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Potential analysis of *Baccharis dracunculifolia* and *Baccharis trimera* for phytoremediation of heavy metals in copper mining tailings area, Southern Brazil

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Abstract

The aim of this study was to investigate the phytoremediation potential promoted by *Baccharis dracunculifolia* DC. and *Baccharis trimera* (Less.) DC. incopper mining tailings area, Southern Brazil. The plants were selected considering their spontaneous growth on tailings. The phytoremediation indexes as a translocation factor (TF), bioconcentration factor (BCF), metal extraction ratio (MER) and plant effective number (PEN) were carried out. Both species showed higher concentration of heavy metals in the roots in relation to the shoots. *B. trimera* showed potential for phytoextraction of Zn, Cd, Cr, Pb and phytostabilization of Ba and Ni, whereas *B. dracunculifolia* showed potential for phytoextraction Pb and phytostabilization of Cu, Zn, and Ba. *B. trimera* showed higher potential in phytoremediation of the metals Cu>Zn>Cr>Ni and Cd than the *B. dracunculifolia*. *B. trimera* requires a smaller number of plants to remove 1 g of Cu, Zn, Cr, Pb, Niand Cd than the *B. dracunculifolia*. The values of PENs for Cu were close to those estimated for *B. dracunculifolia*, but the PENs (Cu) and PENt (Cu) in *B. trimera* are much lower, meaning that a smaller number of plants are required for decontamination. Both species showed potential for phytoremediation of metals and grew spontaneously in the tailing mining area.

Keywords Environmental damage, Contaminated soils, Phytoremediation, Heavy metals

Introduction

The abundance of mineral resources in Brazil is well known. Brazil has about 207 actived mines, producing a wide variety of industrial minerals, including metals (Al, Cu, Cr, Fe, Mg, Nb, Ni, Au, V and Zn), and it is almost 80% of its production [1].

Mining activity is essential for society,and economy.However, in current years, the disruption of the tailings dams of Brumadinho (2019) and Mariana (2015) brought worldwide prominence to Brazil due to the environmental liabilities generated [2]. It was evident that the country has been facing problems regarding the proper control and management of its mining tailings.

Mine tailings are generated after the mineral processing, and consist in a mixture of rock (solid waste) composition that varies according to the type of ore [3]. The generation of mine tailings can affect the quality of the environment and contributes to high concentrations of heavy metals, whether in soil and/or water [4, 5].

Due to the high content of heavy metals, tailings pose a health risk to the environment and must be chemically and physically stabilized. There is a range of techniques that can be used in the remediation process of an area that contains heavy metals, and phytoremediation is a technique for stabilizing mining tailings in both aspects, chemical and physical [6].

Phytoremediation uses plants capable of removing or immobilizing organic or inorganic contaminants [7]. They also have different mechanisms such as phytostabilization and phytoextraction.

Phytoextraction is the uptake of contaminants from soil or water by plant roots and their translocation to and accumulation in aboveground biomass i.e., shoots [8]. Plants that do not transport the metals to the shoots, but instead bind them in the root or the rhizosphere, are preferred by phytostabilization [9, 10]. Both techniques are a way to investigate whether a species has potential for phytoremediation.

The species *Gazania rigens* e *Pelargonium hortorum*that, occur naturally in a copper mining tailings area in Chile, are an example of plants that showed potential in the phytoremediation of heavy metals [11]. However, the species *B. trimera* (carqueja) and *B. dracunculifolia* (Alecrim-of-the-field), although identified in some studies in copper and gold mining areas in southern Brazil [12, 13, 14] are still poorly studied for phytoremediation purposes.

Both species belong to the family Asteraceae. They are a rustic, perennial and dioecious shrub, native to the southern and southeastern regions of Brazil [15, 16], and in South America [17, 18, 19, 20].

B. dracunculifolia plays an important role in the colonization and regeneration of contaminated areas [21,22], being considered in Brazil as a secondary vegetation or, in regeneration and advanced stages of regeneration, that is resulting from natural processes of ecological succession [23]. Some studies have shown that both species have the ability to accumulate heavy metals in their biomass [13, 14, 24].

In this context, the aim of this study was to investigate the phytoremediation potential promoted by *B. dracunculifolia* and *B. trimera* in copper mining tailings area, Southern Brazil.

Materials and Methods

Study area

Camaquã Mines belongs to the municipality of Caçapava do Sul, which it is located in the Southern region of Brazil, state of Rio Grande do Sul (Figure 1).

The Camaquã Mines belongs to the Pampa Biome characterized by a vegetation of the wooded steppe type [25]. The climate is temperate of the subtropical type, classified as humid mesotherm and the region is located in the sub-basin of Arroyo João Dias [26].

The soils that comprise the Camaquã Mine region are classified as A-Chernozemic [27]. The Camaquã Mine region is marked by what remains of the copper mining and it is located on plane levels of mining tailings where the open pit (already mined area) has been filled.

Camaquã Mines region contain one of the largest deposits of basic copper metals associated with Pb-Zn in the southern of Brazil. The exploration of the base metals (mainly copper) has occurred since the 19th century [28]. The region, includes the tailings of Uruguay Mine (Cu) (closed in 1996) which is the specific area of this study.

Plant samples and elements detection

Both species *B. trimera* and *B. dracunculifolia*, are colonist plants on the copper mining tailings of the Uruguay mine. *B. trimera* obtained an average total dry biomass of 2.4 ± 0.7 g (roots), 4.8 ± 2.8 g (shoots),and an average height of 42.0 ± 4.0 cm, while *B. dracunculifolia* showed an average height of 33.5 ± 12.0 cm and dry biomass of 0.9 ± 0.6 g (roots), 3.9 ± 2.2g (shoots).

The plants (*n=12*) were sampled in the copper mining tailings area. The sampling was performed in the summer season (2017) and the collected material was packed in stored in properly identified bags and taken to laboratory. The samples of plants were washed individually and divided into shoots and roots and fresh weight was determined. Afterwards, the biomasses were dried in an oven at 70 ºC for 48 hours and ground to a homogeneous power[29]. For the digestion process, it was used a

3:1 concentrated nitric-perchloric acid (HNO_3-$HClO_4$) according to the methodology described by Tedesco *et al*. [30]. The determination of the elements was performed by ICP-OES (PerkinElmer® - version Optima™ 8300).

