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Phytoextractor Potential of Cultivated Species in Industrial Area Contaminated by Lead

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ABSTRACT: High growth rate is one of the criteria used for the selection of species to be used in metal phytoextraction programs. This study was carried out to characterize the growth characteristics of sunflower (*Helianthus annuus* L.), castor bean (*Ricinus communis* L.), corn (*Zea mays* L), and vetiver [*Vetiveria zizanioides* (L.) Nash] grown on a soil contaminated with lead (Pb), with and without pH correction, to improve agronomic practices regarding phytoremediation programs. The experiment was designed as a randomized block with four replications; treatments were arranged in a split-plot arrangement, with the main plot representing the species (sunflower, castor bean, corn, and vetiver), with or without pH correction and soil fertilization, and the split-plot representing harvest periods (60, 90, and 120 days after planting). After variance analysis and mean comparison analysis of the data by the Tukey test ($p \leq 0.05$), a significant effect was observed from soil pH correction for vetiver in all of the growth variables evaluated, except for the leaf area index at 120 days after planting (DAP). Castor bean and sunflower plants in soil with high acidity conditions, without pH correction (pH˂4.0), were affected by soil Pb levels. Corn plants benefited from soil pH correction and had improved results for the plant height, diameter, and leaf area variables at 60 and 90 DAP, as well as leaf area index at 60 DAP. There was no increase in these variables between the harvest periods evaluated. Regarding phytoextraction potential, corn and vetiver had the highest Pb translocation to the plant shoots at 90 DAP and were therefore considered the most suitable species for phytoremediation of the area under study. Overall, liming was essential for improving species biomass production for all the species studied in soils with high Pb availability in solution.

Keywords: phytoremediation, soil pollution, heavy metal, biological indicator.

INTRODUCTION

An increase in contamination of the soil ecosystem by heavy metals, such as lead (Pb), and expansion of this problem to other ecosystems, requires the establishment of technologies for remediation of contaminated environments. An increase in Pb contamination levels, for example, can induce a series of adverse effects on plant growth and metabolism since Pb can be easily taken up and accumulated by plants; its uptake is regulated by pH, particle size, and soil cation exchange capacity (CEC) (Romeiro et al., 2007).

Some studies have shown effects on biomass production (Alves et al., 2008; Araújo and Nascimento, 2010; Meers et al., 2010), photochemical and carboxylation reactions during photosynthesis (Ahmad et al., 2011; Gautam et al., 2011), inhibition of chlorophyll synthesis (Gupta et al., 2009) and of the activity of Calvin Cycle enzymes, and CO_2 deficiency caused by stomatal closure (Sharma and Dubey, 2005).

Restoring the function and structure of a degraded area is a challenge for researchers and technicians in the environmental field, who aim at similarities with characteristics that existed prior to anthropogenic activity. It is believed that using plants with a capacity to tolerate and simultaneously extract and/or degrade certain compounds (phytoremediation) may be an adequate alternative against the pollution in contaminated areas.

For this technology to succeed, plants need to have a high growth rate, high biomass production, tolerance to the metal in question, and ability to take up and accumulate the metal. Therefore, practices such as soil pH correction in acidic environments are fundamental for establishing plants used in phytoremediation (Clement Carrillo et al., 2005; Pedron et al., 2009; González-Alcaraz et al., 2011; Joris et al., 2012; Aragão et al., 2013).

Growth rate is fundamental in measuring biological productivity and in evaluating the form and function of plants subjected to environmental stresses (Hunt et al., 2002). Based on these parameters, several physiological indicators can be calculated, such as Leaf Area Ratio (LAR), Leaf Area Index (LAI), Relative Growth Rate (RGR), and Net Assimilatory Rate (NAR), which are used to understand the behavioral differences of plant communities growing in stressed environments (Baret et al., 2007).

Among the methods used to evaluate the extraction potential of plant species, parameters such as phytoextraction coefficient and translocation factor are used, which indicate how much Pb accumulated by the plant was translocated to the shoots (Liu et al., 2008; Alves et al., 2008; Araújo and Nascimento, 2010). However, there have been few studies developed under field conditions, making it difficult to extrapolate study results to the real conditions of contaminated areas. Thus, field experiments are essential to evaluate the feasibility of the phytoextraction technique.

