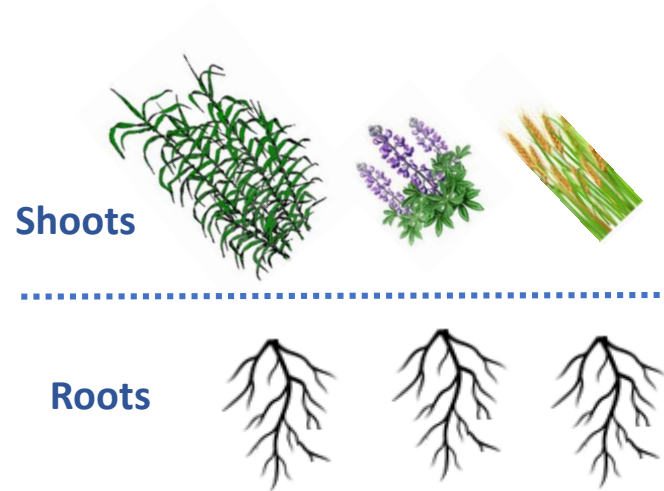
The data in Figure 1 are expressed as root and shoot dry weight (g plant⁻¹). We better clarified this aspect in the y-axis of the Figure 1, thank you.

Metal concentrations in plant roots (especially for Pb and Zn in *H. vulgare* and *L. albus*) seem too high, even for soils with such a with PTE concentrations. Were those data contrasted with previous results/experiments with those species in other contaminated soils?

As highlighted by the review, Pb and Zn concentrations in plant roots (especially for white lupin and *H. vulgare*) are very high. However, Martínez-Alcalá et al. [Chemical and biological properties in the rhizosphere of *Lupinus albus* alter soil heavy metal fractionation. *Ecotoxicology and Environmental Safety* 73 (2010) 595–602] detected more than 6000 mg kg⁻¹ of Zn in roots of lupin plants grown in an acidic soil containing 364 mg kg⁻¹ of Zn. Moreover, Ebbs et al. [Phytoextraction of zinc by Oat (*Avena sativa*), Barley (*Hordeum vulgare*), and Indian Mustard (*Brassica juncea*). *Environmental Science & Technology* 32 (1998) 802-806] detected about 650 mg kg⁻¹ of Zn in shoots of barley plants grown in contaminated soil containing 3100 mg kg⁻¹ of Zn, Andrey et al. [The role of biochar-microbe interaction in alleviating heavy metal toxicity in *Hordeum vulgare* L. grown in highly polluted soils. *Appl. Geochemistry* 104 (2019) 93-101] also found that in a soil heavily contaminated, especially by zinc (6232 mg kg⁻¹), barley plants showed 4372 and 2659 mg kg⁻¹ of Zn in roots and shoots respectively. This suggests that the peculiarity of each contaminated soil (i.e. specific origin, texture, pH, point of zero charge, organic matter content, relative and absolute PTE abundance and speciation, and so on) and of each plant species, produce site-specific results sometimes difficult to compare with others obtained in apparently similar contexts (Lines 345-347, 373).



Assessment at harvest



- Biomass
- PTE-uptake
- PTE Bioaccumulation and Translocation factors
- PTE mineralomasses
- PTE Remediation factors

1 COMBINING GRASS AND LEGUME SPECIES WITH COMPOST FOR ASSISTED
2
3 2 PHYTOSTABILIZATION OF CONTAMINATED SOILS
4
5
6 3

7
8 4 Matteo Garau^a, Paola Castaldi^{a*}, Stefania Diquattro^a, Maria Vittoria Pinna^a, Caterina
9
10 5 Senette^a, Pier Paolo Roggero^{a,b}, Giovanni Garau^{a*}
11
12
13 6

14
15
16 7 ^a Dipartimento di Agraria, University of Sassari, Viale Italia 39, 07100 Sassari, Italy
17

18 8 ^b Nucleo Ricerca Desertificazione, University of Sassari, Sassari, Italy
19
20 9

21
22
23 10 *Corresponding authors. Paola Castaldi, Viale Italia 39, 07100 Sassari, Italy, Tel.:
24
25 11 +39079229214; E-mail address: castaldi@uniss.it
26

27
28 12 Giovanni Garau, Viale Italia 39, 07100 Sassari, Italy, Tel.: +39079229210; E-mail
29
30 13 address: ggarau@uniss.it
31
32
33 14

34
35 15 **Abstract**
36
37 16

38
39
40 17 Assisted phytoremediation, i.e. the combination of amendment and plant cultivation
41
42 18 to remove potentially toxic elements (PTE) from soil, or to reduce their mobility and
43
44 19 toxicity, can represent an effective gentle remediation option for the recovery of PTE-
45
46 20 contaminated soils. The aim of this study was to evaluate the suitability of different
47
48 21 grass and legume species, such as *Arundo donax* L., *Hordeum vulgare* L. and *Lupinus*
49
50 22 *albus* L., in assisted phytoremediation programs of PTE-contaminated soils in
51
52 23 combination with a municipal solid waste compost (MSWC) used at 2 and 4% rates.
53
54
55 24 The soil was heavily contaminated by different PTE, i.e. Pb (15,383 mg·kg⁻¹), Zn
56
57
58
59
60
61
62
63
64
65

1 25 (4,076 mg·kg⁻¹), Sb (109 mg·kg⁻¹), Cd (67 mg·kg⁻¹) and As (49 mg·kg⁻¹). The selected
2
3 26 plant species were able to grow in the contaminated soil, and their biomass production
4
5 27 was significantly influenced by the compost either positively (e.g. *A. donax*) or
6
7 28 negatively (e.g. *H. vulgare* roots). Compost addition significantly decreased or did not
8
9 29 influence the PTE uptake and bioaccumulation factors of *A. donax* and *H. vulgare* roots
10
11 30 and shoots, while it increased those of *L. albus* (particularly in roots) with respect to As,
12
13 31 Sb, Pb and Cu. Finally, MSWC increased the PTE removal efficiency of *A. donax* (and
14
15 32 partially of *L. albus* but not by *H. vulgare*), i.e. its ability to bioaccumulate PTE in the
16
17 33 below ground organs, especially when grown in soils amended with 4% MSWC. The
18
19 34 results indicated that *A. donax*, and in selected cases *L. albus*, can be used in
20
21 35 combination with MSWC for the phytostabilization of PTE-contaminated soils.
22
23
24
25
26
27
28
29
30

31 37 *Keywords:* Potentially toxic elements; Gentle remediation options; Organic
32
33 38 amendments; PTE-uptake; Bioaccumulation factors
34
35
36
37

38 40 **1. Introduction**

39
40
41
42

43 42 Soil contamination by potentially toxic elements (PTE) represents one of the main
44
45 43 global environmental problems, as nowadays too many anthropogenic activities release
46
47 44 PTE in different environmental compartments (Radziemska et al., 2017). In particular,
48
49 45 mining activities represent a source of severe pollution of their surrounding
50
51 46 environment due to the progressive PTE release by unstable waste rocks and tailings
52
53 47 (Castaldi et al., 2005; Wong, 2003). This commonly leads to the loss of land suitable for
54
55 48 crop cultivation (and/or grazing) and can pose serious health concerns given the
56
57
58
59
60
61
62
63
64
65

1 49 potential entry of PTE into the food chain (Radziemska et al., 2017; Duri et al., 2018;
2
3 50 Wong, 2003).

4
5
6 51 The soils in the proximity of mining sites are often characterized by low pH values,
7
8 52 high concentrations of labile (i.e. soluble and easily bioavailable) PTE, poor soil
9
10 53 structure and low level of nutrients due to reduced organic matter inputs (Bacchetta et
11
12 54 al., 2015; Castaldi et al., 2005; Eijsackers, 2010; Garau et al., 2017; Manzano et al.,
13
14 55 2016; Wong, 2003). Moreover, PTE contamination can have a detrimental influence on
15
16 56 soil microbial abundance, diversity and activity (Abou Jauode et al., 2020; Diquattro et
17
18 57 al., 2020; Garau et al., 2017), which in turn can negatively affect plant growth (Castaldi
19
20 58 et al., 2018). For these reasons, both the securing of such areas and the reduction of PTE
21
22 59 spreading have become pressing environmental concerns worldwide.
23
24
25
26

27
28 60 The so called Gentle Remediation Options (GRO), i.e. those approaches or strategies
29
30 61 aimed at preserving or improving soil functions while limiting the environmental impact
31
32 62 of PTE, have emerged in the last decade as promising alternatives for the recovery of
33
34 63 contaminated soils (Abou Jaoude et al., 2020; Cundy et al., 2015). Among GRO, the use
35
36 64 of plants for the *in situ* stabilization of PTE or their extraction (i.e. phytostabilization
37
38 65 and phytoextraction respectively) has been increasingly investigated in the last years
39
40 66 (e.g. Castaldi et al. 2018; Garau et al., 2014; Kumpiene et al., 2014), along with the
41
42 67 influence of chemical additives or organic-based amendments on such processes (i.e.
43
44 68 assisted phytoremediation; Cundy et al., 2015).
45
46
47
48

49
50 69 Plants growing in PTE-contaminated soils are exposed to several stresses and their
51
52 70 ability to overcome these harsh conditions can vary depending on plant genotype, soil
53
54 71 physico-chemical properties and labile PTE concentration. On the other hand, the
55
56 72 amendment addition can substantially affect the plant adaptation and its growth
57
58
59
60
61
62
63
64
65

1 73 performance in such PTE-contaminated soils. Plants can absorb and accumulate PTE in
2
3 74 roots or hypogeal organs, blocking them belowground, but they can also translocate the
4
5 75 contaminants into the aerial part (Barbosa and Fernando, 2018). Therefore, an accurate
6
7
8 76 plant selection is necessary in order to achieve specific phytoremediation objectives,
9
10
11 77 e.g. phytostabilization or phytoextraction (Sánchez-Pardo and Zornoza, 2014; Wong,
12
13 78 2003). Apart from this, such plants should be able to grow in nutrient-poor soils and in
14
15 79 the presence of high concentrations of PTE (Sánchez-Pardo and Zornoza, 2014; Wong,
16
17
18 80 2003).

20 81 Different native species, in particular grasses and legumes, could successfully restore
21
22
23 82 soil fertility and promote ecological recovery (Wong, 2003). This is due to their
24
25 83 capacity to develop an extensive fibrous root system, which improves soil physical
26
27
28 84 structure, attenuates erosion and enhances soil organic matter content (Ying et al.,
29
30 85 2008). In this context, barley (*Hordeum vulgare* L.) could be useful for
31
32 86 phytostabilization purposes given its ability to accumulate PTE in roots (Dago et al.,
33
34
35 87 2014; Ruiz-dí et al., 2010). This crop, characterized by low input requirements, is able
36
37
38 88 to develop specific defense mechanisms against PTE, e.g. the production of
39
40 89 phytochelatins (small cysteine-rich peptides) which are accumulated in the cell vacuole
41
42 90 after PTE binding (Dago et al., 2014). Likewise, studies conducted on giant reed
43
44
45 91 (*Arundo donax* L.) highlighted the ability of this grass helophyte to grow in acidic soils
46
47 92 contaminated by different PTE (i.e. As, Cd, Cu, Pb and Zn), which were mainly
48
49
50 93 accumulated in below ground tissues (roots and rhizomes), and poorly translocated to
51
52 94 aerial parts (Castaldi et al., 2018). Even if this grass is recognised as an invasive species
53
54
55 95 able to form dense monotypic stands in habitats where it establishes (e.g. Hardesty-

1 96 Moore et al., 2020), it should be considered as a potential resource for the recovery of
2
3 97 polluted soils where plant growth and establishment is severely affected.
4

5
6 98 Also legumes proved to be useful for the remediation of PTE-contaminated soils
7
8 99 (Castaldi et al., 2005; Wong, 2003). For instance, white lupin (*Lupinus albus* L.), which
9
10
11 100 is able to grow in adverse soil conditions such as acidic pH, poor fertility and salinity
12
13 101 (Carpena et al., 2003; Castaldi et al., 2005; Sánchez-Pardo and Zornoza, 2014;
14
15 102 Ximénez-Embún et al., 2001), was effectively employed for the phytoremediation of
16
17 103 PTE-contaminated soils (Fumagalli et al., 2014; Zornoza et al., 2018).
18
19

20 104 In this context, the addition of organic-based amendments to contaminated soils, e.g.
21
22 105 municipal solid waste compost, manure, sludge, or biochar, was recognized to facilitate
23
24 106 plant growth and establishment. This can be due to a reduction of labile (and
25
26 107 bioavailable) PTE, to a stimulation of microbial abundance and diversity, and to an
27
28 108 improved mineral content and biogeochemical cycling in the amended soils (Castaldi et
29
30 109 al., 2005, 2018; Garau et al., 2014, 2017; Wong, 2003; Zornoza et al., 2018). Although
31
32 110 previous studies showed that *A. donax*, *H. vulgare* and *L. albus* can be able to
33
34 111 accumulate PTE, and different amendments were tested to enhance their
35
36 112 bioaccumulation abilities (Barbafieri et al., 2017; González et al., 2019; Mășu et al.,
37
38 113 2012; Zornoza et al., 2018), nonetheless their effectiveness as phytostabilizing plants
39
40 114 needs further study, especially in multi-PTE-contaminated soils. Moreover, the role of
41
42 115 organic amendments (e.g. compost) on the phytostabilizing ability of these plant species
43
44 116 has been rarely addressed before.
45
46
47
48
49
50

51
52 117 Although the use of compost in assisted phytoremediation proved in some instances
53
54 118 to be a promising GRO (Abou Jaoude et al., 2020; Manzano et al., 2016), such approach
55
56 119 needs careful case-by-case assessment and optimization due to the great variability of
57
58
59
60
61
62
63
64
65

1 120 soil and environmental conditions, PTE type and concentration, and selected plant
2
3 121 species (Marchand et al., 2010). Accordingly, the aim of the present study was to
4
5 122 evaluate the suitability of three different plant species (i.e. *A. donax*, *H. vulgare* and *L.*
6
7 123 *albus*), in combination with a low-cost and sustainable amendment (i.e. a municipal
8
9 124 solid waste compost: MSWC), for the recovery of a mining soil contaminated by
10
11 125 different PTE such as As, Sb, Pb, Cd and Zn. Research on this issue is particularly
12
13 126 crucial, especially considering that the influence of MSWC on PTE phytostabilizing
14
15 127 abilities of *A. donax*, *H. vulgare* and *L. albus* was rarely (if never) considered before.
16
17 128 Likewise, this is the first study (to our knowledge) comparing the (assisted) PTE
18
19 129 phytostabilizing performances of *A. donax*, *H. vulgare* and *L. albus* in the same
20
21 130 contaminated soil. To this end, plants growth was investigated in a polluted amended
22
23 131 (and unamended) mining soil, and the PTE uptake and partitioning in roots (and
24
25 132 rhizome) and shoots were quantified. The bioaccumulation and translocation factors
26
27 133 were also determined for each plant species along with the respective PTE removal
28
29 134 efficiency, i.e. remediation factors.
30
31
32
33
34
35
36
37
38
39

40 135

41 136 **2. Materials and methods**

42 137

43 138 *2.1. Experimental set-up, soil and compost characteristics*

44 139

45 140 The contaminated soil was collected from an ex-mining area located in the
46
47 141 Southwestern Sardinia (Italy, N 39°40'29.71"; E 8°37'17.97", Montevecchio, Guspini),
48
49 142 where galena (PbS) and sphalerite (ZnS) were the main ores extracted (Castaldi et al.,
50
51 143 2005; Wanty et al., 2013). Soil samples (10) were randomly collected from the upper
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 144 soil layer (0-25 cm) in a site which extended for about 1 ha. The collected soil samples
2
3 145 were pooled in the laboratory to obtain a composite soil that was thoroughly
4
5 146 characterized from a physico-chemical point of view, and then used for the plant-growth
6
7
8 147 experiment. The main features of such soil were previously reported (Garau et al.,
9
10 148 2019a; Table S1). Briefly, the soil was a sandy clay loam (USDA classification) with
11
12 149 sub-acidic pH (i.e. 5.93), substantial content of organic matter (OM, ~3.2%), and high
13
14 150 cation exchange capacity (CEC, 36.86 $\text{cmol}_{(+)}\cdot\text{kg}^{-1}$). The content of the main mineral
15
16 151 elements was in general suitable for crop cultivation (total N 1.3 $\text{g}\cdot\text{kg}^{-1}$, Olsen-P ~23
17
18 152 $\text{mg}\cdot\text{kg}^{-1}$, exchangeable Ca, Mg and K ~23, 11 and 1 $\text{cmol}_{(+)}\cdot\text{kg}^{-1}$ respectively). The
19
20 153 total concentrations of Pb (15,383 $\text{mg}\cdot\text{kg}^{-1}$), Zn (4,076 $\text{mg}\cdot\text{kg}^{-1}$), Cu (181 $\text{mg}\cdot\text{kg}^{-1}$), Sb
21
22 154 (109 $\text{mg}\cdot\text{kg}^{-1}$), Cd (67 $\text{mg}\cdot\text{kg}^{-1}$) and As (49 $\text{mg}\cdot\text{kg}^{-1}$) exceeded the threshold levels
23
24 155 established by the Italian legislation for potentially contaminated sites (D.lgs.
25
26 156 152/2006).