Chemical analyses of tailings

Sample collection of the copper mining tailings was taken from a sampling composed of five replications at a depth of 0 to 20 cm, obtained mainly from the copper mining tailings of the Uruguay Mine (Closed at 1998) in the region of Caçapava do Sul -RS, Brazil (Figure 1).

The tailings samples were dried at room temperature, crushed and sieved (3 mm) prior to analysis. The Physico-chemical properties of the material were determined (Table 1). The pH ratio in water is 1:1.5; (w/v) adapted from the methodology in Landon [31]; CEC: Cation Exchange Capacity; P, Na, Cu and Zn (extractable): extracted with 0.1 M HCl; Mg (exchangeable): extracted with 1.0 M KCl; H + Al: titration; sulfur (S): extracted with 500 M of calcium phosphate; organic matter (O.M) by wet digestion; Cd, Ni, Cr, Pb, Mo, Ba [32]; using internal standards for control and verification of procedures (with recovery between 81 and 105% for metals and Limits of Detection (LD) of: Cd - 0.2; Cr and Ni - 0.4; Cu - 0.6; Pb and Zn - 2.0; ug/g.) and, determined by ICP-OES.

Metal accumulation

Once determined the elements in the roots and shoots systems, as well as in the tailings, it was determined the phytoremediation indexes to evaluate the plant's ability to remediate the contaminated area.

Translocation factor (TF) and Bioconcentration factor (BCF) are parameters to study the soil-to-plant transfer accumulation of heavy metals [33]. The parameters evaluate the phytoextraction potential of the plants.

Translocation factor value is represented in according to the following Equation 1. Translocation factor value greater than 1 indicates the translocation of the metal from root to above-ground part (tailings in this case)[34].

$$\mathrm{TF} = \frac{[\mathrm{metal}]\mathrm{shoots}}{[\mathrm{metal}]\ \mathrm{roots}} (1)$$

Where, $[\mathrm{metal}]_{\mathrm{shoots}}$ and $[\mathrm{metal}]_{\mathrm{roots}}$ are the metals concentrations in dry biomass (mg kg^{-1}).

The bioconcentration factor (BCF) that is used to calculate the distribution of heavy metals between sediment (tailings in this case) and plant is defined by Equation 2. According to Yoon *et al*. [8] and Kamari *et al*. [35], only plant species with both BCF and TF greater than 1 have the potential to be used for phytoextraction.

$$\mathrm{BCF} = \frac{[\mathrm{metal}]\ \mathrm{roots}}{[\mathrm{metal}]\ \mathrm{tailings}} (2)$$

Where, $[\mathrm{metal}]_{\mathrm{roots}}$ is the metals concentration in the dry biomass (mg kg^{-1}) and $[\mathrm{metal}]_{\mathrm{tailings}}$ is metals concentration in the tailings (mg kg^{-1}).

The metal extraction ratio (MER) was also determined. This index expresses the capacity of accumulation of metal in the shoots of the plant in relation to that in the tailings [36] (Equation3).

$$\mathrm{MER} = \left(\frac{[\mathrm{Cplant}]\ \mathrm{X}\ [\ \mathrm{Mplant}]}{[\mathrm{Ctailings}]\ \mathrm{X}\ [\mathrm{zone\ Mrooted}]}\right) 100 \qquad (3)$$

Where, [Cplant] is the concentration of the metal in the plant (mg kg^{-1}); [Mplant] is the dry weight biomass; [Ctailings] is the concentration of the metal in the tailings (mg kg^{-1}) and [zone Mrooted] is the tailings volume occupied by the plant (value adopted of 1 kg).

To determine the number of plants required to extract 1.0 g of element or metal of interest, the PENs (plant effective number) were determined, which considers the biomass of the shoots of the plant and the PENt that takes into calculation the total biomass of the plant (shoots and roots)[37]. Both the PENs and PENt were determined considering the concentration of the target element present in the dry biomass of the plants as well as the dry weight biomass. It was used following equation:

$$\mathrm{PENs} = \frac{level_{shoots}\ X\ mass_{shoots}}{1000} \quad (4)$$

$$\mathrm{PENt} = \frac{level_{\ entire\ plant}\ X\ mass_{\ entire\ plant}}{1000} \quad (5)$$

The phytoremediation potential (g ha^{-1}) was estimated considering the total concentration of the target metal in the plant and weight biomass. For this, the dry biomass production of the plant was estimated considering on studies by Santos *et al*. [38] for *B. dracunculifolia* (3.86514 t ha^{-1}) and Amaral *et al*. [16] (10.3 t ha^{-1}) for *B. trimera*, multiplied by the total concentration of each target metal in the plant (total $mgkg^{-1}$).

The experimental design was completely randomized and the software Statistica® version 7.0 was used. It was performed Analysis of Variance (ANOVA), and the Tukey test ($p < 0.05$) was carried out when ANOVA showed significant results.

Results

Nutrients uptake and heavy metal contents in biomass

The behaviour of both species *B. trimera* and *B. dracunculifolia*in relation to the concentration of macronutrients in the roots was similar. The *B. trimera* showed the following sequence of macronutrient concentrations Ca>K>Mg>S>P, whereas in the *B. dracunculifolia* Ca>K>S>Mg>P, being the sulphur concentration (1,956.8 mg kg^{-1}) higher than the concentration of magnesium (1,142.1 mg kg^{-1}) in *B. trimera* (Figure2A).

The concentrations of the elements in *B. trimera* shoots showed the following order, Fe>Na>Al>Mn>Cu>Zn>Ni>Co, whereas in *B. dracunculifolia* the order was Fe>Al>Na>Mn>Cu>Zn>Ni>Co (Figure2B). Even with an inversion between the aluminum and sodium sequences between the species, the other metals followed the same order in both species (Figure2B). In the roots, this elements concentration followed the same order in both species *B. trimera* and *B. dracunculifolia* (Fe>Al>Na>Cu>Mn>Zn>Ni>Co).

The concentration of Cu in shoots of *B. dracunculifolia* was almost half of the concentration shown by the *B. trimera* (Figure2B). The same behaviour was occurred with the concentrations of Cu in the roots, being more than twice in *B. trimera*, when compared to *B. dracunculifolia* (Figure2B).

The concentrations of Ni in the shoots were similar between the species(Figure2B). The *B. trimera* showed higher concentrations of all elements in both shoots and roots, except for Zn and Ni, compared with *B. dracunculifolia* (Figure2B).