High metal concentration in plant dry matter does not necessarily mean that such plants are effective at extracting metal from the soil since metal extraction is directly related to the amount of dry matter produced by the plant (Zeitouni et al., 2007). Furthermore, differences between species in regard to biomass production can be attributed to different ecophysiological aspects of plants, leading to a differentiated response to Pb exposure (Fellet et al., 2007; Fässler et al., 2010).

The hypothesis of this study is that soil with high levels of contamination by Pb may exhibit increased metal phytoextraction through soil acidity correction. To fill the gap regarding adequate agronomic practices for plant species in phytoextraction programs and the lack of field experiment data, especially under tropical conditions, the aim of the current study was to characterize the growth and extraction potential of vetiver, corn, sunflower, and castor bean cultivated in soil contaminated by Pb, with and without pH correction, in order to obtain information for management of these species in phytoremediation programs.

MATERIALS AND METHODS

The experiment was conducted in an area belonging to the company METAIS PB – LTDA, which has been operating since 1996 in the field of automotive battery recycling. The company is located on BR 101 (highway) km 28 in Rio Tinto, PB, Brazil, with geographical coordinates of 06° 43’ 51.2” S latitude and 35° 07’ 17.1” longitude. It has an altitude of approximately 11 m, with annual average rainfall of around 1,200 mm (AESA, 2010).

Soil from the experimental area was classified as Spodosol according to the World Reference Base for Soil Resources (IUSS, 2007) or *Espodossolo Cárbico hidromórfico* in the Brazilian Soil Classification System (Santos et al., 2013), which was exposed to high Pb concentrations from deposition of by-products arising from the automotive battery recycling process (scrap and waste water). Chemical characterization detected a pH of 3.63 and 1,810.80 mg dm^{-3} of Pb from samples collected in the 0.00-0.20 m depth layer in a 500 m^2 (25 × 20 m) area.

Plants of vetiver [*Vetiveria zizanioides* (L.) Nash], corn (*Zea mays* L.) cv. AG 1051, sunflower (*Helianthus annuus* L.) cv. BRS 122/V-2000, and castor bean (*Ricinus communis* L.) cv. BRS from the Northeast of Brazil were used, which were selected based on a previous study (Boonyapookana et al., 2005; Alves et al., 2008, Araújo and Nascimento, 2010; Meers et al., 2010). In addition, these plants were adapted to stress environments.

Sunflower and castor bean seedlings were produced in polyethylene bags from seeds using a mixture of sand and organic compound as a substrate in a 1:1 ratio; the seedlings were standardized as a function of the first pair of definitive leaves. In contrast, vetiver seedlings were produced by tillering of clumps, standardized as a function of their mass (±5 g), which were then transplanted in the experimental plot area. Corn seeds were sown directly in the field.

Seedlings were transplanted to 15 m^2 (5 × 3 m) experimental plots, adopting a spacing of 0.5 × 0.3 m (100 plants/plot) for sunflower and vetiver, 0.5 × 0.2 m (150 plants/plot) for corn, and 0.5 × 1.0 m (30 plants/plot) for castor bean. Fertilization and crop treatments were performed when necessary, as well as irrigation in periods of increased water requirements.

Growth analysis was composed of three evaluation times (60, 90, and 120 days after transplanting - DAP), at which time two plants were collected per experimental plot. Plant samples were randomly selected within each plot. The following variables were evaluated for each evaluation time: plant height (H), root collar diameter (Diam), number of leaves (NL), leaf area (LA), using the digital leaf area meter (ADC BioScientific, model AM 300), leaf area index (LAI), total dry matter (TDM), and leaf area ratio (LAR). After that, roots, leaves, stems, and grains were separated into parts (root and shoot parts), stored in paper bags, and dried in a laboratory oven with forced air circulation regulated at a temperature of 65 °C. The total dry matter at each harvest time was determined as a function of the dry matter of the parts, with results expressed in g per plant.