27
28
29
30
31 157 The composite soil (~ 120 kg) was divided in 3 subsamples (~ 40 kg each) which
32
33 158 randomly received one of the following treatments: no treatment, i.e. polluted untreated
34
35 159 soil (Control); 2 % (w/w) MSWC (MSWC-2%); 4 % (w/w) MSWC (MSWC-4%). The
36
37 160 MSWC used derived from municipal and green waste composting and was provided by
38
39 161 the Facility Plant Secit S.p.A. Consorzio Zir (Chilivani-Ozieri, Italy). Before addition to
40
41 162 the polluted soil, MSWC was dried at 105 °C for 48 hours, finely ground and sieved to
42
43 163 < 2 mm. The main characteristics of the MSWC were previously reported by Diquattro
44
45 164 et al. (2018) (Table S1). Briefly, the MSWC had a sub-alkaline pH (i.e. 7.93) with 3.3
46
47 165 $\text{mS}\cdot\text{cm}^{-1}$ electrical conductivity (EC), the pH_{PZC} was 5.6, and the OM content was 27.3
48
49 166 %. The MSWC had a high cation exchange capacity (CEC, 92.3 $\text{cmol}_{(+)}\cdot\text{kg}^{-1}$), dissolved
50
51 167 organic carbon (DOC, 0.82 $\text{mg}\cdot\text{kg}^{-1}$) and humic acids content (14.24 %). After
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 168 amendment addition, treated and untreated soils were mixed, moisture content raised to
2
3 169 60 % of their water holding capacity, and then incubated for 4 months at 20 °C. During
4
5
6 170 this time, they were mixed twice a week and their water content maintained constant.
7

8 171 After the 4-months of contact, soil sub-samples from each treatment were air-dried
9
10 172 and chemical analyses were repeated to evaluate the influence of MSWC on the
11
12 173 different soil chemical parameters. A detailed description of the analyses carried out
13
14 174 was previously reported (Garau et al., 2019a) while the main soil chemical parameters
15
16 175 (after incubation with MSWC) are here resumed. Briefly, the addition of MSWC at 2
17
18 176 and 4% rates resulted in an increase of soil pH (6.5 and 6.8 respectively) and
19
20
21 177 exchangeable Ca (26 and 28 $\text{cmol}_{(+)}\cdot\text{kg}^{-1}$ respectively) and K (1.5 and 2.0 $\text{cmol}_{(+)}\cdot\text{kg}^{-1}$
22
23 178 respectively), while a significant decrease of exchangeable Mg was detected. Moreover,
24
25
26 179 increases of 5.8 and 14.3 % of CEC, 127 and 336 % of DOC, and 4 and 5 % of OM was
27
28
29 180 observed in MSWC-2% and MSWC-4% respectively, compared to the control soil.
30
31
32
33 181

34 35 182 *2.2. Plant-growth experiment and plant analysis* 36

37 183
38
39
40 184 Immediately after the incubation period, the soil from each treatment was used to fill
41
42 185 36 plastic pots (19 cm diameter, 17 cm height) each containing some 3 kg of soil, which
43
44 186 were separately planted with seeds of *H. vulgare* and *L. albus* and clonal ramets of *A.*
45
46 187 *donax*. These plant species were selected because of their potentials as phytostabilizing
47
48 188 plants and their tolerance to harsh conditions, e.g. poor fertility, acidic soils, salinity,
49
50 189 low water availability (Barbafieri et al., 2017; Castaldi et al., 2005, 2018; González et
51
52
53 190 al., 2019; Mășu et al., 2012; Zornoza et al., 2018).
54
55
56
57
58
59
60
61
62
63
64
65

1 191 *A. donax* was collected from a natural site in Southwestern Sardinia (Italy) and
2
3 192 vegetatively propagated (Castaldi et al. 2018). Six barley (cv. Arda) and white lupin (cv.
4
5 193 Multitalia) seeds and three giant reed rhizome cuttings were separately planted in 4
6
7 194 replicated pots from each treatment. A total of 36 pots were prepared (4 replicated pots
8
9 195 x 3 treatments x 3 plant species). Barley and white lupin were grown over 6 months,
10
11 196 from October 2018 to March 2019, while giant reed was grown over 18 months, from
12
13 197 October 2017 to March 2019, in a naturally-lit greenhouse at an average temperature of
14
15 198 20-25 °C and 60-70% relative humidity.
16
17
18
19

20 199 At harvest, root-adhering soil collected from plants subjected to the same treatment
21
22 200 was bulked together, sieved to < 2 mm and soil pH, EC, total organic C, N and DOC
23
24 201 were determined (Gazzetta Ufficiale, 1992; Table S2). Moreover, the mobility of Cd,
25
26 202 Cu, Pb and Zn (i.e. their water-soluble and exchangeable fraction) was determined in
27
28 203 root-adhering soil by treating soil samples (1 g) with 25 mL of a 0.5 M Ca(NO₃)₂
29
30 204 solution and shaking for 16 h at 20 °C (Basta and Gradwohl, 2000). Likewise, the
31
32 205 mobility of As and Sb in root-adhering soil was assessed by treating soil samples (1 g)
33
34 206 with 25 mL of a 0.05 M (NH₄)₂SO₄ solution and shaking for 4 h at 20 °C (Wenzel et al.,
35
36 207 2001). Following each extraction, soil samples were centrifuged at 3500 rpm for 15 min
37
38 208 and filtered (Whatman 41 filter) to separate the liquid and solid phases. PTE
39
40 209 concentrations in filtered solutions were determined using a Perkin Elmer Analyst 200
41
42 210 flame atomic absorption spectrometer (AAS) (for Zn quantification) or a Perkin Elmer
43
44 211 AAnalyst 400-HGA 900 atomic adsorption spectrometer equipped with a graphite
45
46 212 furnace (for As, Sb, Cd, Pb and Cu quantification).
47
48
49
50
51
52
53

54 213 At harvest, shoots were separated from roots. In the case of *A. donax* roots and
55
56 214 rhizomes were pooled together (hereafter mentioned as roots). Shoot and roots were
57
58
59
60
61
62
63
64
65

1 215 accurately washed with deionised water and oven dried at 55 °C for 72 h to determine
2
3 216 the respective dry weight. The PTE content (i.e. Pb, Cd, Zn, Cu, As and Sb) in shoots
4
5 217 and roots was determined after mineralization of plant tissues with H₂O₂ and a mixture
6
7
8 218 of 69% HNO₃ and ultrapure H₂O (ratio 1:1), in a Microwave Milestone MLS 1200
9
10 219 (EPA Method 3052). After mineralization, the total concentration of PTE was
11
12 220 determined using a Perkin Elmer AAnalyst 200 flame atomic absorption spectrometer
13
14 221 (for Zn quantification) or a Perkin Elmer AAnalyst 400-HGA 900 atomic adsorption
15
16 222 spectrometer equipped with a graphite furnace (for As, Sb, Cd, Pb and Cu
17
18 223 quantification). Peach leaf was used as standard reference material (NIST-SRM 1547).
19
20
21

22 224 The PTE bioaccumulation (BAF), translocation (TF) and remediation (RF) factors
23
24 225 were then calculated (Bonanno and Vymazal, 2017; Moameri and Khalaki, 2019) for
25
26 226 each plant species grown in each soil along with the respective mineralomasses (MM)
27
28
29 227 (Lebrun et al. 2018):
30
31

- 32 228 - BAF_r was calculated as the ratio between the PTE concentration in roots and that
33
34 229 present in soil;
35
36 230 - BAF_s was calculated as the ratio between the PTE concentration in shoots and
37
38 231 that present in soil;
39
40 232 - TF was calculated as the ratio between the PTE concentration in shoots and that
41
42 233 present in roots;
43
44 234 - MMr was calculated as the root biomass x PTE concentration in roots;
45
46 235 - MMs was calculated as the shoot biomass x PTE concentration in shoots;
47
48 236 - RFr was calculated as (root biomass in the pot x PTE concentration in root) / (soil
49
50 237 mass in the pot x PTE concentration in soil) x 100;
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 238 - RFs was calculated as (shoot biomass in the pot x PTE concentration in shoot) /
2
3 239 (soil mass in the pot x PTE concentration in soil) x 100.
4

5
6 240

7
8 241 *2.3. Data analysis*
9

10 242

11
12
13 243 For each plant species, root and shoot biomass and PTE concentration in root and
14
15 244 shoot were determined in triplicate, and mean values \pm standard errors were reported in
16
17
18 245 tables and figures. Likewise, BAF, TF, MM, and RF indexes were calculated and
19
20 246 expressed as mean values \pm standard errors. For each plant species, a one-way Analysis
21
22
23 247 of Variance (One-way ANOVA) was carried out to investigate the effects of treatments
24
25 248 on the different parameters analyzed. Prior to the ANOVA, the homogeneity of variance was
26
27
28 249 tested by the Cochran's test (Winer, 1971) and data were transformed whenever necessary.
29
30 250 Where significant *P*-values were obtained ($P < 0.05$), differences between individual
31
32 251 means were compared using the post-hoc Fisher's least significance difference test
33
34
35 252 (LSD, $P < 0.05$). Statistical analyses were carried out using the NCSS 2007 Data
36
37 253 Analysis software (v. 07.1.21; Kaysville, Utah).
38
39

40 254

41
42 255 **3. Results and discussion**
43

44 256

45
46
47 257 *3.1. Influence of MSWC on plant growth*
48

49 258

50
51
52 259 The amendment rate influenced significantly the biomass production of *A. donax*,
53
54 260 (Fig. 1), i.e. the growth of this helophyte species followed the order: MSWC-4% >
55
56
57 261 MSWC-2% > Control. In particular, the root biomass increased more than 1.5- and 3.9-
58
59
60
61
62
63
64
65

1 262 fold for MSWC-2% and -4% respectively compared to control plants. Moreover, the
2
3 263 shoot biomass increased by 2.3- and 4.5-fold for plants grown on MSWC-2% and -4%
4
5
6 264 respectively, compared to control plants (Fig. 1). Compost had a different effect on *H.*
7
8 265 *vulgare* growth, i.e. root biomass decreased by 1.4- and 1.7-fold in plants grown on
9
10 266 MSWC-2% and -4% respectively, while shoot biomass increased by 1.2- and 1.3-fold
11
12
13 267 (Fig. 1). Despite the average shoot and root yield of *L. albus* decreased at increasing
14
15
16 268 compost addition, such differences were not significant (Fig. 1).

17
18 269 These results clearly showed that MSWC had a quite different influence on plant
19
20 270 growth in the contaminated soil. The significant increase of shoot and root biomass of
21
22
23 271 giant reed in amended soils can be likely due to the enhanced soil fertility attributes
24
25 272 recorded in such soils after incubation with compost, e.g. OM, total N, available P,
26
27
28 273 CEC, exchangeable K and Ca, and DOC followed the order MSWC-4% > MSWC-2% >
29
30 274 control soil (Table S1; Garau et al., 2019a). Moreover, the concentration of labile PTE
31
32
33 275 was significantly lower in amended soils due to a PTE-immobilizing capability of
34
35 276 MSWC (Garau et al., 2019a), and this could have favored plant growth and biomass
36
37 277 production as observed by other studies (Castaldi et al., 2018; Mășu et al., 2012;
38
39
40 278 Zornoza et al., 2018). A similar response was observed in the case of barley shoots, but
41
42 279 not roots whose dry weight declined at increasing compost rate. Such increased root
43
44
45 280 yield of barley in control soil could be explained by a possible PTE influence on the
46
47 281 cytokinin level. Cytokinins, a class of phytohormones, can modulate plant growth and
48
49
50 282 development, and their contents in plant tissues can change upon PTE stress (Pál et al.,
51
52 283 2018).

53
54 284 Differently from giant reed and barley, the addition of MSWC showed a non
55
56
57 285 significant effect on white lupin roots and shoots (Fig. 1). This could be explained by
58
59
60
61
62
63
64
65

1 286 considering that this plant grows well in acidic soils (pH ~5.0) and its biomass,
2
3 287 particularly root, commonly decreases as the pH raises (e.g. Kerley, 2000; Tang et al.,
4
5 288 1995). In this context, the pH increase recorded in MSWC-amended soils could be
6
7 289 responsible for the observed phenomena and could mask a possible positive impact of
8
9 MSWC on plant growth due to PTE immobilization in soil and increased fertility
10
11 290 attributes.
12
13 291

14
15 292 The results highlighted an overall ability of the selected plants, when combined with
16
17 MSWC, to grow satisfactorily on a PTE heavily contaminated soil (see for comparison
18
19 293 yield data from Gorovtsov et al., 2019; Fumagalli et al., 2014; Yang et al., 2012).
20
21 294 However, given the inconsistent influence of compost on shoot and root growth, the
22
23 295 actual effectiveness of the tested assisted phytoremediation approach needs further
24
25 296 investigation. In this context, the estimation of PTE uptake by the plants,
26
27 297 bioaccumulation, translocation and mineralomasses can be useful to select plant species
28
29 298 to combine with MSWC for the phytoremediation of PTE-contaminated soils.
30
31 299
32
33 300

34
35
36
37 301 *3.2. Influence of MSWC on PTE uptake in plant tissues*
38
39

40 302
41
42 303 With the exception of white lupin, MSWC addition reduced significantly or did not
43
44 304 affect the PTE uptake by shoot and root of the selected plants (Fig.s 2-4). Furthermore,
45
46 305 as a general trend, much higher PTE concentrations were detected in roots compared to
47
48 306 shoots, thus supporting the phytostabilizing potential of the plant species under study
49
50 307 (Castaldi et al., 2005, 2018; Fumagalli et al., 2014; Gorovtsov et al., 2019).
51
52 308

53
54 309 While MSWC addition mostly reduced the PTE uptake in giant reed and barley
55
56 310 plants, compost rate did not show a consistent effect on PTE uptake as instead was
57
58
59
60
61
62
63
64
65

1 310 observed for plant growth. In particular, As and Sb concentration in roots of *A. donax*
2
3 311 decreased by 1.2- and 1.3-fold for As, and by 1.2-fold for Sb in MSWC-2% and -4%
4
5 312 plants respectively, compared to control roots (Fig. 2). Compost did not affect
6
7
8 313 significantly the Sb concentration in roots of barley, while the As concentration
9
10 314 decreased by 1.7- and 1.5-fold in MSWC-2% and -4% roots respectively, compared to
11
12
13 315 control roots. Arsenic in *A. donax* and *H. vulgare* shoots was not detected, while
14
15 316 reduced Sb concentrations were detected in shoots of both grasses when MSWC-2%
16
17
18 317 was added to the soil (Fig. 2). On the contrary, MSWC addition significantly increased
19
20 318 both As and Sb uptake by roots and shoots of white lupin: (e.g. As uptake in roots
21
22 319 increased by more than 2.7- and 2.3-fold, and Sb uptake increased by ~14- and 7-fold in
23
24 320 MSWC-2% and -4% plants respectively; Fig. 2).

27 321 These results confirmed that *A. donax* and *H. vulgare* are able to retain most of As
28
29 322 and Sb in below ground organs (Castaldi et al., 2018; Zeng et al., 2019), and indicated
30
31 323 that MSWC addition did not modify the overall partitioning of these PTE between roots
32
33 324 and shoots, while reducing (in most cases) their concentrations. However, this was not
34
35 325 the case of *L. albus* (Fig. 2). All this clearly indicated that the interaction between
36
37 326 MSWC and plant species had a significant influence on PTE mobilization and uptake ,
38
39 327 and that this latter aspect is hardly predictable based on the sole knowledge of PTE
40
41 328 labile concentrations in soil before planting. For instance, it was previously shown that
42
43 329 MSWC addition to this soil significantly reduced labile Sb, while labile As (which was
44
45 330 present at concentrations $< 1 \text{ mg}\cdot\text{kg}^{-1}$ soil) remained unchanged (Fig. S1; Garau et al.,
46
47 331 2019a). However, Sb and As uptake did not follow such trend, with the only exception
48
49 332 of Sb in giant reed roots (Fig. 2), whereas in the other cases PTE uptake was either
50
51 333 reduced in MSWC-treated soils (e.g. As in barley roots) or greatly stimulated (e.g. Sb
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 334 and As in white lupin roots). This latter case was remarkable and could be explained
2
3 335 with the ability of *L. albus* to release great amounts of organic anions, such as citrate
4
5 336 and malate, from its typical proteoid roots (e.g. Yan et al., 2002). Such organic anions,
6
7
8 337 whose metal complexing abilities increase as the pH raises (Quin et al., 2004), as it was
9
10 338 the case in MSWC-treated soils (Table S1), could be responsible for the partial
11
12 339 solubilization of Fe/Al oxy-hydroxides, which represent the largest sink of both PTE in
13
14 340 the soil under study (Garau et al., 2019a), with the consequent release of labile As and
15
16 341 Sb in amended soils (Castaldi et al. 2013). However, after plant growth, labile As and
17
18 342 Sb significantly decreased in amended soils compared to control ones (Fig. S2) likely
19
20
21 343 reflecting the highest uptake of these PTE in MSWC-treated soils (Fig. 2).