Both species presented similar concentrations of heavy metals in roots than in shoots, except for Cd and V (Figure2C).

Phytoremediation index

The translocation factor (TF) in *B. dracunculifolia* was higher than one (TF>1) for Fe, Cd, Cr, Pb and Zn. In *B. trimera,* only Pb obtained value of TF>1 (Table 2).In *B. dracunculifolia*, the bioconcentration factors greater than one (BCF>1) were detected for the metals Zn, Cd, Cr, Ni, Pb and Ba; however, the *B. trimera* showed the BCF>1 for Cu, Zn, Pb and Ba (Table 2).

Both species showed TF>1 for Pb and BCF>1 for Zn, Pb, Ba. The species *B. dracunculifolia* showed BCF>1 and TF>1 for metals Zn, Cd, Cr, Pb and BCF>1 and TF<1 only for Ba (Table 2). However, *B. trimera* showed BCF>1 and TF>1 only for Pb and BCF>1 and TF<1 for the metals Cu, Zn, Ba (Table 2).

Both *B. dracunculifolia* and *B. trimera* exhibited high value MER index for extraction of Zn and Ba metals (Table 2). Although, MER index of Cr and Pb were not so high in both species, they were higher than one (MER>1). Considering the copper element, only the *B. trimera* obtained MER>1 (Table 2).

The *B. trimera* species requires a smaller number of plants to remove 1 g of Cu, Zn, Cr, Pb, Ni, Cd, for both PENs and PENt in relation to *B. dracunculifolia* (Table 2).

Regarding the presented results, *B. trimera* species showed a higher potential in phytoremediation of Cu>Zn>Cr>Ni>Cd than *B. dracunculifolia* (Figure3). While *B. trimera* showed potential to remove 6,039.60 gha^{-1} of Cu, the *B. dracunculifolia* would remove 992.10 g ha^{-1}, even that, it is a good potential of the *B. dracunculifolia*. The specie *B. trimera* would remove more than twice as much Cd and Pb as *B. dracunculifolia* (Figure3).

Discussion

There is an increasing search for species of plants which are able to adapt to areas under extreme conditions such as copper mining tailings in the Camaquã Mines. The impacted physical structure of mining tailings, the low nutrient content and high concentration of heavy metals restricts the conditions for proper development of plant species[14].

In this context the species *B. dracunculifolia* and *B. trimera* are growing spontaneously under the copper mining tailings. Species of the genus *Baccharis*, such as *B. trimera* and *B. dracunculifolia* naturally vegetate environments such as roadsides, steep and high-altitude areas, acidic or mildly acidic soils with elevated contents of Al, Ca,Mg, K and low P content [39]. The species also showed good development and adaptation in altered or disturbed sites [40, 41], as it is the case ofthe cooper tailings area in the Mines of Camaquã region.

B. trimera and *B. dracunculifolia* were in early stages of development over the copper mining tailings area in the present study, since the *B. trimera* height ranges from 0.5-1.6 m [42]. The height of *B. dracunculifolia* usually ranges from 2-4 m [17, 20, 43].

Therefore, depending on the period of development in which species are, the production of dry biomass can variety. The biomass production of *B. trimera*, for example, infertile soils can variety from 3.5 to 10.3 t ha^{-1}. However, under natural conditions, the value ranges from 0.046 to 47.9 t ha^{-1}[16, 44, 45].

Some studies have shown that the production of the biomass of *B. trimera* can achieve 21.89 g plant^{-1}[16]. In *B. trimera* with a mean height of 33.5 cm, the dry biomass in the roots was 0.9 g plant^{-1}, and in the shoots 3.9 g plant^{-1}, whereas *B.*

dracunculifolia with a mean height of20-30 cm, the dry biomass was 1.58 g $plant^{-1}$ for roots and 6.14 g $plant^{-1}$for shoots [16, 46, 47]. Values are much higher than those found in this study.

The increase in the biomass production of both species would enhance their ability to phytoremediation, as a copper mining tailings area in this study. The variation in biomass production is related to the amount of nutrients available in the mining tailing. Thus, fertilization generates an increase in the biomass production of *B. trimera* (carqueja) to a certain extent [39]. In highly fertile soil, *B. trimera* does not respond to mineral or organic nitrogen fertilization, meaning that *B. trimera* develops well with low N, P and K contents [16], as the species in the present study.

Plants in mining areas in Southern Brazil are called "savanna metallophile" and presents mechanisms of tolerance and resistance to heavy metals [48], as the species *B. trimera* and *B. dracunculifolia* in mining tailings area. It is commonly the presence of species of the family Asteraceae in areas that are in the process of environmental regeneration. Melo-Júnior *et al.* [49] in a floristic survey in a degraded region found more than 16 species of the Asteraceae family, among them were the *B. dracunculifolia* and *B. crispa*.

Some species of the genus *Baccharis* are already known as indicative of the initial stages of environmental regeneration (*B. trimera*) and indicative of primary vegetation of the middle and advanced stages of regeneration (*B. dracunculifolia*) according to the Brazilian legislation [23]. This was verified in this study for both species, even after 24 years of passive vegetation, since 1996 that was finished the activities in the mine.

Depending on the ability of plants to adapt under adverse conditions, the species showed different phytoremediation mechanisms, capable of extracting or stabilizing metals, in the soil or in their system [50], as is the case of *B. trimera* and *B. dracunculifolia*, which showed mechanisms of phytoextraction, phytoaccumulation and phytostabilization of metals (Table 2).

Both species seem to face difficulties in translocation of some metals to the shoots, this suggests resistance mechanisms, such as the exclusion of metals [51]. Thus, the transfer of the metal to the plant prevents it from accumulating this metal in its shoots biomass. This can be seen in the analysis of Table 2.

When evaluating native plants in mining areas, Estrada *et al*. [52] found that higher concentrations of Cu, Pb, and Zn in roots biomass in different species studied were higher in the species of impacted areas (mining) than in other areas. This difference was observed by the authors in concentrations of Pb (158 mgkg^{-1}), Cu (689 mg kg^{-1}), and Zn (514 mg kg^{-1}) in *B. dactyloides*, among others. This can also be seen in the species *B. trimera* and *B. dracunculifolia*, which presented high concentrations of metals and their biomass (Figures2and 3).