Based on the total dry matter and leaf area, the leaf area ratio (LAR) was quantified for each evaluation time, representing the ratio between LA and TDM (dm^2 g^{-1}) of the plant, in which LAR = LA/TDM, and the leaf area index (LAI) represents the total leaf area per unit area of the lot, in which LAI = LA/AP, where AP is the area occupied by the plants (cm^2). For each interval between two evaluation times, the relative growth rates (RGR) were obtained, using the following equation for average values: $RGR = LnTDM_n - LnTDM_{n-1}/T_n - T_{n-1}$, in which Ln is the neperian logarithm and T is the time. The net assimilatory rate (NAR) was obtained, which represents the rate of increase for dry matter weight per unit of LA in the plant, per unit of time ($g\ dm^{-2}\ d^{-1}$), through the following equation: $NAR = (TDM_n - TDM_{n-1}) \times (LnLA_n - L_nLA_{n-1}) / (LA_n - LA_{n-1}) \times (T_n - T_{n-1})$.

Samples of plant material were digested in nitric-perchloric acid to determine Pb contents through Atomic Absorption Spectrophotometry (Tedesco et al., 1995). Phytoextraction coefficients and the translocation factor were calculated based on element concentrations through the following formulas (Alves et al., 2008): PC = Pb content ($mg\ kg^{-1}$) in the plant shoots/initial Pb content ($mg\ kg^{-1}$) in the soil, in which PC is the phytoextraction coefficient, and TI = (AAs/AAt) × 100, in which: TI is the translocation index; AAs is the amount accumulated in the shoots, in mg per plant; and AAt is the total amount accumulated in the plant, in mg per plant.

The experimental design adopted was randomized blocks, with four replications. Treatments were in a split-plot arrangement, in which the main plot was represented by the species studied (sunflower, castor bean, corn, and vetiver), with and without pH correction and soil fertilization, and harvest time was represented in the split-plots (60, 90, and 120 days after planting).

Results were subjected to variance analyses and comparison of averages through the Tukey test at $p \leq 0.05$.

RESULTS AND DISCUSSION

There was a significant effect from pH correction of the soil for the crops in the growth variables analyzed (Table 1). This shows that soil with excessive acidity (pH 3.63) influenced plant growth and development, mainly due to higher Pb solubility, as well as Mn and Al in the soil solution (Boonyapookana et al., 2005; González-Alcaraz et al., 2011), leading to phytotoxicity problems and lack of nutrient availability to plants. Lead inhibits of water reception via aquaporins and ion transport in the plant plasmatic membrane, causing reduced growth (Yang et al., 2004; Sharma and Dubey, 2005). It also inhibits photosynthesis, which is considered by Singh et al. (1997) as one of the metabolic processes most sensitive to Pb toxicity.

Under soil acidity correction, there was an increase in root collar diameter, number of leaves, leaf area, leaf area ratio, and leaf area index throughout the growth period of vetiver in contaminated soil (120 DAP); this was not observed in the other species analyzed (Table 1).

Leaf area ratio, which is the leaf area used for photosynthesis, and the leaf area index, an estimation of crop yield capacity, increased up to 90 DAP, indicating higher tolerance of vetiver in environments stressed by Pb compared to the other species analyzed. According to Ludwig et al. (2010), these results indicate that the species maintained conversion of photoassimilates for leaf expansion and light capture for a longer time. This is also shown by growth of new leaves from the vetiver species at 90 DAP in opposition to senescence and abscission processes.

Soil correction for corn benefited crop growth in terms of height (H), diameter (Diam), and leaf area (LA) in the 60 and 90 DAP periods, and benefitted leaf area index (LAI) only at 60 DAP. However, an increase in these variables was not verified between the growth periods evaluated.