22
23
24
25 344 Differently from As and Sb, a more uniform trend across plant species was recorded
26
27 345 for Cd and Zn uptake (note that the concentration of this later PTE was very high in
28
29 346 roots of control barley and lupin as also recorded in other studies, e.g. Martínez-Alcalá
30
31 347 et al., 2010; Gorovtsov et al. 2019). Significant reductions were highlighted in shoots
32
33 348 and roots of plants grown on amended soils, with the exception of Cd in shoots of white
34
35 349 lupin (Fig. 3), while an inconsistent influence of compost rate was also observed. For
36
37 350 instance, the concentration of Cd in roots decreased by ~2- and 3-fold in *A. donax*, 4-
38
39 351 and 2-fold in *H. vulgare* and 4- and 7-fold in *L. albus* grown in MSWC-2% and -4%
40
41 352 respectively, compared to control roots (Fig. 3). Interestingly, Cd uptake in shoots was
42
43 353 generally limited compared to that absorbed by roots in all species under study. This is
44
45 354 noteworthy, since Cd is generally highly translocated and bioaccumulated in shoots
46
47 355 (Castaldi et al., 2005; Llugany et al., 2012; Sánchez-Pardo et al., 2015). These uptake
48
49 356 data confirmed the role of MSWC in reducing the labile Cd and Zn in soil (Fig. S1;
50
51 357 Garau et al., 2019a) and suggested that the interactions between MSWC, plant and soil
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 358 microbial community had a poor influence on the re-mobilization of these PTE.
2
3 359 Importantly, this was supported by the PTE mobility data recorded in soil after plant
4
5 360 growth, i.e. significantly lower concentrations were detected in MSWC-treated soils
6
7
8 361 compared to unamended controls (Fig. S2).
9

10 362 This was also the case of Pb and Cu uptake, whose trend was similar for *A. donax*
11
12 363 and *H. vulgare*: the addition of compost significantly reduced (or left unchanged) the
13
14
15 364 uptake of these PTE. However, Pb and Cu uptake by the roots of *L. albus* was
16
17
18 365 substantially increased in MSWC-amended soils (Fig. 4). For instance, Pb concentration
19
20 366 in roots decreased by ~ 23% in giant reed and 69% in barley grown in MSWC-4%,
21
22
23 367 compared to control roots. On the other hand, Pb and Cu concentrations in white lupin
24
25 368 roots increased up to ~ 2.4- and 1.5-fold respectively for plants grown on MSWC (Fig.
26
27
28 369 4).

29
30 370 The reduced Pb and Cu uptake, which was observed for *A. donax* and *H. vulgare*
31
32 371 after soil amendment, followed the labile concentrations of these PTE in amended and
33
34
35 372 unamended soils before planting (Fig. S1; Garau et al., 2019a). The increased Pb and
36
37
38 373 Cu uptake by white lupin roots in MSWC-amended soils (particularly relevant for Pb)
39
40 374 further supported the specificity of this plant compared to both grasses and could be
41
42 375 explained by an increased mobilization of these PTE in the lupin rhizosphere in the
43
44
45 376 presence of MSWC. However, labile (i.e. water-soluble and exchangeable) Cu and Pb
46
47
48 377 decreased in MSWC-soils after lupin growth (Fig. S2), probably as a result of the high
49
50 378 root uptake of these PTE. Differently from Cd and Zn, the majority of Cu and Pb in the
51
52 379 contaminated soil (before planting) was extracted after EDTA treatment (Fraction 3,
53
54
55 380 Fig. S1; Garau et al., 2019a), suggesting a substantial presence (and accessibility) in soil
56
57 381 of sparingly soluble Cu and Pb precipitates, e.g. metal (Me) oxi-hydroxides and/or Me
58
59
60
61
62
63
64
65

1 382 phosphates (Basta and Gradwohl, 2000). As earlier mentioned, organic compounds (e.g.
2
3 383 citrate and malate) released by white lupin roots (Yan et al., 2002) in compost-amended
4
5 384 soils could be responsible for a partial re-solubilization of such sparingly soluble
6
7 385 precipitates, which determined an increase of labile Cu and Pb and a consequent higher
8
9 386 uptake of these PTE (Dinkelaker et al., 1989; Ma et al., 2016; Quin et al., 2004; Yan et
10
11 387 al., 2002). However, as previously mentioned, labile Cu and Pb significantly decreased
12
13 388 in MSWC-amended soils after lupin growth (Fig. S2).

14
15
16
17
18 389 Taken together, the obtained results highlighted an overall decrease of PTE
19
20 390 concentration in shoots and roots of *A. donax* and *H. vulgare* in amended soils, while
21
22 391 substantial increase of As, Sb, Pb and Cu uptake was noticed for *L. albus* roots (Fig.s 2,
23
24 392 4). In this latter case, PTE immobilization in roots should be regarded as positive since
25
26 393 it is contributing to reduce labile PTE in soil (Fig. S2). This finally suggests that all the
27
28 394 selected plant species can be eligible as potential candidates for assisted
29
30 395 phytostabilization in combination with MSWC.
31
32
33
34
35
36

37 397 *3.3. Influence of MSWC on PTE bioaccumulation (BAF), translocation (TF),* 38 39 40 398 *mineralomasses (MM) and remediation (RF) factors*

41
42 399
43
44
45 400 Plant species suitable for phytoremediation programs are primary selected based on
46
47 401 their ability to grow satisfactorily in contaminated soils, as well as to preferentially
48
49 402 accumulate the contaminants in roots (phytostabilizing plants) or to translocate them in
50
51 403 the above ground organs (phytoextracting plants; Sinhal et al., 2015). In order to
52
53 404 evaluate the respective phytoremediation potential of *A. donax*, *H. vulgare* and *L. albus*,
54
55 405 PTE bioaccumulation factors (i.e. BAF_r and BAF_s), translocation factor (TF),
56
57
58
59
60
61
62
63
64
65

1 406 mineralomasses (i.e. MMr and MMs) and remediation factors (i.e. RFr and RFs) were
2
3 407 determined.
4

5
6 408

7
8 409 *3.3.1. Bioaccumulation factors (BAFr and BAFs)*
9

10
11 410

12
13 411 The bioaccumulation factors BAFr and BAFs, which quantify the plant efficiency to
14
15 412 uptake and accumulate the selected PTE in roots or shoots (Bonanno and Vymazal,
16
17 413 2017) were mostly <1 irrespectively of the plant species and MSWC addition (i.e. 0.06
18
19 414 10^{-3} - 0.81). The only exceptions were Zn and Cd BAFr in control plants of barley and
20
21 415 lupin (e.g. 1.51 and 2.90 for Zn and Cd in control plants of lupin; Tables 1-3). Overall,
22
23 416 this indicated much lower concentrations of PTE in plant tissues than those recorded in
24
25 417 soil as well as the low extractive capacity of the selected plants.
26
27

28
29
30 418 The BAF decrease observed in the former plants was attributed to a reduced PTE
31
32 419 uptake of plants grown on compost-amended soils. This supported a stable
33
34 420 immobilization of the contaminants by MSWC and a negligible influence of the root
35
36 421 activity of *A. donax* and *H. vulgare* on PTE re-mobilization phenomema, as highlighted
37
38 422 by PTE mobility data recorded after plant growth (Fig. S2). This is relevant as such re-
39
40 423 mobilization phenomena are not rare in assisted phytoremediation experiments (e.g.
41
42 424 Castaldi et al., 2009). However, significant BAF increases were previously reported for
43
44 425 *A. donax* growing on different soils mainly contaminated by As and amended with the
45
46 426 same MSWC used in this study (Castaldi et al., 2018). This likely indicates that soil
47
48 427 components, including microbial community, can play a major role in
49
50 428 mobilization/immobilization phenomena resulting from the combined action of organic-
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 429 based amendments and root activity. Furthermore, this emphasizes the need of a case by
2
3 430 case, or soil by soil, evaluation of the most suitable phytoremediation practices.
4

5 431 Significant increases of As, Sb, Pb and Cu BAF factors (especially BAF_r) were
6
7 432 recorded for white lupin grown on MSWC-amended soils. This was attributed to the
8
9 433 solubilization ability of lupin roots towards these PTE in amended soils. However, it is
10
11 434 important to underline the very low BAF values (always <1) detected for all plants
12
13 435 which somehow limit the environmental relevance of such increases. An opposite trend
14
15 436 was noticed for Cd and Zn (Table 3): the decrease of Cd and Zn BAF_r in amended soils
16
17 437 (e.g. 2.9 and 1.5 in control in plants vs 0.5 in MSWC-4%) was remarkable as these PTE
18
19 438 are commonly very mobile in soil (Adriano et al., 2001).
20
21
22
23
24
25
26
27

28 440 3.3.2. Translocation factor (TF)

29
30 441
31
32 442 Overall, all TFs were < 1 for control plants (Tables 1-3) indicating that *A. donax*, *H.*
33
34 443 *vulgare* and *L. albus* can be considered as potential phytostabilizing species as
35
36 444 previously pointed out by other authors (Bonanno, 2013; Bonanno and Vymazal, 2017;
37
38 445 Castaldi et al., 2005, 2018). Moreover, compost had a very limited influence on PTE
39
40 446 translocation from roots to shoots, apart from Cd in *A. donax* grown on MSWC-4% soil,
41
42 447 where TF increased from 0.51 to 1.17 (Table 1). In particular, TF values remained
43
44 448 unchanged (e.g. Cu, Zn) or mostly decreased for *A. donax* grown on MSWC-4% soils
45
46 449 (e.g. Sb, Pb). However also PTE concentrations in plant tissues were decreased in this
47
48 450 plant (Fig. 2), which made these increases irrelevant. TF values in *H. vulgare* and *L.*
49
50 451 *albus* were either slightly increased (e.g. Pb, Cu for barley and As, Cd, Zn for lupin),
51
52 452 decreased (e.g. Cd, Zn for barley and Pb and Cu for lupin) or remained unvaried (e.g.
53
54
55
56
57
58
59
60
61
62
63
64
65

1 453 Sb for barley and lupin) (Tables 1-3). These results reflected the different
2
3 454 bioaccumulation of PTE in the different parts of the plants grown in the amended and
4
5
6 455 unamended soils.

7
8 456 Taken together, the results obtained suggest that the addition of compost did not
9
10 457 substantially influence the PTE partitioning between shoots and roots, with these latter
11
12
13 458 remaining the main sinks of PTE. Despite this, TF values suggested different PTE
14
15 459 translocation abilities between plant species, e.g. Pb in *A. donax* vs *H. vulgare*, or Cd in
16
17
18 460 *L. albus* vs *H. vulgare*, which could depend on the species considered, growth stage and
19
20 461 root physiology, as well as on distinct rhizosphere microbial communities.

21
22
23 462

24 25 463 3.3.3. PTE mineralomasses and remediation factors (RF)

26
27 464

28
29 465 PTE mineralomasses (MMr and MMs) quantify the actual PTE amounts
30
31 466 bioaccumulated by the plants (Lebrun et al., 2018) and as such they can be useful to
32
33 467 estimate the contribution of each species in PTE immobilization. In this sense, also the
34
35 468 remediation factors (RFR and RFs) can be helpful, as it indicates how effectively PTE
36
37 469 are absorbed by belowground organs.

38
39
40 470 Although MM values cannot be used to discriminate phytostabilizing from
41
42 471 phytoextracting plants, irrespective of plant species, MMr values of control plants were
43
44 472 generally higher than MMs ones confirming that PTE were preferentially stored within
45
46 473 the root system (Tables 1-3). From an environmental point of view, this can be
47
48 474 considered favorable since PTE immobilization belowground limits the risk of
49
50 475 contaminants spreading and thus their entry in the food chain. This finally confirms the
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 476 suitability of giant reed, barley and white lupin as PTE phytostabilizers, while rules out
2
3 477 their relevance as phytoextractants.
4

5
6 478 The addition of MSWC did not change this trend, with the exception of Cd for which
7
8 479 MMs > MMr. However, compost addition (especially MSCW-4%) significantly
9
10 480 increased both MM of *A. donax* (Table 1) as a likely result of its improved growth in the
11
12 481 amended soil. RF values were very low in all plants (Moameri and Khalaki, 2019),
13
14 482 however MSWC addition increased the RF of *A. donax*, particularly in plants grown in
15
16 483 MSWC-4%, clearly indicating that PTE were extracted more efficiently by *A. donax*
17
18 484 grown in compost treated soil.
19
20
21

22
23 485 As regards to *H. vulgare*, MSWC addition mostly reduced MMr and RFr values
24
25 486 (Table 2). These results could be due to the reduced root biomass detected in compost-
26
27 487 amended plants (Fig. 1). In addition, the biostimulation effect of MSWC on barley
28
29 488 shoots was not always accompanied by a parallel MMs and RFs increase (Table 2), thus
30
31 489 pointing out to a negligible (or even repressive) effect of MSWC on PTE mobilization
32
33 490 and absorption by barley (Fig. S2). However, what observed could be the consequence
34
35 491 of a dilution effect, i.e. higher biomass in barley plants grown in the amended soil with
36
37 492 the same PTE accumulation capacity of control plants. These results seem to indicate
38
39 493 that the MSWC used in this study is likely not the best amendment to combine with
40
41 494 barley if increased PTE mineralomasses (MMr in particular) are desired.
42
43
44
45
46

47 495 Compost addition mostly increased As, Sb and Pb MM values in *L. albus*, while Cu,
48
49 496 Cd and Zn MM were mainly reduced, even if they were similar to control plants (Table
50
51 497 3). Also the RF values in MSWC-amended soils varied depending on the PTE
52
53 498 considered, i.e. they increased for As, Sb and Pb while decreased for Zn, Cu and Cd.
54
55
56
57
58
59
60
61
62
63
64
65

1 499 These data could suggest a better suitability of white lupin, when combined with
2
3 500 MSWC, as phytostabilizer for selected PTE, such as As, Sb and Pb.
4
5
6 501

8 502 4. **Conclusions**

9

10 503

11
12
13 504 The results obtained showed that *A. donax*, *H. vulgare* and *L. albus* were able to
14
15 505 grow in a PTE-polluted soil, and that MSWC amendment had different effects on plant
16
17
18 506 growth, i.e. both stimulating and repressive ones. When grown in the presence of
19
20 507 MSWC, all plant species but barley improved their PTE phytostabilizing capabilities,
21
22
23 508 overall showing significantly greater PTE bioaccumulation in roots, as well as low
24
25 509 translocation from roots to shoots. This suggests that the use of the tested MSWC
26
27
28 510 should be avoided if barley is selected as phytostabilizing plant. On the contrary,
29
30 511 MSWC substantially improved the white lupin bioaccumulation performance with
31
32 512 respect to selected elements (i.e. As, Sb and Pb). For this reason, *L. albus* could be
33
34
35 513 recommended as phytostabilizer together with MSWC in those cases where As, Sb and
36
37
38 514 Pb are the main soil contaminants, as it was in our case. Finally, *A. donax* which
39
40 515 showed consistently higher mineralomasses and lower BAF factors in amended soils,
41
42 516 appeared as the best choice for the assisted phytostabilization of the PTE-contaminated
43
44
45 517 soil. The perennial nature of such helophyte grass and its great adaptability to harsh
46
47 518 environmental conditions makes this plant as one of the best candidates for MSWC-
48
49 519 assisted phytoremediation of PTE contaminated soils.
50

51
52 520

54 521 **Credit Author Statement**

55
56
57 522

1 523 **Matteo Garau:** Investigation, Methodology, Formal analysis, Writing - Original draft
2
3 524 preparation. **Paola Castaldi:** Conceptualization, Formal analysis, Resources, Writing -
4
5
6 525 Review & Editing. **Stefania Diquattro:** Methodology, Formal analysis. **Maria Vittoria**
7
8 526 **Pinna:** Methodology, Formal analysis. **Caterina Senette:** Methodology. **Pier Paolo**
9
10 527 **Roggero:** Conceptualization, Resources, Project administration. **Giovanni Garau:**
11
12
13 528 Conceptualization, Formal analysis, Writing - Review & Editing.
14
15
16 529