Other studies have also demonstrated high concentration of metals in the biomass of plant species growing under the area of mining tailings, for example, Menares *et al*. [53] determined low concentrations of Cu, Zn, Mg and Fe in the species *B. linearis* under tailings of copper mining in Chile. In contrast, both *B. dracunculifolia* and *B. trimera* showed very high Cu and Fe concentrations in the biomass compared to results obtained by Menares *et al*. [53].

The metals accumulated in shoots indicate that *B. dracunculifolia* is more efficient in translocation of Zn, Fe, Cd, Cr and Pb than *B. trimera*, which showed high efficiency only for lead. Resistance mechanisms may be involved as low absorption, permeability and or active efflux of the metals by *B. trimera*, which reflects in the low translocation of these metals [54].

The translocation factor for Cu, Pb and Zn were higher than one for all species studied by Estrada *et al*. [52] in soils contaminated with heavy metals, such as *P. incanum*, also a native of Rio Grande do Sul (Brazil), which obtained TF=2 for lead and TF=3 for Cu and Z. *B. sarotroides*growing in copper mining areas showed high translocation values for the metals Cu, Cr, and Mo[55].Translocation factors found by these authors were higher than those found in *B. dracunculifolia* and *B. trimera* for the same metals (Table 2).High concentration of metals in the roots may be due a slow translocation considering the exposure to high concentration of metals in tailings[56]. Nevertheless, the *B. dracunculifolia* has potential for phytostabilization and phytoaccumulation for application in the recovery of areas contaminated with toxic metals [47, 57].

When the metal is transferred from the soil to the biomass of the plant, the plant uses mechanisms such as exudation, that send toxic compounds to isolate sites, such as apoplast, in order to avoid their entry into the symplast [58]. In this way, the plant restricts the absorption and translocation of the metals, demonstrating tolerance to the metal. Therefore, typical symptoms of intoxication were not shown in the *B. dracunculifolia* and *B. trimera*, since both species showed similar tolerance to concentrations which were considered to be toxic by Kabata-Pendias [59] for the metals Cu (20-100 mgkg^{-1}), Cr (5-30 mg kg^{-1}) and Ni (10-100 mg kg^{-1}).

The *B. dracunculifolia* is a species that achieves a high survival in places with low nutrient concentration [22] being indicated for environmental regeneration [60, 61] because it presents a good adaptation in degraded areas [62].This was shown in the study of Boechat *et al.* [13] in which *B. trimera*, in gold mining areas in Southern Brazil obtained metal contents (Cu, Zn, Cd, Ni, Pb, Ba) higher than those found in this study for the same species (Figures 2and 3). Whereas, Silva *et al*. [63] showed low concentration of metals (Cd, Co, Cr, Cu, Pb Zn) in the whole plant of *B. trimera*. Although, *B. trimera* shows variations in terms of metals concentration in its biomass, it showed TF>1 for metals Zn, Cd, Pb and BCF>1 for Cu, Zn, Cd and Ba [13], demonstrating its potential in phytoremediation of metals.

On steel slag, the species *A. thaliana* had low biomass production, low BCF and TF, but MER>1% for Cd (MER=7.7%), Cu (MER=8.1%) and Pb (MER=1.8%) [64]. The rate of extraction of the metal is related to the production of biomass by the plant so that the more biomass promotes higher rate of extraction of the metal [36, 64]. Thus, both *B. trimera* and *B. dracunculifolia* presented lower extraction rates for Cu, Pb, Cd compared to *A. thaliana* but presented very high rates for Zn and Ba.

Analyzing the phytoremediation factors in the *B. trimera* and *B. dracunculifolia*, it can be seen that *B. trimera* showed a potential for phytoextraction (TF>1 and BCF>1) of Zn, Cd, Cr, Pb and phytostabilization (TF<1 and BCF>1) of Ba and Ni, whereas *B. dracunculifolia* showed potential for phytoextraction of Pb and phytostabilization of Cu, Zn and Ba. In phytostabilization, plants immobilize the metals in the rhizosphere while in phytoextraction they translocate the metals to the shoots [50].

In this context, the potential of *B. trimera* and *B. dracunculifolia* in the removal of heavy metals contained in contaminated soils is higher than those found by Andreazza *et al*. [65] in the species *B. pilosa* (Asteracea family). According to the author, this species had characteristics of hyperaccumulating Cu. In Cu contaminated soils, *B. pilosa* would need 83,001 shoots of plants for the copper removal (PENs in inceptisol) and 3,536 whole plants (PENt in mollisol) also for Cu.

The values of PENs for Cu were close to those estimated for *B. dracunculifolia*, but the PENs (Cu) and PENt (Cu) in *B. trimera* are much lower, meaning that a smaller number of plants are required for decontamination (Figure3). Both species (*B.*

trimera and *B. dracunculifolia*) present a phytoremediation potential in areas contaminated with heavy metals.

Conclusions

The results showed that *B. trimera* showed potential for phytoextraction of Zn, Cd, Cr, Pb and phytostabilization of Ba and Ni, whereas *B. dracunculifolia* showed potential for phytoextraction of Pb and phytostabilization of Cu, Zn, and Ba in tailings area. Both species showed a high ratio of Zn and Ba metals extraction.

Considering the copper element, only *B. trimera* obtained MER>1, which it showed the potential to remove Cu. Besides, *B. trimera* requires a smaller number of plants to remove 1 g of Cu, Zn, Cr, Pb, Ni, Cd, comparing to *B. dracunculifolia*.

The values of PENs for copper were close to those estimated for *B. dracunculifolia*, but the PENs (Cu) and PENt (Cu) in *B. trimera* are much lower, meaning that a smaller number of plants are required for decontamination. It is concluded that *B. trimera* showed a higher phytoremediation potential of Cu>Zn>Cr>Ni>Cd metals in relation to *B. dracunculifolia*, although both species exhibited potential to be applied in phytoremediation in tailings area.

The results must be viewed carefully, as they are the initial data of an in-situ experiment. I consider plants to behave differently in other areas. Therefore, this work opens space for new studies involving such plants.

Authors' Contributions TFA and RA conceptualized the study. TFA performed the main experimental work, evaluated the dataset, and wrote the main text of the manuscript. TFA and FAOC performed the analyses. SP, MSQ and CFD were involved in proofreading of the manuscript.

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Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with Ethical Standards

Competing Interests The authors declare that they have no competing interests.

Ethics Approval and Consent to Participate Not applicable. The manuscript does not contain data collected from humans or animals.

Consent for Publication Not applicable. The manuscript does not contain any individual person's data.

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Table 1 Chemical-physical characteristics of copper mining tailings.

Tailigns Texture		Value in Tailings	Ref. Value
Clay	%	13.0	41.0-60.0e*
pH	1:1	6.2	6.0-6.5d
OM	%	0.5	-
CEC	$cmol_c\, dm^3$	6.7	>15.0e
Na	(mg/kg)	9.3	5000.0d
P	(mg/kg)	77.0	800.0d
S	(mg/kg)	1.2	700.0d
Mn	(mg/kg)	11.0	418.0c
Cu	(mg/kg)	259.7	7.0-11.0a
Zn	(mg/kg)	0.9	19.0-20.0a
Cd	(mg/kg)	<0.2	0.3-0.4a
Cr	(mg/kg)	15.3	16.0-21.0a
Ni	(mg/kg)	9.0	4.0-7.0a
Pb	(mg/kg)	<2.0	13.0-16.0a
Ba	(mg/kg)	0.3	≤150b
Mo	(mg/kg)	3.3	≤30b

CEC: Cation-exchange capacity; OM: Organic Matter;*[a][66], [b][67], [c][59], [d][68], [e][69].

Table 2 Phytoremediation indexes by *B. dracunculifolia* and *B. trimera.*

Metals	TF	BCF	MER	PENs	PENt
			B.dracunculifolia		
			----%----	number of plants	
Cu	0.41a*	0.77b	0.40c	8,586b	1,308b
Zn	1.12a	24.01b	21.78c	35,635b	10,666b
Fe	1.03a	nd**	nd	405b	116b
Cd	1.09a	1.14b	0.29c	21,754,045a	2,290,952a
Cr	1.08a	2.20b	1.07c	35,820b	7,512b
Ni	0.92a	1.60b	0.75c	87,946b	18,119b
Pb	1.12a	2.18b	1.31c	139,871b	47,308b
Al	0.81a	nd	nd	806b	162b
Co	0.45a	nd	nd	6,999,739b	578,942b
Ba	0.78a	603.16a	245.27b	6,349b	1,564b
V	0.86a	nd	nd	426,894b	111,162b
			B. trimera		
Metals	TF	BCF	MER	PENs	PENt
			----%----	number of plants	
Cu	0.23a	1.83b	1.86c	3,349b	376b
Zn	0.75a	17.39b	20.97b	24,085b	6,126b
Fe	0.36a	nd	nd	315b	26b
Cd	0.23a	0.99b	0.86c	6,089,032ab	672,261b
Cr	0.91a	0.89b	1.27c	23,484b	6,735b
Ni	0.85a	0.67b	0.93c	56,821b	15,817b
Pb	1.11a	1.83b	2.79c	68,902b	21.,46b
Al	0.39a	nd	nd	463b	39b
Co	0.24a	nd	nd	929,026b	103,338b
Ba	0.98a	278.00ab	380.16a	3,907b	1,051b
V	0.38a	nd	nd	214,260b	20,843b

TF: translocation factor; BCF: bioconcentration factor; MER: metal extraction ratio, PENs:plant effective number of the shoots; PENt: total plant.
*Values are means and, means followed by the same letter within a column are not significantly different at the 95% confidence level (Tukey's test). **nd means not determined.

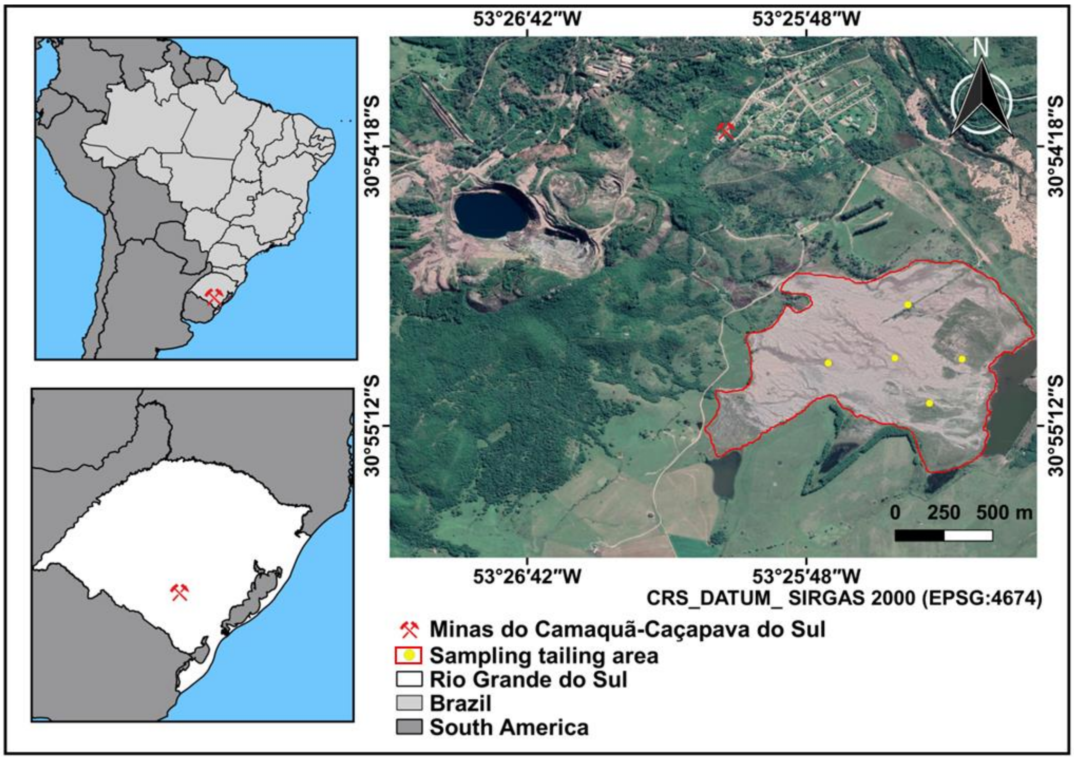

Fig 1 Location map of the copper mining tailings area, Minas do Camaquã, Southern Brazil.