17
18 530 **Acknowledgments**
19

20 531
21
22
23 532 The financial support of the Regione Sardegna (L.R. 7/2007 Progetti di ricerca
24
25 533 fondamentale o di base - Annualità 2014, CUP: B52F17001030002), of the
26
27
28 534 PROGRAMMA OPERATIVO F.S.E. 2014-2020 and of the University of Sassari
29
30 535 (Fondo di Ateneo per la Ricerca 2019) are gratefully acknowledged.
31
32

33 536
34
35 537
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 538 **References**
2
3 539
4
5
6 540 Abou Jaoude, L., Castaldi, P., Nassif, N., Pinna, M.V., Garau, G., 2020. Biochar and
7
8 541 compost as gentle remediation options for the recovery of trace elements-
9
10 542 contaminated soils. *Sci. Total Environ.* 711, 134511.
11
12
13 543 Adriano, D.C., 2001. Bioavailability of trace metals. *Trace Elements in Terrestrial*
14
15 544 *Environments*, 2nd ed. Springer, New York, pp. 61–89.
16
17
18 545 Bacchetta, G., Cappai, G., Carucci, A., Tamburini, E., 2015. Use of native plants for the
19
20 546 remediation of abandoned mine sites in mediterranean semiarid environments. *Bull.*
21
22 547 *Environ. Contam. Toxicol.* 94, 326–333.
23
24
25 548 Barbafieri, M., Pedron, F., Petruzzelli, G., Rosellini, I., Franchi, E., Bagatin, R.,
26
27 549 Voccianta, M., 2017. Assisted phytoremediation of a multi-contaminated soil:
28
29 550 Investigation on arsenic and lead combined mobilization and removal. *J. Environ.*
30
31 551 *Manage.* 203, 316–329.
32
33
34
35 552 Barbosa, B., Fernando, A.L., 2018. Aided Phytostabilization of Mine Waste, in: Prasad,
36
37 553 M.N.V., de Favas, P.J.C., Maiti, S.K. (Ed.), *Bio-Geotechnologies for mine site*
38
39 554 *rehabilitation*. Elsevier, Amsterdam, pp. 147–157.
40
41
42 555 Basta, N., Gradwohl, R., 2000. Estimation of Cd, Pb, and Zn bioavailability in smelter-
43
44 556 contaminated soils by a sequential extraction procedure. *J. Soil Contam.* 9, 149–
45
46 557 164.
47
48
49
50 558 Bonanno, G., 2013, Comparative performance of trace element bioaccumulation and
51
52 559 biomonitoring in the plant species *Typha domingensis*, *Phragmites australis* and
53
54 560 *Arundo donax*. *Ecotox. Environ. Safe.* 97, 124–130.
55
56
57 561 Bonanno, G., Vymazal, J., 2017, Compartmentalization of potentially hazardous
58
59
60
61
62
63
64
65

1 562 elements in macrophytes: insights into capacity and efficiency of accumulation. J.
2
3 563 Geochem. Explor. 181, 22–30.
4
5
6 564 Carpena, R.O., Vázquez, S., Esteban, E., Fernández-Pascual, M., Rosario, M., Felipe,
7
8 565 D., Zornoza, P., 2003. Cadmium-stress in white lupin: effects on nodule structure
9
10 566 and functioning. Plant Physiol. Biochem. 41, 911–919.
11
12
13 567 Castaldi, P., Santona, L., Melis, P., 2005. Heavy metal immobilization by chemical
14
15 568 amendments in a polluted soil and influence on white lupin growth. Chemosphere
16
17 569 60, 365–371.
18
19
20 570 Castaldi, P., Silveti, M., Manzano, R., Brundu, G., Roggero, P.P., Garau, G., 2018.
21
22 571 Mutual effect of *Phragmites australis*, *Arundo donax* and immobilization agents on
23
24 572 arsenic and trace metals phytostabilization in polluted soils. Geoderma 314, 63–72.
25
26
27 573 Castaldi, P., Silveti, M., Mele, E., Garau, G., Deiana, S., 2013. Arsenic mobilization by
28
29 574 citrate and malate from a red mud–treated contaminated soil. J. Environ. Qual. 42,
30
31 575 774–781.
32
33
34 576 Castaldi, P., Melis, P., Silveti, M., Deiana, P., Garau, G., 2009. Influence of pea and
35
36 577 wheat growth on Pb, Cd, and Zn mobility and soil biological status in a polluted
37
38 578 amended soil. Geoderma 151, 241–248.
39
40
41 579 Cundy, A., Bardos, P., Puschenreiter, M., Witters, N., Mench, M., Bert, V., Friesl-Hanl
42
43 580 W., Müller, I., Weyens, N., Vangronsveld, J., 2015. Developing effective decision
44
45 581 support for the application of “gentle” remediation options: The GREENLAND
46
47 582 project. Remediation J. 25(3), 101–114.
48
49
50 583 Dago, À., González, I., Ariño, C., Díaz-cruz, J.M., Esteban, M., 2014. Chemometrics
51
52 584 applied to the analysis of induced phytochelatin in *Hordeum vulgare* plants
53
54 585 stressed with various toxic non-essential metals and metalloids. Talanta 118, 201–
55
56
57
58
59
60
61
62
63
64
65

1 586 209.
2
3 587 Diquattro, S., Garau, G., Castaldi, P., 2018. Municipal solid waste compost as a novel
4
5
6 588 sorbent for antimony(V): adsorption and release trials at acidic pH. Environ. Sci.
7
8 589 Pollut. Res. 25, 5603–5615.
9
10 590 Diquattro, S., Garau, G., Mangia, N.P., Drigo, B., Lombi, E., Vasileiadis, S., Castaldi,
11
12
13 591 P., 2020. Mobility and potential bioavailability of antimony in contaminated soils:
14
15
16 592 Short-term impact on microbial community and soil biochemical functioning.
17
18 593 Ecotox. Environ. Safe. 196, 110576.
19
20 594 Dinkelaker, B., Romheld, V., Marschner H., 1989. Citric-acid excretion and
21
22
23 595 precipitation of calcium citrate in the rhizosphere of white lupin (*Lupinus albus* L.)
24
25 596 Plant Cell Environ. 12(3), 285-292.
26
27 597 Dlgs. 152/2006. Decreto legislativo 3 aprile 2006, n. 152. Norme in materia ambientale,
28
29
30 598 G.U. n. 88 del 14 aprile 2006.
31
32 599 Domínguez, M.T., Montiel-Rozas, M.M., Madejón, P., Diaz, M.J., Madejón, E., 2017.
33
34
35 600 The potential of native species as bioenergy crops on trace-element contaminated
36
37 601 Mediterranean lands. Sci. Total Environ. 590–591, 29–39.
38
39 602 Duri L.G., Fiorentino N., Cozzolino E., Ottaiano, L., Agrelli, D., Fagnano M., 2018.
40
41
42 603 Bioassays for evaluation of sanitary risks from food crops cultivated in potentially
43
44 604 contaminated sites. Ital. J. Agron. 13, 45–52.
45
46 605 Eijsackers, H., 2010. Earthworms as colonisers: Primary colonisation of contaminated
47
48
49 606 land , and sediment and soil waste deposits. Sci. Total Environ. 408, 1759–1769.
50
51 607 Fresno, T., Moreno-Jiménez, E., Zornoza, P., Peñalosa, J.M., 2018. Aided
52
53
54 608 phytostabilisation of As- and Cu-contaminated soils using white lupin and
55
56 609 combined iron and organic amendments. J. Environ. Manage. 205, 142–150.
57
58
59
60
61
62
63
64
65

1 610 Fumagalli, P., Comolli, R., Ferrè, C., Ghiani, A., Gentili, R., Citterio, S., 2014. The
2
3 611 rotation of white lupin (*Lupinus albus*, L.) with metal-accumulating plant crops : A
4
5 612 strategy to increase the benefits of soil phytoremediation. J. Environ. Manage. 145,
6
7 613 35–42.
8
9
10 614 Garau, G., Silvetti, M., Castaldi, P., Mele, E., Deiana, P., Deiana, S., 2014. Stabilising
11
12 615 metal(loid)s in soil with iron and aluminium-based products: microbial,
13
14 616 biochemical and plant growth impact. J. Environ. Manage. 139, 146–153.
15
16
17 617 Garau, M., Garau G., Diquattro S., Roggero P.P., Castaldi, P., 2019a, Mobility,
18
19 618 bioaccessibility and toxicity of potentially toxic elements in a contaminated soil
20
21 619 treated with municipal solid waste compost. Ecotox. Environ. Safe. 186, 109766.
22
23
24 620 Garau, G., Diquattro, S., Lauro, G.P., Deiana, S., Castaldi, P., 2019b. Influence of
25
26 621 Pb(II) in the sorption of As(V) by a Ca-polygalacturonate network, a root mucilage
27
28 622 model. Soil Sci. Plant Nutr. 65(3), 305–315.
29
30
31 623 Garau, G., Silvetti, M., Vasileiadis, S., Donner, E., Diquattro, S., Deiana, S., Lombi, E.,
32
33 624 Castaldi, P., 2017. Use of municipal solid wastes for chemical and microbiological
34
35 625 recovery of soils contaminated with metal (loid)s. Soil Biol. Biochem. 111, 25–35.
36
37
38 626 Gazzetta Ufficiale, 1992, Metodi ufficiali di analisi chimica dei suoli. DM 11 maggio
39
40 627 1992, suppl. G.U. 121, 25maggio 1992 [Official Gazette of the Italian Republic.
41
42 628 Official methods for chemical.
43
44
45 629 González, Á., García-gonzalo, P., Gil-díaz, M.M., Alonso, J., Lobo, M.C., 2019.
46
47 630 Compost-assisted phytoremediation of As-polluted soil. J. Soil. Sediment. 19,
48
49 631 2971–2983.
50
51
52 632 Gorovtsov, A., Rajput, V., Minkina, T., Mandzhieva, S., Sushkova, S., Kornienko, I.,
53
54 633 Tatiana, V.G., Chokheli, V., Aleshukina, I., Zinchenko, V., Fedorenko, E.,
55
56
57
58
59
60
61
62
63
64
65

1 634 Movsesyan, H., 2019. The role of biochar-microbe interaction in alleviating heavy
2
3 635 metal toxicity in *Hordeum vulgare* L. grown in highly polluted soils. Appl.
4
5
6 636 Geochem. 104, 93–101.
7
8 637 Gulías, J., Melis, R., Scordia, D., Cifre, J., Testa, G., Cosentino, S.L. and Porqueddu,
9
10
11 638 C., 2018. Exploring the potential of wild perennial grasses as a biomass source in
12
13 639 semi-arid Mediterranean environments. Ital. J. Agron. 13, 937.
14
15 640 Kerley, S., 2000. Changes in root morphology of white lupin (*Lupinus albus* L.) and its
16
17
18 641 adaptation to soils with heterogeneous alkaline/acid profiles. Plant Soil 218, 197–
19
20 642 205.
21
22 643 Kumpiene, J., Bert, V., Dimitriou, I., Eriksson, J., Friesl-Hanl, W., Galazka, R., Herzig,
24
25 644 R., Janssen, J., Kidd, P., Mench, M., Müller, I., Neu, S., Oustriere, N.,
26
27 645 Puschenreiter, M., Renella, G., Roumier, P.H., Siebielec, G., Vangronsveld, J.,
28
29 646 Manier, N., 2014. Selecting chemical and ecotoxicological test batteries for risk
30
31 647 assessment of trace element-contaminated soils (phyto)managed by gentle
32
33 648 remediation options (GRO). Sci. Total Environ. 496, 510–522.
34
35
36
37 649 Hardesty-Moore, M., Orr, D., McCauley, D.J., 2020. Invasive plant *Arundo donax*
38
39 650 alters habitat use by carnivores. Biol. Invasions 22, 1983–1995.
40
41
42 651 Lebrun, M., Miard, F., Nandillon, R., Hattab-hambli, N., Scippa, G., Bourgerie, S.,
43
44 652 Morabito, D., 2018. Eco-restoration of a mine technosol according to biochar
45
46 653 particle size and dose application: study of soil physico-chemical properties and
47
48 654 phytostabilization capacities of *Salix viminalis*. J. Soil Sediment 18, 2188–2202.
49
50
51 655 Liu, Y., Guo, Z., Xiao, X., Wang, S., Jiang, Z., Zeng, P., 2017. Phytostabilisation
52
53 656 potential of giant reed for metals contaminated soil modified with complex organic
54
55 657 fertiliser and fly ash : A field experiment. Sci. Total Environ. 576, 292–302.
56
57
58
59
60
61
62
63
64
65

1 658 Llugany, M., Miralles, R., Corrales, I., Barceló, J., Poschenrieder, C., 2012. *Cynara*
2
3 659 *cardunculus* a potentially useful plant for remediation of soils polluted with
4
5
6 660 cadmium or arsenic. *J. Geochem. Explor.* 123, 122–127.
7
8 661 Ma, Y., Oliveira, R.S., Freitas, H., Zhang, C., 2016. Biochemical and molecular
9
10 662 mechanisms of plant-microbe-metal interactions: relevance for phytoremediation.
11
12
13 663 *Front. Plant Sci.* 7, 918.
14
15 664 Manzano, R., Silveti, M., Garau, G., Deiana, S., Castaldi, P., 2016. Influence of iron-
16
17 665 rich water treatment residues and compost on the mobility of metal(loid)s in mine
18
19 666 soils. *Geoderma* 283, 1–9.
20
21
22 667 Marchand, L., Mench, M., Jacob, D.L., Otte, M.L., 2010. Metal and metalloid removal
23
24 668 in constructed wetlands, with emphasis on the importance of plants and
25
26 669 standardized measurements: A review. *Environ. Pollut.* 158, 3447–3461.
27
28
29 670 Martínez-Alcalá, I., Walker, D.J., Bernal, M.P., 2010. Chemical and biological
30
31 671 properties in the rhizosphere of *Lupinus albus* alter soil heavy metal fractionation.
32
33 672 *Ecotox. Environ. Safe.* 73, 595–602.
34
35
36 673 Mășu, S., Dragomir, N., Morariu, F., 2012. The bioaccumulation of heavy metals in
37
38 674 barley (*Hordeum vulgare* L) cultivated on fly ash dump mixed with compost and
39
40 675 natural zeolite materials. *Sci. Pap. Anim. Sci. Biotechnol.* 45, 237–241.
41
42
43 676 Moameri, M., Khalaki, M.A., 2019. Capability of *Secale montanum* trusted for
44
45 677 phytoremediation of lead and cadmium in soils amended with nano-silica and
46
47 678 municipal solid waste compost. *Environ. Sci. Pollut. Res.* 26, 24315–24322.
48
49
50 679 Nehnevajova, E., Ramireddy, E., Stolz, A., Gerdemann-Knörck, M., Novák, O., Strnad,
51
52 680 M., Schmölling, T., 2019. Root enhancement in cytokinin-deficient oilseed rape
53
54 681 causes leaf mineral enrichment, increases the chlorophyll concentration under
55
56
57
58
59
60
61
62
63
64
65

1 682 nutrient limitation and enhances the phytoremediation capacity. BMC Plant
2
3 683 Biology 19, 83.
4
5
6 684 Pál, M., Janda, T., Szalai, G., 2018. Interactions between plant hormones and thiol-
7
8 685 related heavy metal chelators. Plant Growth Regul. 85, 173-185.
9
10
11 686 Qin, F., Shan, X-Q., Wei, B., 2004. Effects of low-molecular-weight organic acids and
12
13 687 residence time on desorption of Cu, Cd, and Pb from soils. Chemosphere 57, 253–
14
15 688 263.
16
17
18 689 Radziemska, M., Gusiatin, Z.M., Bilgin, A., 2017. Potential of using immobilizing
19
20 690 agents in aided phytostabilization on simulated contamination of soil with lead.
21
22 691 Ecol. Eng. 102, 490–500.
23
24
25 692 Ruiz-di, B., Ferna, M., Puertas-mej1, M.A., 2010. Effect of cadmium ion excess over
26
27 693 cell structure and functioning of *Zea mays* and *Hordeum vulgare*. Biochem. Syst.
28
29 694 Ecol. 38, 285–291.
30
31
32 695 Sánchez-Pardo, B., Zornoza, P., 2014. Ecotoxicology and environmental safety
33
34 696 mitigation of Cu stress by legume–Rhizobium symbiosis in white lupin and
35
36 697 soybean plants. Ecotox. Environ. Safe. 102, 1–5.
37
38
39 698 Silvetti, M., Demurtas, D., Garau, G., Deiana, S., Castaldi, P., 2017. Sorption of Pb, Cu,
40
41 699 Cd, and Zn by municipal solid waste composts: metal retention and desorption
42
43 700 mechanisms. Clean-Soil Air Water 45, 1600253.
44
45
46
47 701 Sinhal, V.K., Srivastava, A., Singh, V.P., 2015. Phytoremediation: a technology to
48
49 702 remediate soil contaminated with heavy metals. Intern. J. Green Herbal Chem. 4,
50
51 703 439–460.
52
53
54 704 Tang, C., Robson, A.D., Longnecker, N.E., Buirchell, B.J., 1995. The growth of
55
56 705 *Lupinus* species on alkaline soils. Aust. J. Agric. Res. 46, 255-68.
57
58
59
60
61
62
63
64
65

1 706 Wanty, R.B., Podda, F., De Giudici, G., Cidu, R., Lattanzi, P., 2013. Zinc isotope and
2
3 707 transition-element dynamics accompanying hydrozincite biomineralization in the
4
5 708 Rio Naracauli, Sardinia, Italy. *Chem. Geol.* 337-338, 1–10.
6
7
8 709 Wenzel, W.W., Kirchbaumer, N., Prohaska, T., Stingeder, G., Lombi, E., Adriano,
9
10 710 D.C., 2001. Arsenic fractionation in soils using an improved sequential extraction
11
12 711 procedure. *Anal. Chim. Acta* 436, 309-323.
13
14
15 712 Winer, B.J., 1971. *Statistical principles in experimental design* (2nd edition). McGraw
16
17 713 Hill, New York.
18
19
20 714 Wong, M.H., 2003. Ecological restoration of mine degraded soils, with emphasis on
21
22 715 metal contaminated soils. *Chemosphere* 50, 775–780.
23
24
25 716 Wu, F., Xu, F., Ma, X., Luo, W., Lou, L., Wong, M.H., 2018. Do arsenate reductase
26
27 717 activities and oxalate exudation contribute to variations of arsenic accumulation in
28
29 718 populations of *Pteris vittata*? *J. Soil. Sediment.* 18, 3177–3185.
30
31
32 719 Ximénez-Embún, P., Madrid-Albarrán, Y., Cámara, C., Cuadrado, C., Burbano, C.,
33
34 720 Múzquiz, M., 2001. Evaluation of lupinus species to accumulate heavy metals
35
36 721 from waste waters. *Int. J. Phytoremediat.* 3, 369–379.
37
38
39 722 Yan, F., Zhu, Y., Muller, C., Zorb, C., Schubert, S., 2002. Adaptation of H⁺-pumping
40
41 723 and plasma membrane H⁺ ATPase activity in proteoid roots of white lupin under
42
43 724 phosphate deficiency. *Plant Physiol.* 129(1), 50–63.
44
45
46 725 Yang, M., Xiao, X.-Y., Miao, X.-F., Guo, Z.-H., Wang, F.-Y., 2012. Effect of
47
48 726 amendments on growth and metal uptake of giant reed (*Arundo donax* L.) grown
49
50 727 on soil contaminated by arsenic, cadmium and lead *Trans. Nonferrous Met. Soc.*
51
52 728 *China* 22, 1462-1469.
53
54
55 729 Ying, T., Yong-Ming, L., Chang-Yong, H., Jian, L., Zhen-Gao, L., Christie, P. 2008.
56
57
58
59
60
61
62
63
64
65

1 730 Tolerance of grasses to heavy metals and microbial functional diversity in soils
2
3 731 contaminated with copper mine tailings. *Pedosphere* 18, 363–370.
4
5
6 732 Zeng, P., Guo, Z. Xiao, X., Peng, C., Huang, B., Feng, W., 2019. Ecotoxicology and
7
8 733 environmental safety complementarity of co-planting a hyperaccumulator with
9
10 734 three metal(loid)-tolerant species for metal(loid)-contaminated soil remediation.
11
12
13 735 *Ecotox. Environ. Safe.* 169, 306–315.
14
15
16 736 Zornoza, P., Pe, J.M., Fresno, T., Moreno-Jim, E., 2018. Aided phytostabilisation of As-
17
18 737 and Cu-contaminated soils using white lupin and combined iron and organic
19
20 738 amendments. *J. Environ. Manage.* 205, 142–150.
21
22
23 739
24
25 740
26
27

28 741 **Figure captions**

29 742
30
31
32 743 **Fig. 1.** Roots and shoots dry weight of *A. donax*, *H. vulgare* and *L. albus* grown on the
33
34 744 unamended and amended soils. For each part of plant species, mean values followed by
35
36 745 different letters denote statistically significant differences according to the Fisher's
37
38 746 Least Significant Difference (LSD) test ($P < 0.05$).
39
40
41

42 747
43
44 748 **Fig. 2.** Concentrations of As and Sb in roots and shoots of *A. donax*, *H. vulgare* and *L.*
45
46 749 *albus* grown on the amended and unamended soils. For each plants part, mean values
47
48 750 followed by different letters denote statistically significant differences according to the
49
50 751 Fisher's Least Significant Difference (LSD) test ($P < 0.05$).
51
52
53

54 752
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

753 **Fig. 3.** Concentrations of Cd and Zn in roots and shoots of *A. donax*, *H. vulgare* and *L.*
754 *albus* grown on the amended and unamended soils. For each plants part, mean values
755 followed by different letters denote statistically significant differences according to the
756 Fisher's Least Significant Difference (LSD) test ($P < 0.05$).

757
758 **Fig. 4.** Concentrations of Pb and Cd in roots and shoots of *A. donax*, *H. vulgare* and *L.*
759 *albus* grown on the amended and unamended soils. For each plants part, mean values
760 followed by different letters denote statistically significant differences according to the
761 Fisher's Least Significant Difference (LSD) test ($P < 0.05$).

762
763
764 **Fig. S1.** PTE released after sequential extraction of soils before plant growth. For each
765 PTE and within each fraction, bars with different letters denote statistically significant
766 differences at $P < 0.05$ according to the post-hoc Fisher's least significant difference
767 test. Graphs are from Garau et al. (2019) Mobility, bioaccessibility and toxicity of
768 potentially toxic elements in a contaminated soil treated with municipal solid waste
769 compost. *Ecotoxicology and Environmental Safety* 186 (2019) 109766.
770 <https://doi.org/10.1016/j.ecoenv.2019.109766>

771
772 **Fig. S2.** Labile (i.e. water-soluble and exchangeable) PTE extracted from the different
773 soils after plant growth (mean values \pm standard deviations; $n = 3$). For each PTE and
774 plant species, bars with different letters indicate statistically significant differences
775 according to the Fisher's least significant difference test ($P < 0.05$).

776

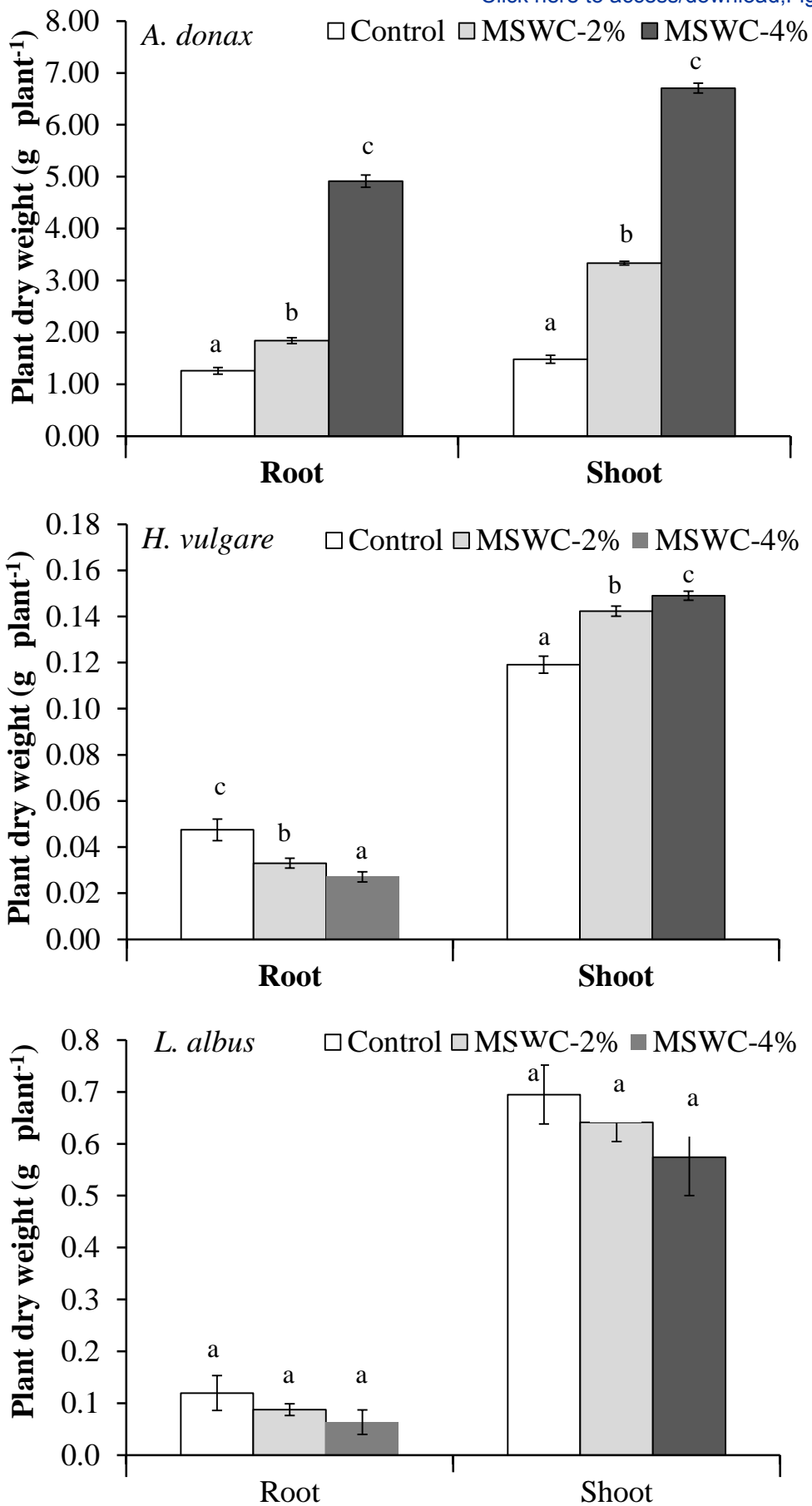


Figure 1

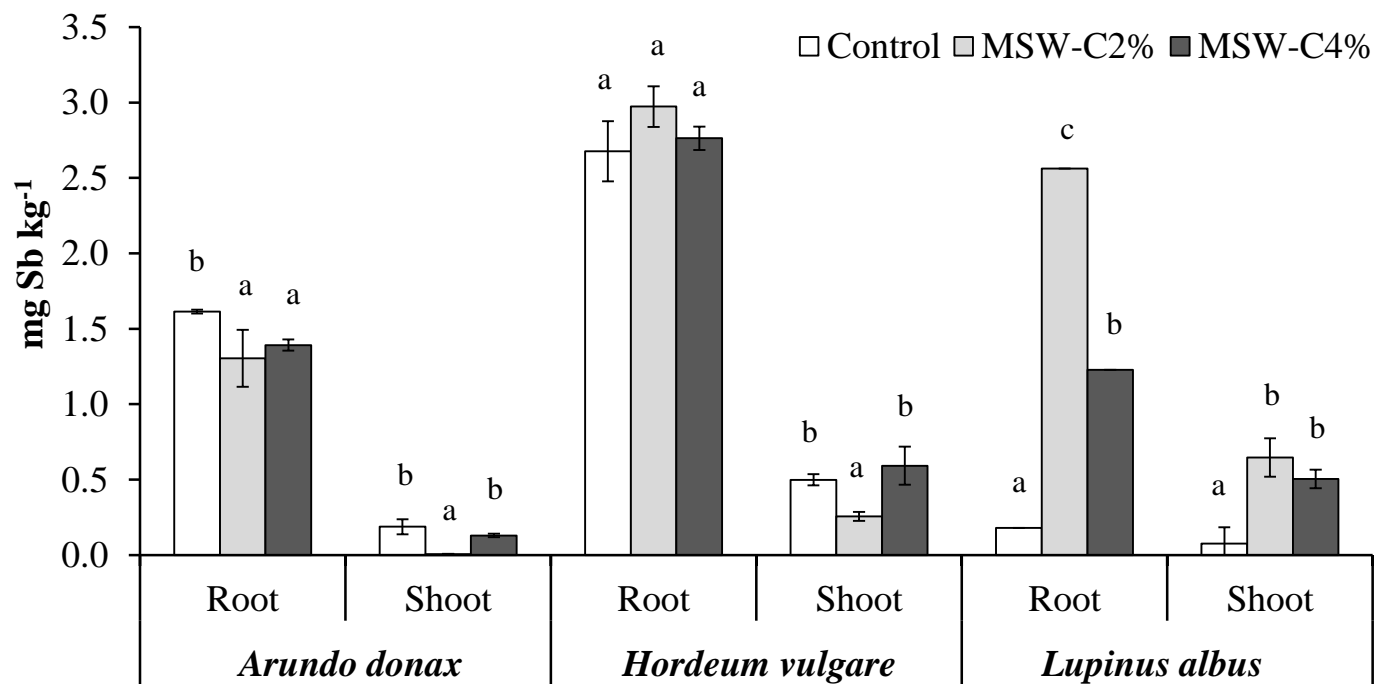
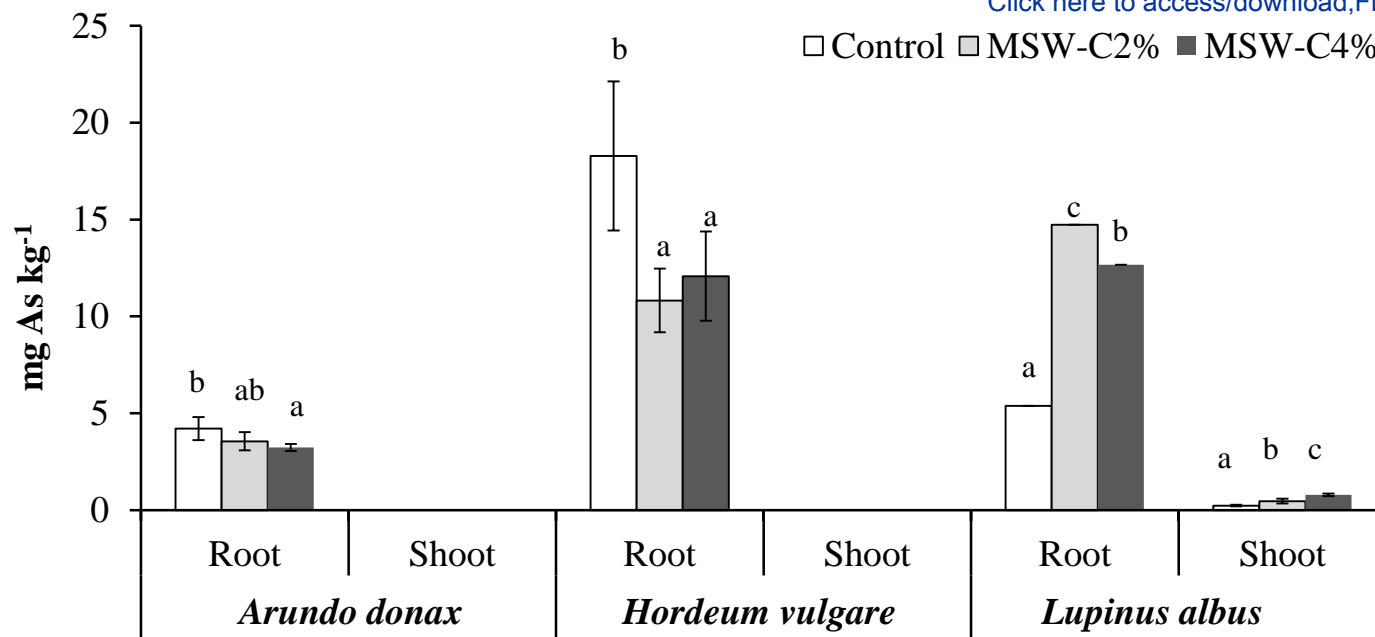