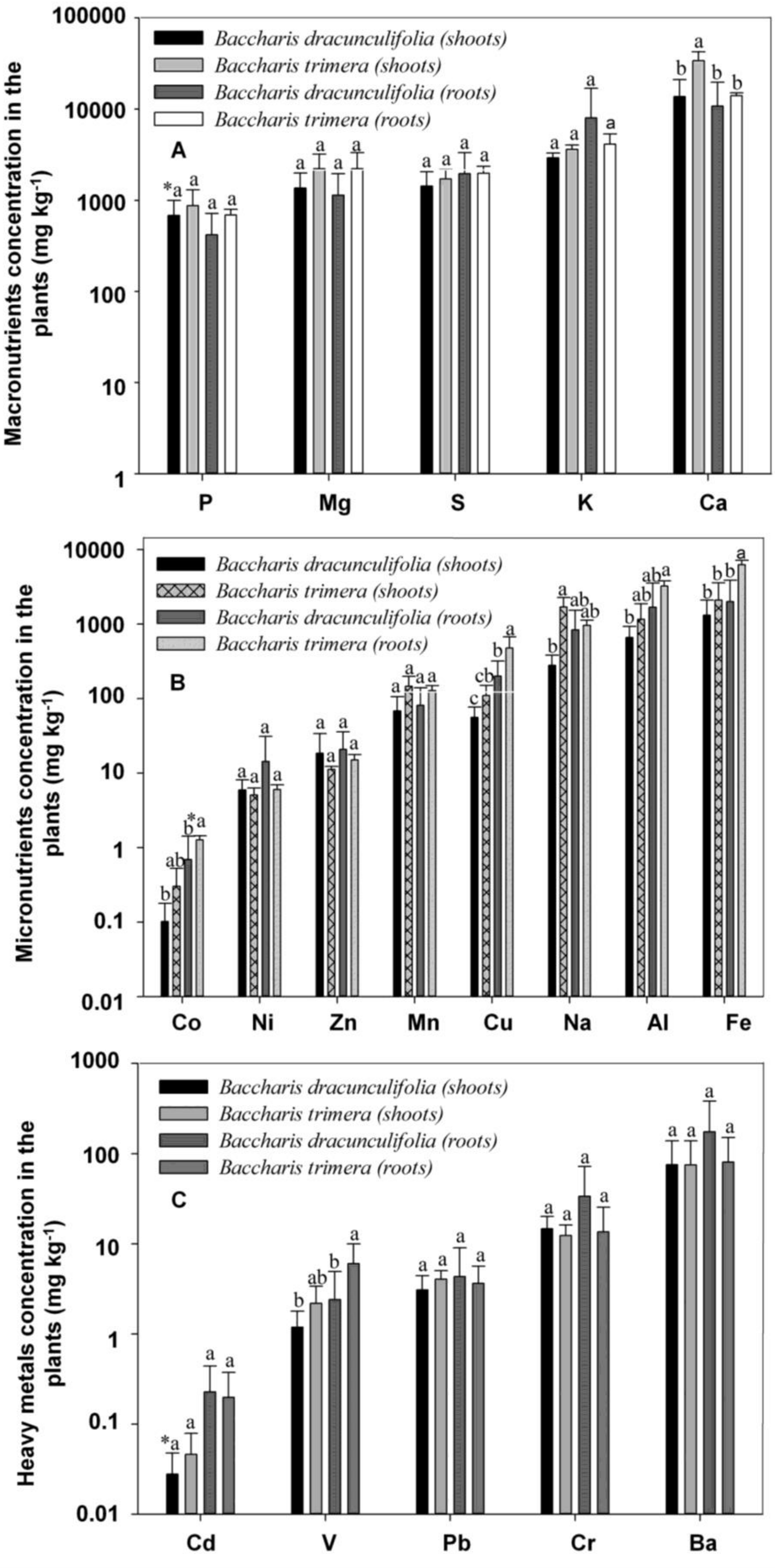

Fig 2 Macronutrients (a), micronutrients (b) and heavy metals (c) concentration in dry biomass of *B. dracunculifolia* and *B. trimera*. *Means followed by the same letter within a column are not significantly different at the 95% confidence level (Tukey's test).

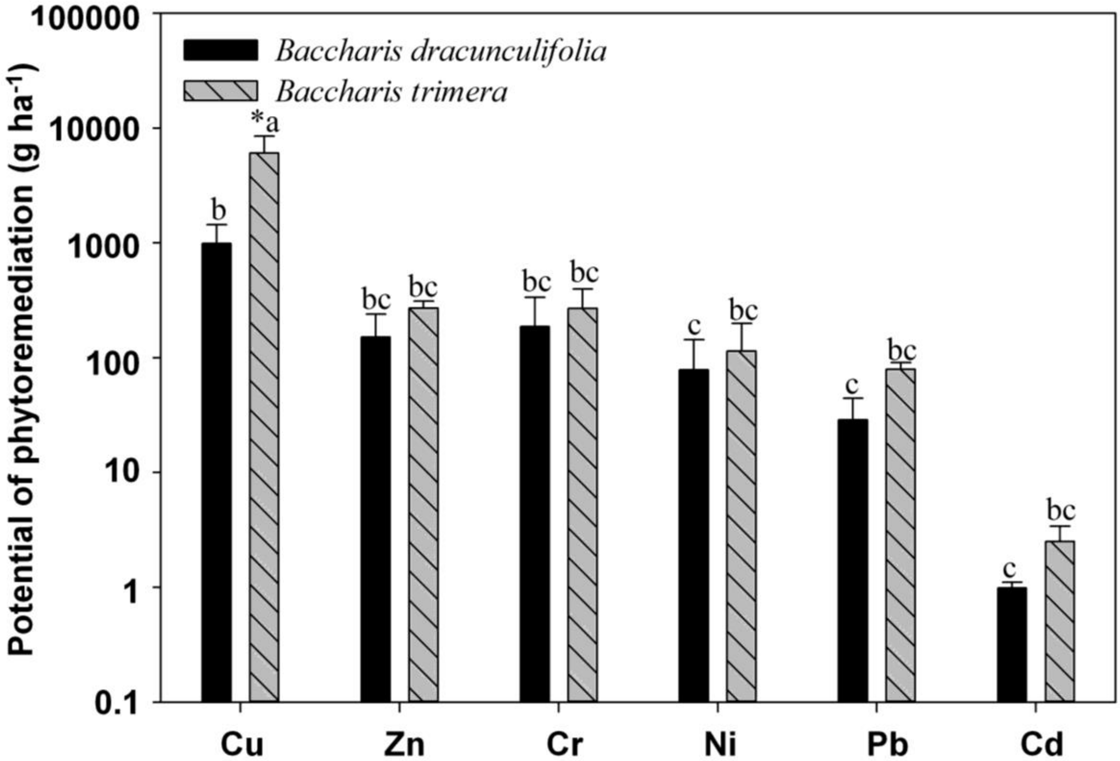

Fig3 Potential of phytoremediation of *B. dracunculifolia* and *B. trimera*. Error bars are calculations of standard error. *Means followed by the same letter within a column are not significantly different at the 95% confidence level (Tukey's test).