Figure 2

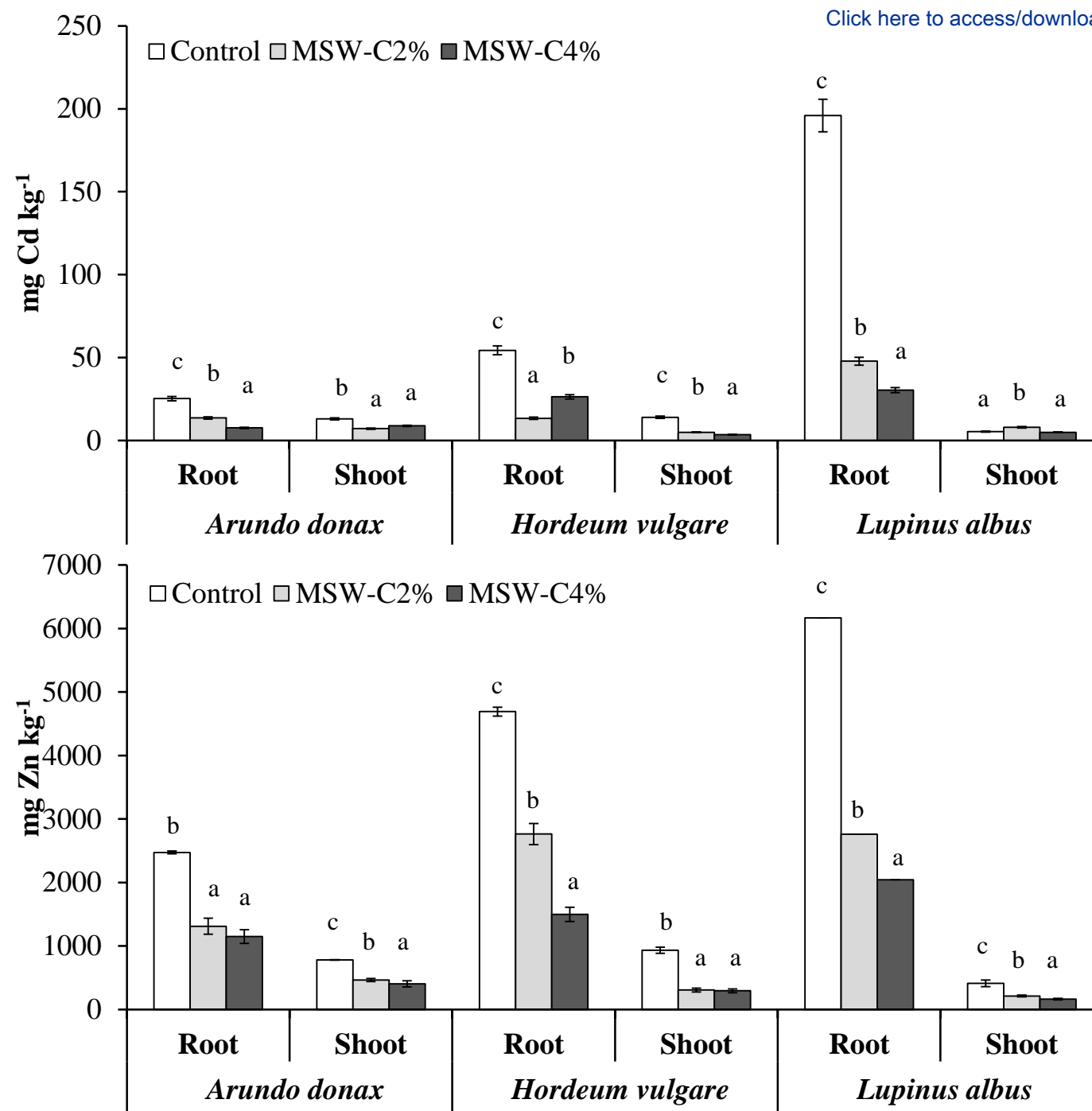


Figure 3

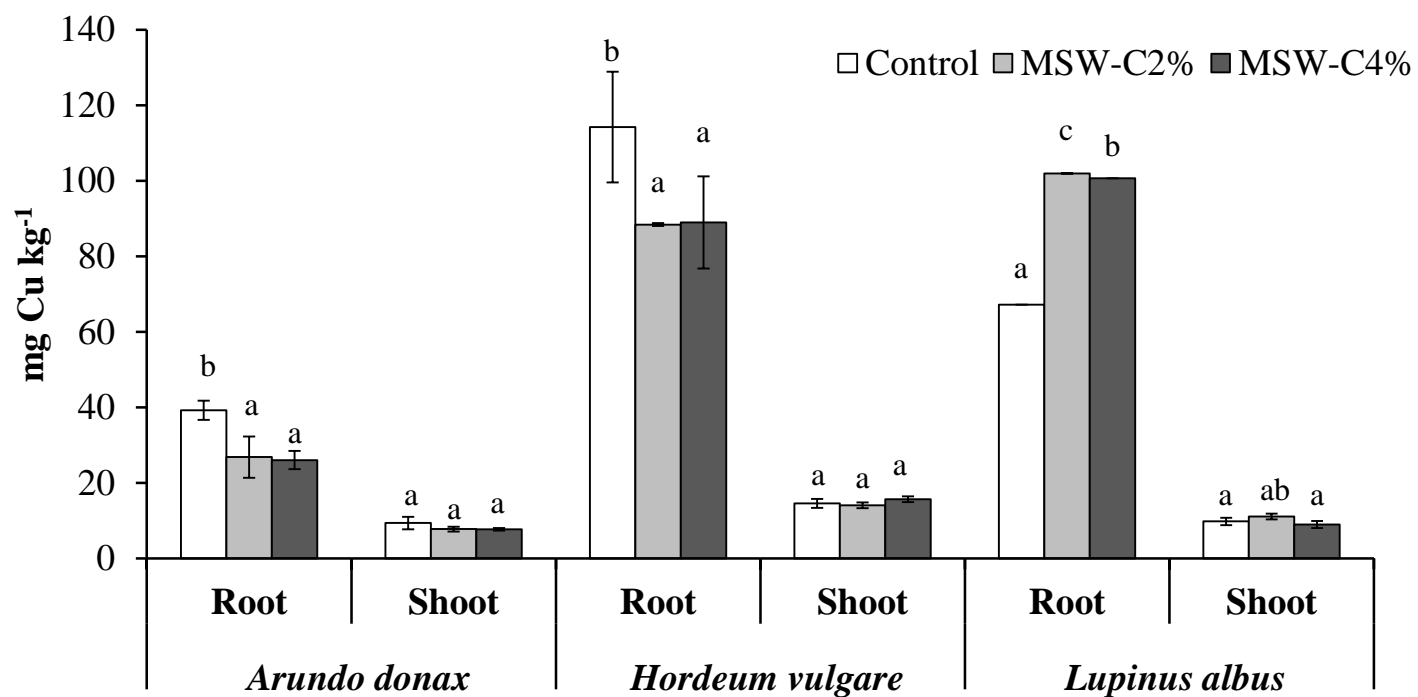
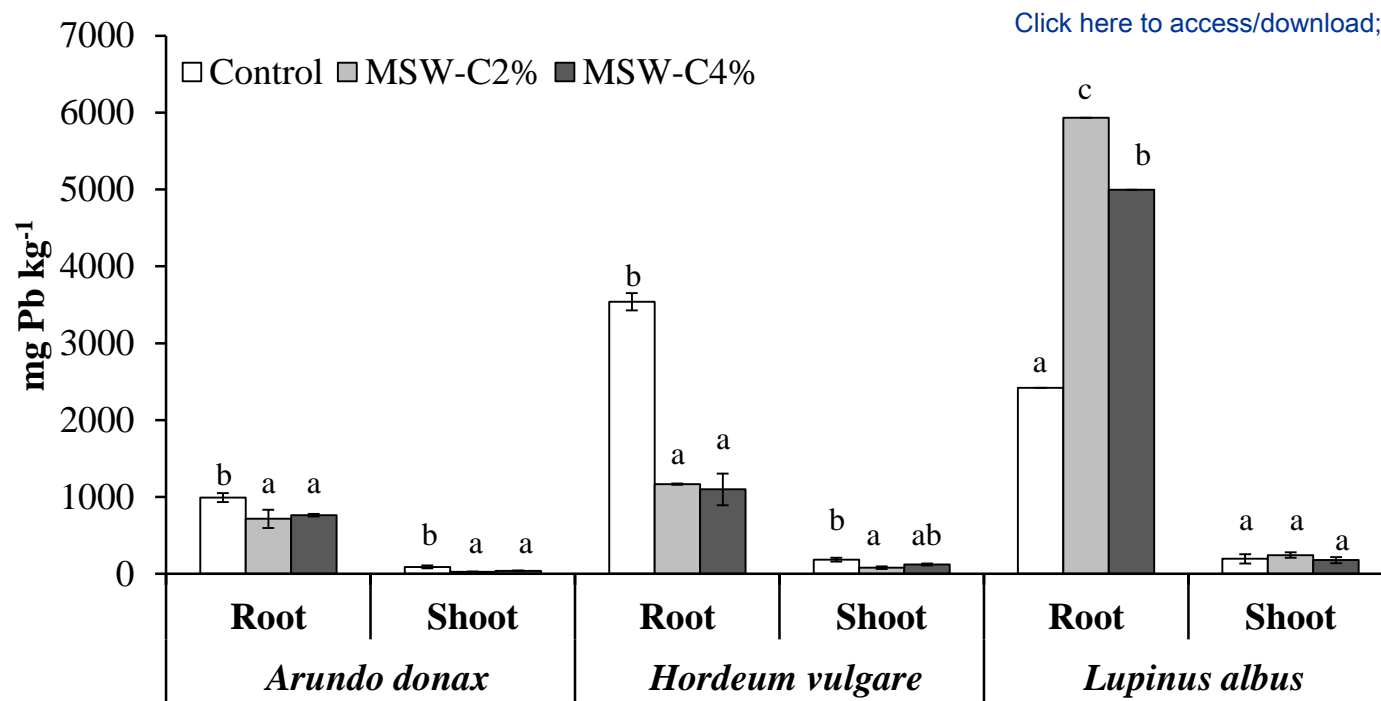


Figure 4

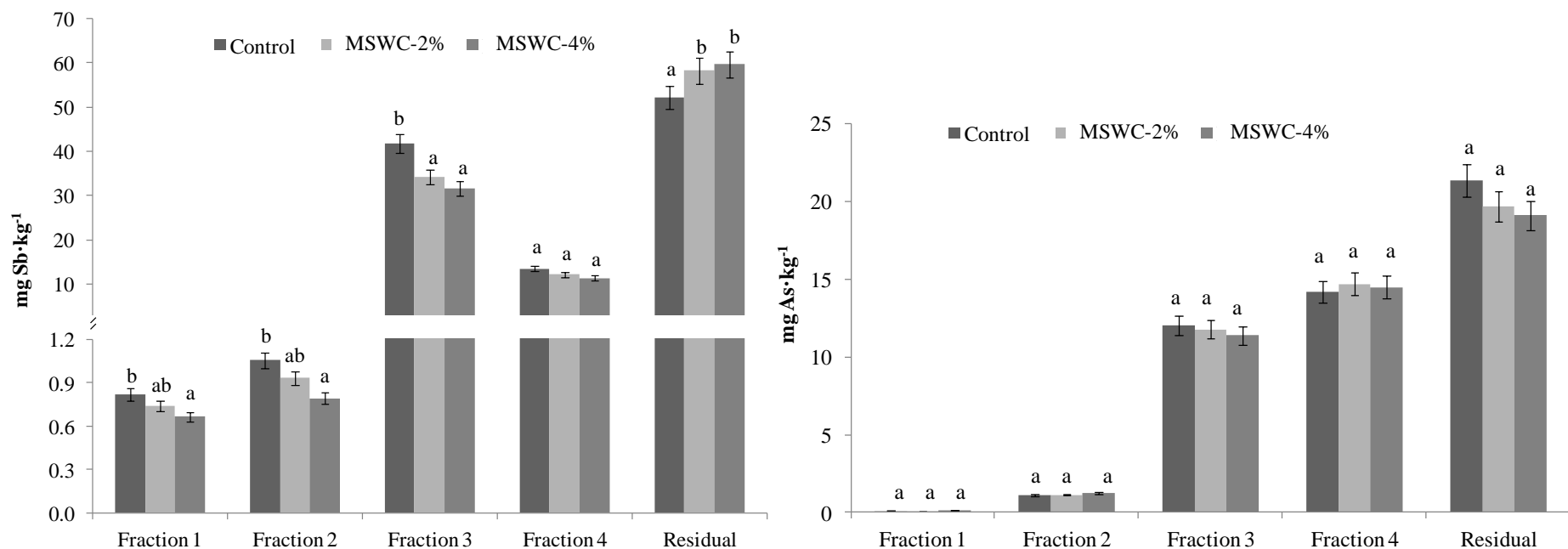


Figure S1. PTE released after sequential extraction of soils before plant growth. For each PTE and within each fraction, bars with different letters denote statistically significant differences at $P < 0.05$ according to the post-hoc Fisher's least significant difference test. Graphs are from Garau et al. (2019) Mobility, bioaccessibility and toxicity of potentially toxic elements in a contaminated soil treated with municipal solid waste compost. *Ecotoxicology and Environmental Safety* 186 (2019) 109766. <https://doi.org/10.1016/j.ecoenv.2019.109766>

Fraction 1. Water soluble and exchangeable As and Sb extracted with 0.05M $(\text{NH}_4)_2\text{SO}_4$

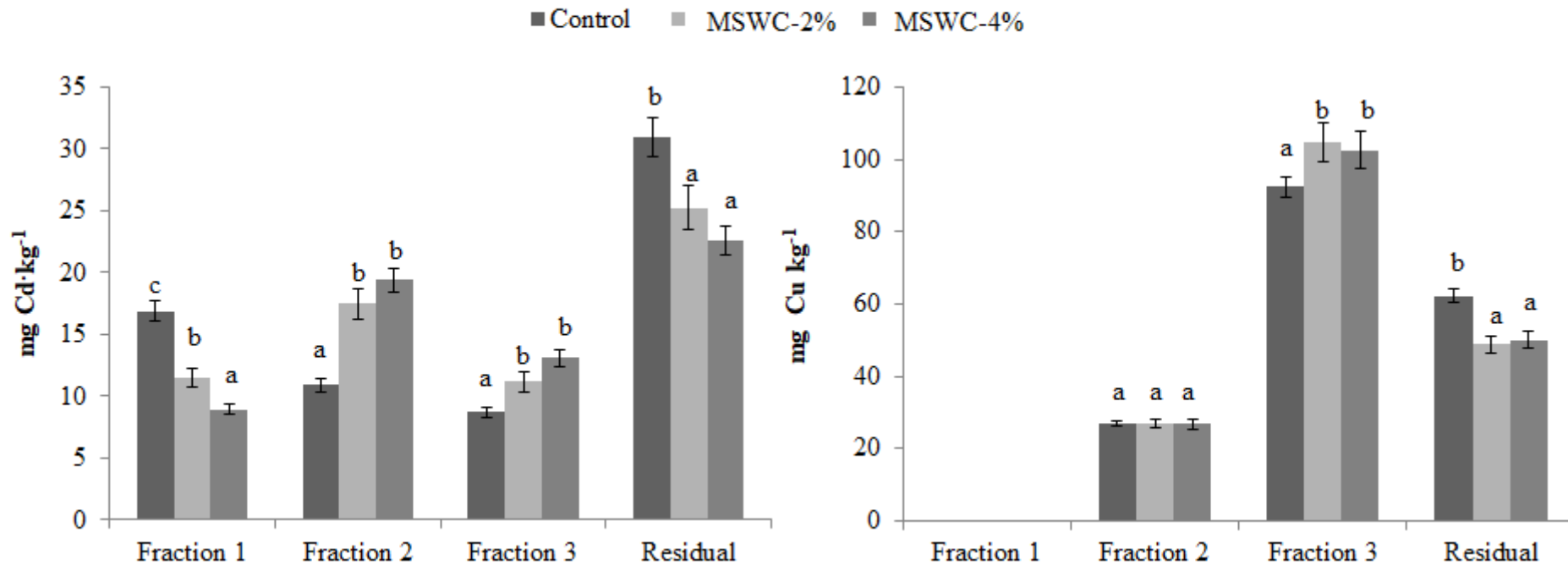
Fraction 2. Specifically sorbed As and Sb extracted with 0.05M $\text{NH}_4\text{H}_2\text{PO}_4$

Fraction 3. As and Sb associated with amorphous Fe and Al hydrous oxides extracted with 0.2M NH_4^+ -oxalate buffer solution

Fraction 4. As and Sb associated with crystallized Fe and Al hydrous oxides extracted with 0.2M NH_4^+ -oxalate buffer + 0.1M ascorbic acid solution

Residual. As and Sb released after acid digestion with H_2O_2 and $\text{HNO}_3 + \text{HCl}$ (3:1 ratio).

All the relevant details on the sequential extraction applied can be found at <https://doi.org/10.1016/j.ecoenv.2019.109766>.