Figures

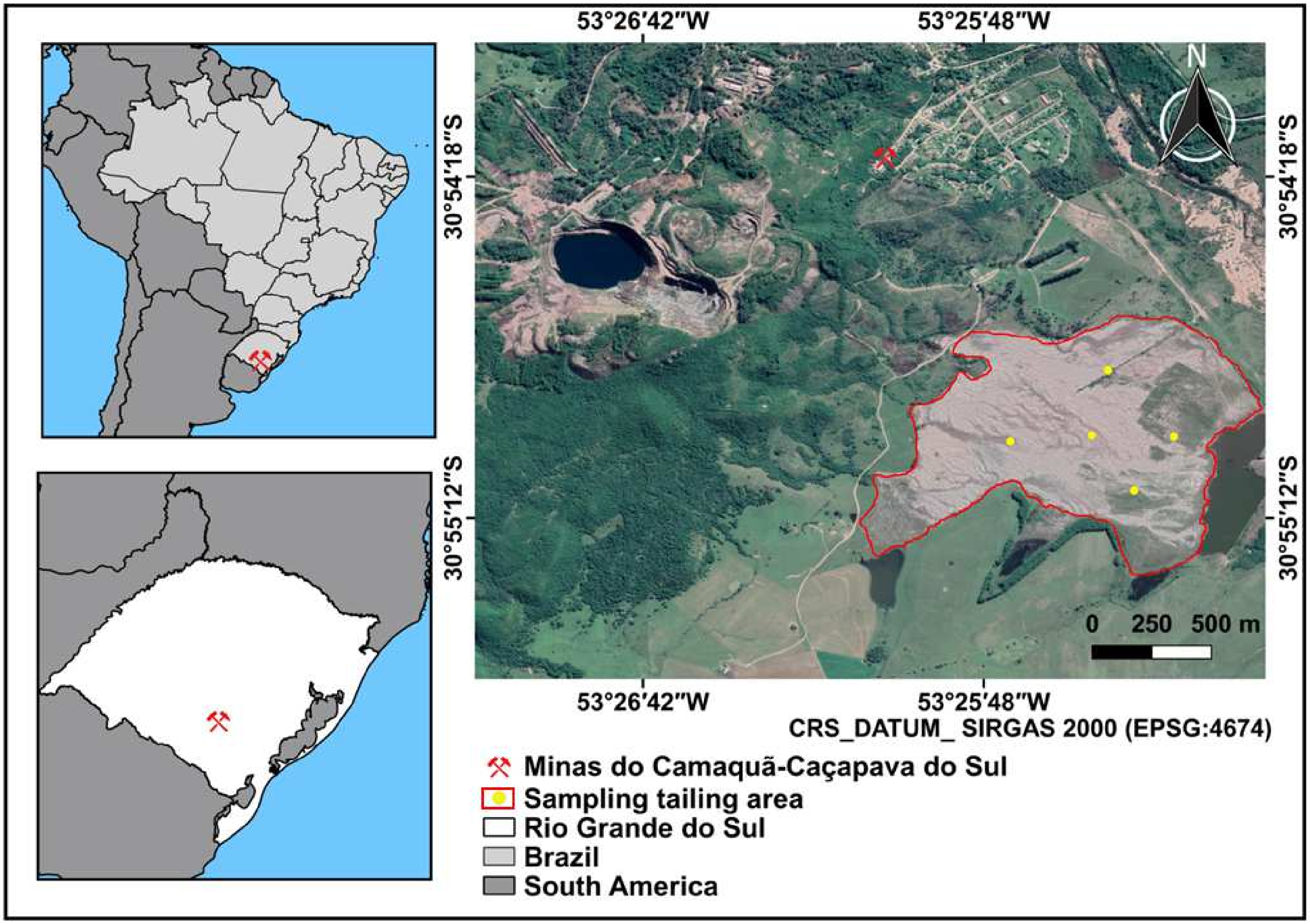

Figure 1

Location map of the copper mining tailings area, Minas do Camaquã, Southern Brazil. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

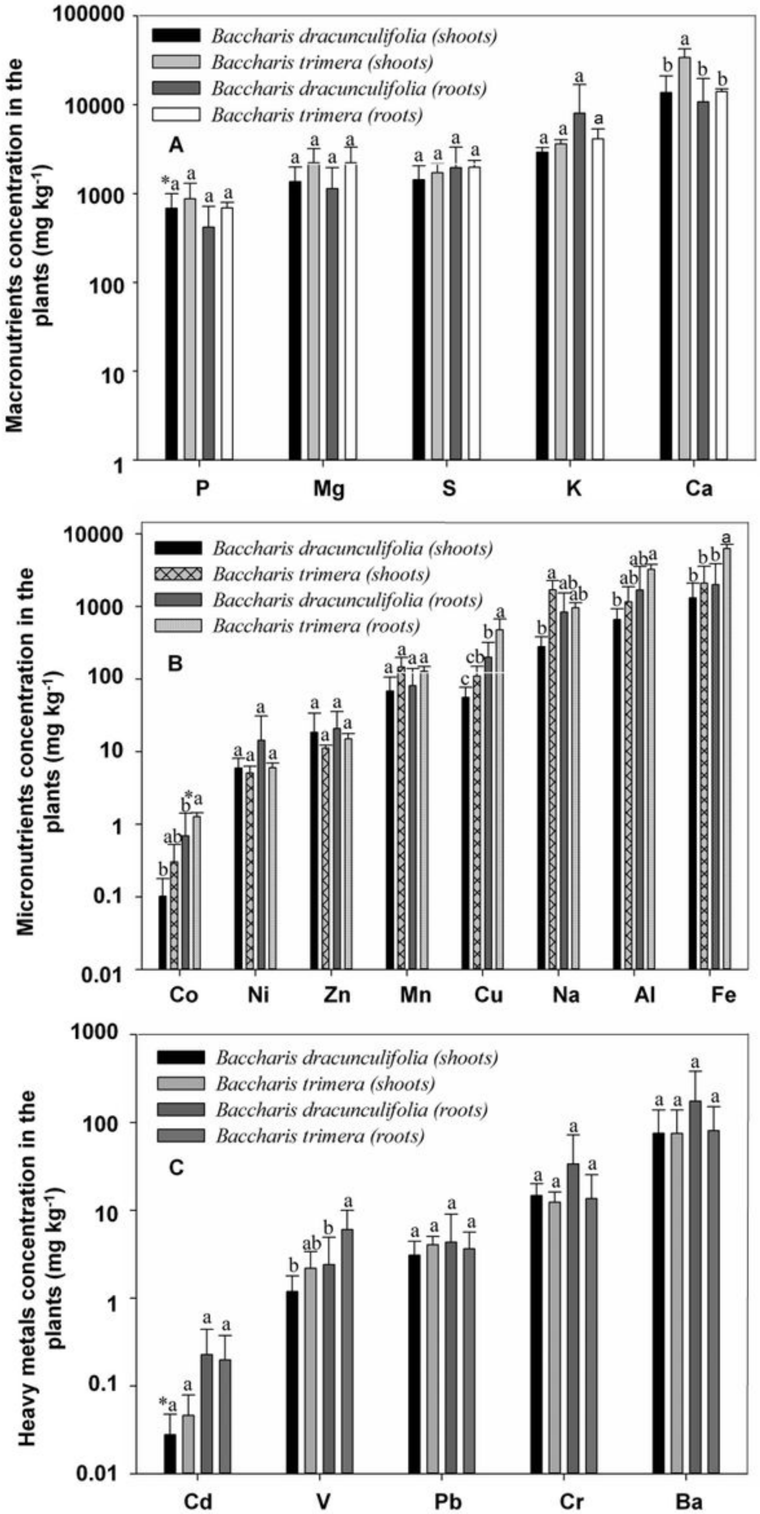

Figure 2

Macronutrients (a), micronutrients (b) and heavy metals (c) concentration in dry biomass of B. dracunculifolia and B. trimera. *Means followed by the same letter within a column are not significantly different at the 95% confidence level (Tukey's test).

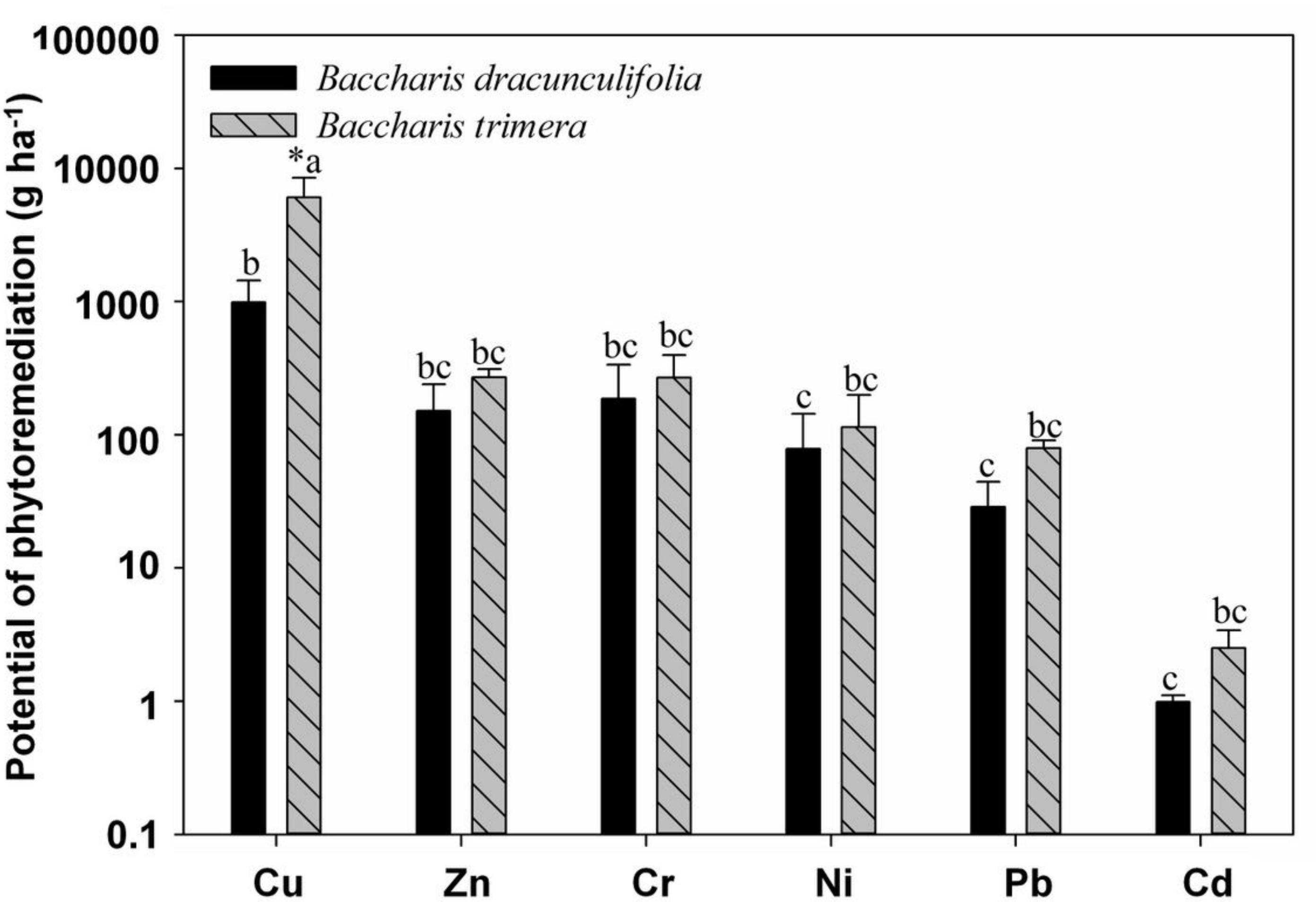

Figure 3

Potential of phytoremediation of B. dracunculifolia and B. trimera. Error bars are calculations of standard error. *Means followed by the same letter within a column are not significantly different at the 95% confidence level (Tukey's test).