Fraction 1. Water soluble and exchangeable Cd and Cu extracted with 0.5M Ca(NO₃)₂

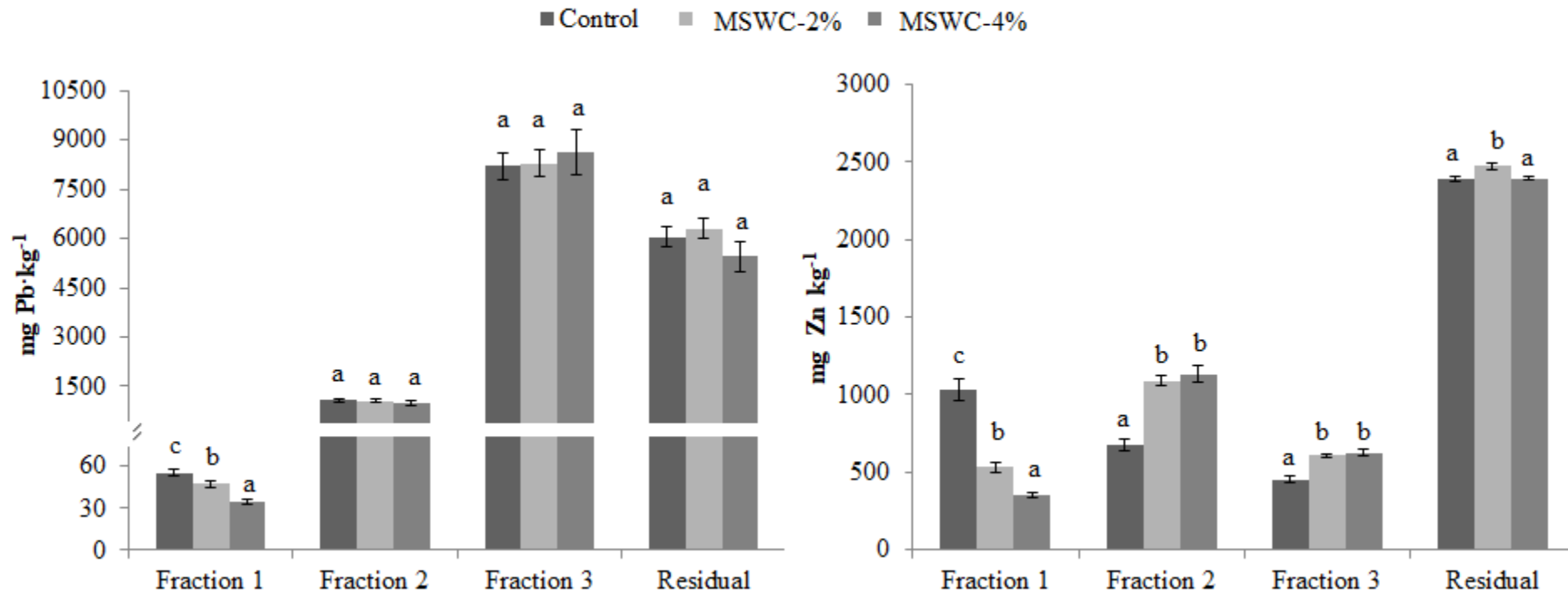
Fraction 2. Cd and Cu forming weak surface complexes extracted with 1M NaOAc solution at pH 5.0

Fraction 3. Surface complexed and precipitated Cd and Cu extracted with 0.1M Na₂EDTA solution

Residual. Cd and Cu released after acid digestion with H₂O₂ and HNO₃ + HCl (3:1 ratio).

All the relevant details on the sequential extraction applied can be found at <https://doi.org/10.1016/j.ecoenv.2019.109766>.

Graphs are from Garau et al. (2019) Mobility, bioaccessibility and toxicity of potentially toxic elements in a contaminated soil treated with municipal solid waste compost. *Ecotoxicology and Environmental Safety* 186 (2019) 109766. <https://doi.org/10.1016/j.ecoenv.2019.109766>.



Fraction 1. Water soluble and exchangeable Pb and Zn extracted with 0.5M Ca(NO₃)₂

Fraction 2. Pb and Zn forming weak surface complexes extracted with 1M NaOAc solution at pH 5.0

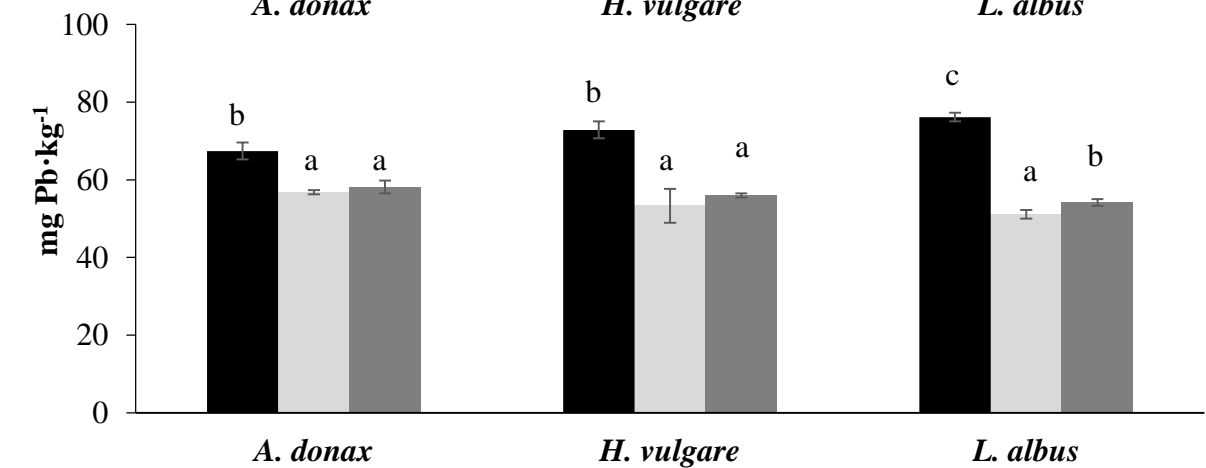
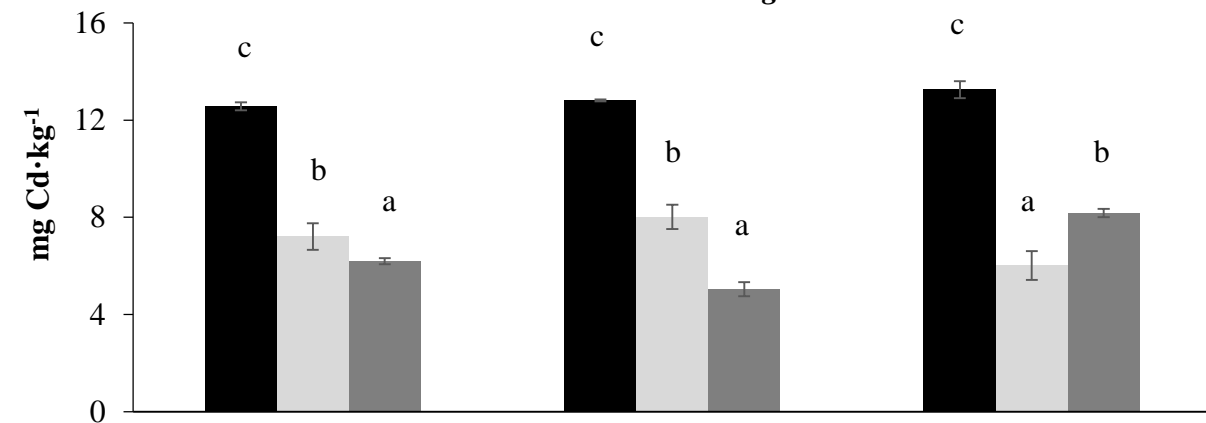
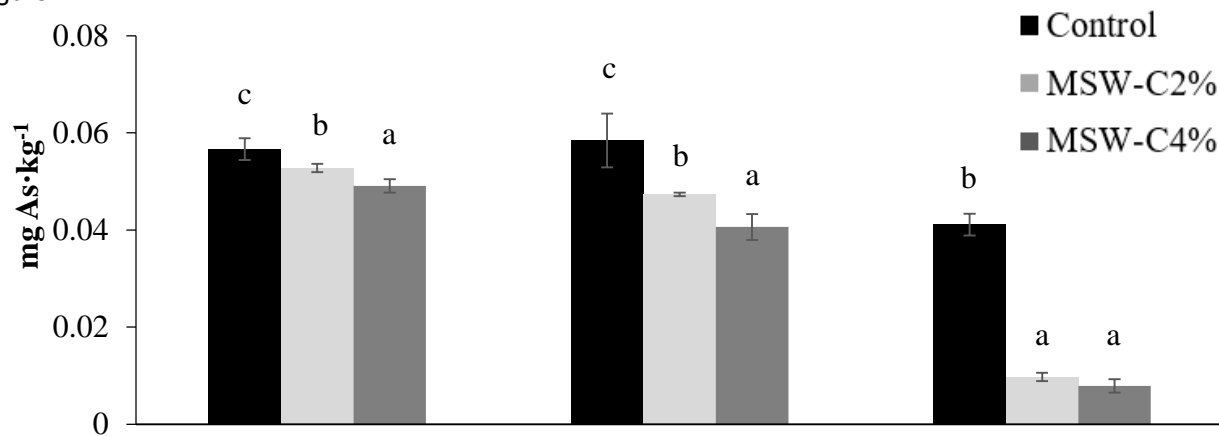
Fraction 3. Surface complexed and precipitated Pb and Zn extracted with 0.1M Na₂EDTA solution

Residual. Pb and Zn released after acid digestion with H₂O₂ and HNO₃ + HCl (3:1 ratio).

All the relevant details on the sequential extraction applied can be found at <https://doi.org/10.1016/j.ecoenv.2019.109766>.

Graphs are from Garau et al. (2019) Mobility, bioaccessibility and toxicity of potentially toxic elements in a contaminated soil treated with municipal solid waste compost. *Ecotoxicology and Environmental Safety* 186 (2019) 109766. <https://doi.org/10.1016/j.ecoenv.2019.109766>.

Figure



[Click here to access/download;Figure;Figure S2.pptx](#)

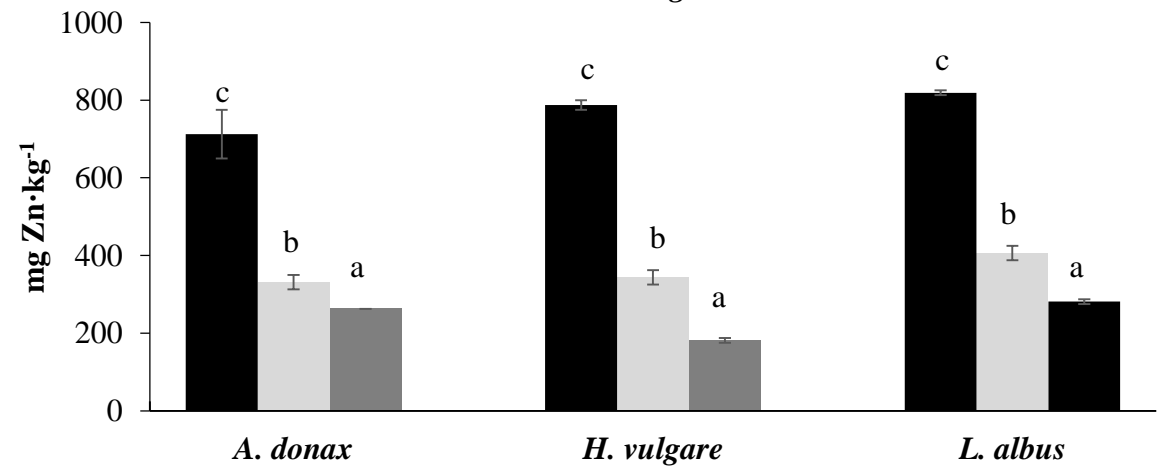
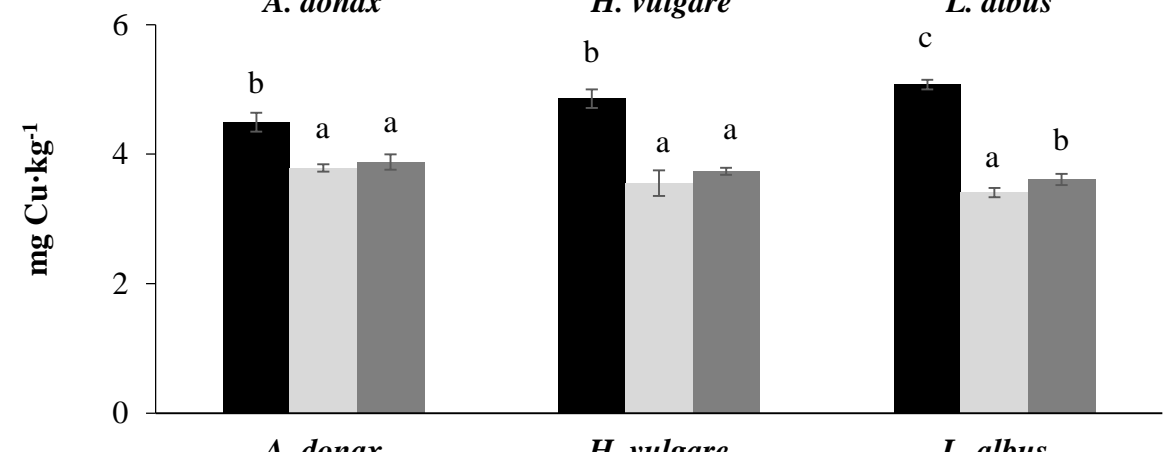
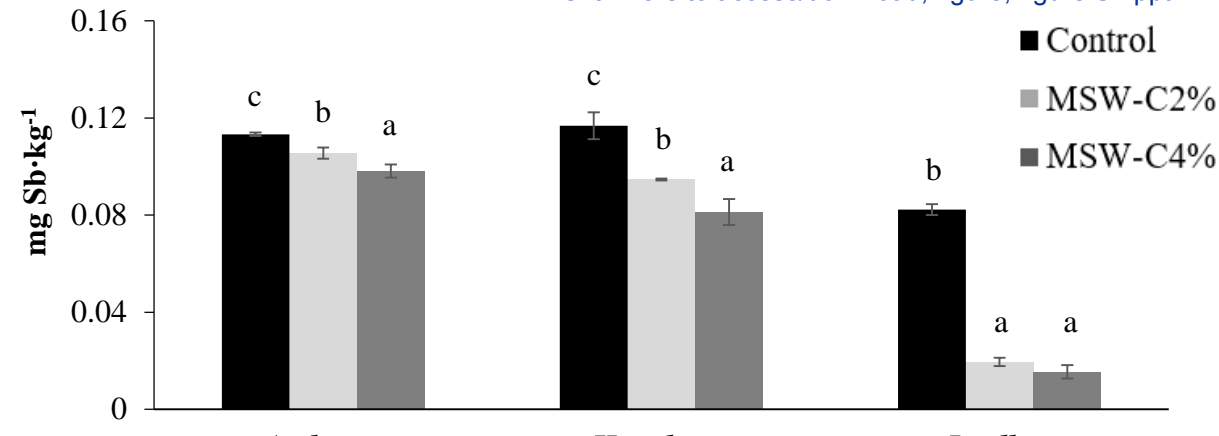


Figure S2. Labile (i.e. water-soluble and exchangeable) PTE extracted from the different soils after plant growth (mean values \pm standard deviations; $n = 3$). For each PTE and plant species, bars with different letters indicate statistically significant differences according to the Fisher's least significant difference test ($P < 0.05$).

Table 1

Bioaccumulation (BAFr and BAFs), translocation (TF) and remediation (RFR and RFs) factors and mineralomasses (MMr and MMs) of PTE in *A. donax*.

		<i>Arundo donax</i>						
		BAFr	BAFs	TF	MMr	MMs	RFR	RFs
As	Control	0.09 ^a	-	-	5.30·10 ^{-3 a}	-	3.62·10 ^{-3 a}	-
	MSWC-2%	0.08 ^a	-	-	6.53·10 ^{-3 a}	-	4.60·10 ^{-3 a}	-
	MSWC-4%	0.07 ^a	-	-	15.90·10 ^{-3 b}	-	11.44·10 ^{-3 b}	-
Sb	Control	14.74·10 ^{-3 b}	1.71·10 ^{-3 b}	0.12 ^c	2.03·10 ^{-3 a}	0.28·10 ^{-3 a}	0.62·10 ^{-3 a}	0.08·10 ^{-3 b}
	MSWC-2%	12.28·10 ^{-3 a}	0.06·10 ^{-3 a}	4.51·10 ^{-3 a}	2.40·10 ^{-3 a}	0.02·10 ^{-3 a}	0.75·10 ^{-3 a}	0.01·10 ^{-3 a}
	MSWC-4%	13.38·10 ^{-3 ab}	1.24·10 ^{-3 a}	0.09 ^b	6.84·10 ^{-3ab}	0.87·10 ^{-3 b}	2.19·10 ^{-3 b}	0.28·10 ^{-3 c}
Cd	Control	0.37 ^c	0.19 ^b	0.51 ^a	31.72·10 ^{-3 b}	19.25·10 ^{-3 a}	15.68·10 ^{-3 a}	9.52·10 ^{-3 a}
	MSWC-2%	0.21 ^b	0.11 ^a	0.52 ^a	25.04·10 ^{-3 a}	23.68·10 ^{-3 a}	12.74·10 ^{-3 a}	12.07·10 ^{-3 a}
	MSWC-4%	0.12 ^a	0.14 ^a	1.17 ^b	37.39·10 ^{-3 c}	58.95·10 ^{-3 b}	19.45·10 ^{-3 b}	30.66·10 ^{-3 b}
Zn	Control	0.61 ^b	0.19 ^b	0.32 ^a	3.11 ^b	1.16 ^a	0.03 ^a	9.45·10 ^{-3 a}
	MSWC-2%	0.31 ^a	0.11 ^a	0.36 ^a	2.41 ^a	1.54 ^a	0.02 ^a	12.08·10 ^{-3 a}
	MSWC-4%	0.28 ^a	0.10 ^a	0.35 ^a	5.65 ^c	2.70 ^b	0.05 ^b	22.06·10 ^{-3 b}
Pb	Control	0.06 ^b	5.77·10 ^{-3 c}	0.09 ^b	1.25 ^a	0.13 ^a	2.71·10 ^{-3 a}	0.28·10 ^{-3 ab}
	MSWC-2%	0.05 ^a	1.87·10 ^{-3 a}	0.04 ^a	1.32 ^a	0.10 ^a	2.79·10 ^{-3 a}	0.21·10 ^{-3 a}
	MSWC-4%	0.05 ^a	2.23·10 ^{-3 b}	0.04 ^a	3.74 ^b	0.23 ^b	8.26·10 ^{-3 b}	0.50·10 ^{-3 b}
Cu	Control	0.22 ^b	0.05 ^b	0.24 ^a	0.05 ^a	13.81·10 ^{-3 a}	9.06·10 ^{-3 a}	2.54·10 ^{-3 a}
	MSWC-2%	0.15 ^a	0.04 ^a	0.30 ^a	0.05 ^a	25.87·10 ^{-3 a}	9.12·10 ^{-3 a}	4.78·10 ^{-3 b}
	MSWC-4%	0.14 ^a	0.04 ^a	0.30 ^a	0.13 ^b	51.39·10 ^{-3 b}	23.73·10 ^{-3 b}	9.55·10 ^{-3 c}

For each PTE, BAF, TF and MM values followed by different letters indicate statistically significant differences according to the Fisher's Least Significant Difference (LSD) test ($P < 0.05$).

Table 2

Bioaccumulation (BAFr and BAFs), translocation (TF) and remediation (RFr and RFs) factors and mineralomasses (MMr and MMs) of PTE in *H. vulgare*.

		<i>Hordeum vulgare</i>						
		BAFr	BAFs	TF	MMr	MMs	RFr	RFs
As	Control	0.29 ^a	-	-	0.87·10 ⁻³ ^b	-	1.19·10 ⁻³ ^b	-
	MSWC-2%	0.23 ^a	-	-	0.29·10 ⁻³ ^a	-	0.50·10 ⁻³ ^a	-
	MSWC-4%	0.26 ^a	-	-	0.40·10 ⁻³ ^a	-	0.47·10 ⁻³ ^a	-
Sb	Control	0.02 ^a	4.55·10 ⁻³ ^b	0.19 ^b	0.13·10 ⁻³ ^b	0.06·10 ⁻³ ^b	0.08·10 ⁻³ ^c	0.04·10 ⁻³ ^b
	MSWC-2%	0.03 ^a	2.41·10 ⁻³ ^a	0.09 ^a	0.08·10 ⁻³ ^a	0.04·10 ⁻³ ^a	0.06·10 ⁻³ ^b	0.02·10 ⁻³ ^a
	MSWC-4%	0.03 ^a	5.69·10 ⁻³ ^b	0.21 ^b	0.09·10 ⁻³ ^a	0.09·10 ⁻³ ^c	0.05·10 ⁻³ ^a	0.06·10 ⁻³ ^b
Cd	Control	0.81 ^c	0.21 ^c	0.26 ^b	2.58·10 ⁻³ ^c	1.66·10 ⁻³ ^c	2.55·10 ⁻³ ^c	1.64·10 ⁻³ ^b
	MSWC-2%	0.20 ^a	0.08 ^b	0.37 ^c	0.36·10 ⁻³ ^a	0.70·10 ⁻³ ^b	0.45·10 ⁻³ ^a	0.71·10 ⁻³ ^a
	MSWC-4%	0.41 ^b	0.05 ^a	0.13 ^a	0.87·10 ⁻³ ^b	0.52·10 ⁻³ ^a	0.74·10 ⁻³ ^b	0.54·10 ⁻³ ^a
Zn	Control	1.15 ^c	0.23 ^b	0.20 ^b	0.22 ^c	0.11 ^b	3.64·10 ⁻³ ^c	1.82·10 ⁻³ ^b
	MSWC-2%	0.65 ^b	0.07 ^a	0.11 ^a	0.07 ^b	0.04 ^a	1.43·10 ⁻³ ^b	0.68·10 ⁻³ ^a
	MSWC-4%	0.37 ^a	0.07 ^a	0.21 ^b	0.05 ^a	0.04 ^a	0.66·10 ⁻³ ^a	0.72·10 ⁻³ ^a
Pb	Control	0.23 ^b	12.00·10 ⁻³ ^b	0.05 ^a	0.17 ^b	0.02 ^b	0.73·10 ⁻³ ^b	0.10·10 ⁻³ ^b
	MSWC-2%	0.07 ^a	5.04·10 ⁻³ ^a	0.07 ^b	0.03 ^a	0.01 ^a	0.16·10 ⁻³ ^a	0.05·10 ⁻³ ^a
	MSWC-4%	0.07 ^a	8.05·10 ⁻³ ^{ab}	0.11 ^c	0.04 ^a	0.02 ^{ab}	0.13·10 ⁻³ ^a	0.08·10 ⁻³ ^{ab}
Cu	Control	0.63 ^b	0.08 ^a	0.13 ^a	5.42·10 ⁻³ ^b	1.73·10 ⁻³ ^a	1.99·10 ⁻³ ^b	0.64·10 ⁻³ ^a
	MSWC-2%	0.49 ^a	0.08 ^a	0.16 ^{ab}	2.39·10 ⁻³ ^a	2.00·10 ⁻³ ^b	1.08·10 ⁻³ ^a	0.74·10 ⁻³ ^b
	MSWC-4%	0.50 ^a	0.09 ^a	0.18 ^b	2.94·10 ⁻³ ^a	2.33·10 ⁻³ ^c	0.90·10 ⁻³ ^a	0.87·10 ⁻³ ^c

For each PTE, BAF, TF and MM values followed by different letters indicate statistically significant differences according to the Fisher's Least Significant Difference (LSD) test ($P < 0.05$).

Table 3.

Bioaccumulation (BAFr and BAFs), translocation (TF) and remediation (RFr and RFs) factors and mineralomasses (MMr and MMs) of PTE in *L. albus*.

		<i>Lupinus albus</i>						
		BAFr	BAFs	TF	MMr	MMs	RFr	RFs
As	Control	0.17 ^a	4.72·10 ^{-3 a}	0.04 ^b	0.64·10 ^{-3 a}	0.16·10 ^{-3 a}	0.44·10 ^{-3 a}	0.11·10 ^{-3 a}
	MSWC-2%	0.31 ^b	9.69·10 ^{-3 b}	0.03 ^a	1.29·10 ^{-3 c}	0.29·10 ^{-3 b}	0.91·10 ^{-3 c}	0.21·10 ^{-3 b}
	MSWC-4%	0.27 ^{ab}	17.07·10 ^{-3 c}	0.06 ^c	0.80·10 ^{-3 b}	0.45·10 ^{-3 c}	0.58·10 ^{-3 b}	0.33·10 ^{-3 c}
Sb	Control	1.65·10 ^{-3 a}	0.70·10 ^{-3 a}	0.43 ^b	0.02·10 ^{-3 a}	0.05·10 ^{-3 a}	0.01·10 ^{-3 a}	0.02·10 ^{-3 a}
	MSWC-2%	0.02 ^c	6.08·10 ^{-3 b}	0.25 ^a	0.22·10 ^{-3 c}	0.41·10 ^{-3 c}	0.07·10 ^{-3 c}	0.13·10 ^{-3 c}
	MSWC-4%	0.01 ^b	4.84·10 ^{-3 b}	0.41 ^b	0.08·10 ^{-3 b}	0.29·10 ^{-3 b}	0.02·10 ^{-3 b}	0.09·10 ^{-3 b}
Cd	Control	2.90 ^c	0.08 ^a	0.03 ^a	23.41·10 ^{-3 c}	3.72·10 ^{-3 ab}	11.57·10 ^{-3 c}	1.84·10 ^{-3 a}
	MSWC-2%	0.73 ^b	0.12 ^b	0.17 ^b	4.20·10 ^{-3 b}	5.09·10 ^{-3 b}	2.14·10 ^{-3 b}	2.59·10 ^{-3 b}
	MSWC-4%	0.47 ^a	0.08 ^a	0.16 ^b	1.92·10 ^{-3 a}	2.83·10 ^{-3 a}	1.00·10 ^{-3 a}	1.47·10 ^{-3 a}
Zn	Control	1.51 ^c	0.10 ^b	0.07 ^a	0.74 ^c	0.29 ^c	6.03·10 ^{-3 c}	2.33·10 ^{-3 c}
	MSWC-2%	0.65 ^b	0.05 ^a	0.08 ^b	0.24 ^b	0.14 ^b	1.90·10 ^{-3 b}	1.07·10 ^{-3 b}
	MSWC-4%	0.50 ^a	0.04 ^a	0.08 ^b	0.13 ^a	0.09 ^a	1.06·10 ^{-3 a}	0.76·10 ^{-3 a}
Pb	Control	0.16 ^a	0.01 ^a	0.08 ^b	0.29 ^a	0.14 ^{ab}	0.63·10 ^{-3 a}	0.29·10 ^{-3 ab}
	MSWC-2%	0.38 ^c	0.02 ^a	0.04 ^a	0.52 ^c	0.16 ^b	1.11·10 ^{-3 c}	0.33·10 ^{-3 b}
	MSWC-4%	0.33 ^b	0.01 ^a	0.04 ^a	0.32 ^b	0.10 ^a	0.70·10 ^{-3 b}	0.23·10 ^{-3 a}
Cu	Control	0.37 ^a	0.05 ^a	0.15 ^b	8.03·10 ^{-3 b}	6.79·10 ^{-3 b}	1.47·10 ^{-3 b}	1.25·10 ^{-3 b}
	MSWC-2%	0.57 ^c	0.06 ^b	0.11 ^a	8.95·10 ^{-3 b}	7.10·10 ^{-3 b}	1.65·10 ^{-3 c}	1.31·10 ^{-3 b}
	MSWC-4%	0.56 ^b	0.05 ^a	0.09 ^a	6.39·10 ^{-3 a}	5.13·10 ^{-3 a}	1.19·10 ^{-3 a}	0.95·10 ^{-3 a}

For each PTE, BAF, TF and MM values followed by different letters indicate statistically significant differences according to the Fisher's Least Significant Difference (LSD) test ($P < 0.05$).

1 **Table S1.**

2 Characteristics of MSWC, untreated polluted (control) and MSWC-amended soils (dry matter basis)
 3 before plant growth (mean values \pm standard deviations; $n = 3$). For each row, and only for soils,
 4 mean values followed by different letters indicate statistically significant differences according to
 5 the Fisher's least significant difference test ($P < 0.05$).

	MSWC	Control soil	MSWC-2%	MSWC-4%
pH	7.93	5.93 ^a	6.53 ^b	6.78 ^c
Electric Conductivity (EC, mS cm ⁻¹)	3.26	1.34 ^a	1.75 ^b	2.07 ^c
Total organic matter (%)	47.45	3.24 ^a	3.99 ^b	4.85 ^c
Total N (%)	2.18	0.13 ^a	0.17 ^b	0.23 ^c
Dissolved organic carbon (DOC, mg·g ⁻¹)	0.817	0.11 ^a	0.25 ^b	0.48 ^c
P available (mg·kg ⁻¹)	62.24	22.62 ^a	32.83 ^b	44.82 ^c
Cation Exchange capacity (CEC, cmol ₍₊₎ ·kg ⁻¹)	92.30	36.86 ^a	39.01 ^{ab}	42.04 ^b
Exchangeable Na (cmol ₍₊₎ ·kg ⁻¹)	-	0.44 ^a	0.79 ^b	1.24 ^c
Exchangeable K (cmol ₍₊₎ ·kg ⁻¹)	-	1.03 ^a	1.55 ^b	2.09 ^c
Exchangeable Ca (cmol ₍₊₎ ·kg ⁻¹)	-	22.84 ^a	25.91 ^{ab}	27.92 ^b
Exchangeable Mg (cmol ₍₊₎ ·kg ⁻¹)	-	10.88 ^a	9.72 ^a	9.95 ^a
<i>Total PTE (mg·kg⁻¹)</i>				
As	n.d.	48.75 ^a	47.29 ^a	46.31 ^a
Cd	n.d.	67.45 ^a	65.43 ^b	64.08 ^b
Cu	19.24	181.45 ^a	180.34 ^a	179.44 ^a
Pb	3.72	15,383 ^a	15,690 ^a	15,116 ^a
Sb	n.d.	109.48 ^b	106.20 ^a	104.01 ^a
Zn	30.52	4,076 ^a	4,261 ^a	4,082 ^a

6 n.d. = not detected.

7 Data are from Garau et al. (2019) Mobility, bioaccessibility and toxicity of potentially toxic
 8 elements in a contaminated soil treated with municipal solid waste compost. *Ecotoxicology and*
 9 *Environmental Safety* 186 (2019) 109766. <https://doi.org/10.1016/j.ecoenv.2019.109766>.

Table S2

Main chemical characteristics of the untreated polluted (control) and MSWC-amended soils (dry matter basis) after plant growth (mean values \pm standard deviations; $n = 3$). For each row mean values followed by different letters indicate statistically significant differences according to Fisher's least significant difference test ($P < 0.05$).

	Plant	Control	MSW-C2%	MSW-C4%
pH _{H2O}	<i>A. donax</i>	6.35 \pm 0.01 ^a	6.89 \pm 0.01 ^b	7.21 \pm 0.02 ^c
	<i>H. vulgare</i>	6.37 \pm 0.02 ^a	6.98 \pm 0.02 ^b	7.27 \pm 0.02 ^c
	<i>L. albus</i>	6.09 \pm 0.03 ^a	6.82 \pm 0.04 ^b	7.01 \pm 0.01 ^c
EC (mS cm ⁻¹)	<i>A. donax</i>	0.75 \pm 0.02 ^a	0.77 \pm 0.02 ^a	0.88 \pm 0.02 ^b
	<i>H. vulgare</i>	1.49 \pm 0.00 ^b	1.51 \pm 0.01 ^b	1.33 \pm 0.02 ^a
	<i>L. albus</i>	1.05 \pm 0.06 ^b	0.73 \pm 0.08 ^a	1.56 \pm 0.05 ^c
Total organic matter (%)	<i>A. donax</i>	3.24 \pm 0.04 ^a	3.80 \pm 0.04 ^b	4.59 \pm 0.08 ^c
	<i>H. vulgare</i>	3.42 \pm 0.06 ^a	3.97 \pm 0.1 ^b	4.64 \pm 0.01 ^c
	<i>L. albus</i>	3.84 \pm 0.07 ^a	4.31 \pm 0.11 ^b	4.91 \pm 0.06 ^c
Total N (%)	<i>A. donax</i>	0.12 \pm 0.01 ^a	0.15 \pm 0.00 ^b	0.21 \pm 0.00 ^c
	<i>H. vulgare</i>	0.11 \pm 0.00 ^a	0.16 \pm 0.00 ^b	0.20 \pm 0.00 ^c
	<i>L. albus</i>	0.14 \pm 0.00 ^a	0.18 \pm 0.00 ^b	0.22 \pm 0.00 ^c
DOC (mg·g ⁻¹)	<i>A. donax</i>	0.05 \pm 0.00 ^a	0.09 \pm 0.00 ^b	0.09 \pm 0.00 ^b
	<i>H. vulgare</i>	0.07 \pm 0.00 ^c	0.04 \pm 0.00 ^b	0.02 \pm 0.00 ^a
	<i>L. albus</i>	0.05 \pm 0.00 ^a	0.14 \pm 0.00 ^b	0.26 \pm 0.00 ^c

Declaration of interests

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

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author Agreement Statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed.

We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Signed by all authors as follows:

Matteo Garau,

Paola Castaldi,

Stefania Diquattro,

Maria Vittoria Pinna,

Caterina Senette,

Pier Paolo Roggero,

Giovanni Garau