Castor bean and sunflower were significantly affected by Pb concentration, not benefiting from soil correction (Table 1). Sunflower proved to be more sensitive concentration of the metal in the soil, which indicates its low tolerance. The stress caused by Pb possibly

Table 1. Plant height (H), root collar diameter (Diam), number of leaves (NL), leaf area (LA), leaf area ratio (LAR), and leaf area index (LAI) of vetiver, corn, castor bean, and sunflower species, obtained in different evaluation periods, without (-W/C) and witht (+W/C) correction of soil pH (mean of four replications)

Period	H		Diam		NL		LA		LAR		LAI	
	-W/C	+W/C	-W/C	+W/C	-W/C	+W/C	-W/C	+W/C	-W/C	+W/C	-W/C	+W/C
day	cm						cm^2		$cm^2\ g^{-1}$			
						Vetiver						
60	31.3 Ba	78.5 Aa	0.2 Ba	6.8 Aa	12 Ba	38 Ab	1351.8 Ba	31526.2 Ab	192.0 Ba	1660.1 Aa	8223.6 Ba	197038.9 Ab
90	43.0 Ba	98.3 Aa	0.3 Ba	9.1 Aab	8 Ba	71 Aa	1116.9 Ba	82825.0 Aa	146.4 Ba	2114.1 Aab	6890.7 Ba	517656.4 Aa
120	31.5 Ba	86.5 Aa	0.3 Ba	5.7 Ab	5 Ba	78 Aa	2287.4 Ba	70361.7 Aa	487.2 Aa	982.0 Ab	14296.2 Ba	439760.5 Aa
						Corn						
60	60.3 Ba	89.5 Aa	0.6 Ba	12.3 Aa	6 Aa	11 Aa	1479.3 Ba	13917.9 Aa	472.9 Aa	466.2 Aa	9245.4 Ba	86987.3 Aa
90	19.3 Bb	70.0 Aa	0.4 Ba	10.5 Aa	5 Aa	10 Aa	523.8 Aa	4641.8 Aa	117.8 Aa	205.5 Aa	3273.8 Aa	29011.25 Aa
120	-	-	-	-	-	-	-	-	-	-	-	-
						Castor bean						
60	29.0 Aa	27.9 Aa	0.51 Ba	8.5 Aa	4 Aa	6 Aa	269.4 Aa	8952.8 Aa	151.1 Aa	542.2 Aa	538.9 Aa	17905.6 Aa
90	25.3 Aa	30.5 Aa	0.6 Aa	1.0 Aa	2 Aa	8 Aa	95.1 Ba	12470.7 Aa	52.0 Aa	536.8 Aa	190.1 Aa	24941.4 Aa
120	28.6 Aa	30.4 Aa	0.5 Aa	1.1 Aa	3 Aa	6 Aa	91.4 Aa	1924.8 Aa	35.7 Aa	125.4 Aa	182.7 Aa	3849.7 Aa
						Sunflower						
60	42.8 a	64.1 Aa	0.6 B	5.8 Aa	17 a	16 Aa	4339.1 A	3033.3 Aa	528.6 A	277.6 Aa	27119.1 A	18958.2 Aa
90	-	55.8 a	-	0.6 a	-	16 a	-	613.1 a	-	77.9 a	-	3832.2 a
120	-	-	-	-	-	-	-	-	-	-	-	-

Means followed by the same letter, uppercase letters for lines and lowercase letters for columns, within characteristics evaluated for each species, do not differ among themselves by the Tukey test ($p<0.05$).

influenced the leaf growth process and/or leaf senescence since the leaves are responsible for production of most carbohydrates essential for plant growth and development, and are responsible for 90 % of the dry matter accumulated in the plants, resulting from photosynthetic activity (Hermann and Câmara, 1999).

Relative growth rate (RGR) is a valuable tool for understanding plant adaptation under stress conditions since it is an efficiency indicator (Ludwig et al., 2010). No significant effect of soil acidity correction on relative growth rate was found in any of the species analyzed, except in the 90 DAP period for castor bean (Figure 1). Therefore, there was higher efficiency of castor bean in dry biomass production in this period when conducted under correction of soil pH and negative RGR values when acidity correction was not performed. Such negative values, also observed in the other species, may represent consumption of plant reserves to meet a higher demand of energy for plant maintenance (Gomide et al., 2003).

The net assimilatory rate (NAR) reflects the balance between photosynthesis and respiration; it is more influenced by environmental conditions than by plant genetic potential. Regarding this aspect, it can be observed for all the species that soil pH correction did not positively influence the phytoassimilate balance (Figure 2), and negative NAR values indicated reduction in photosynthetic efficiency and an increase in C respiratory losses, as well as higher leaf senescence (Table 1) (Ferrari et al., 2008).

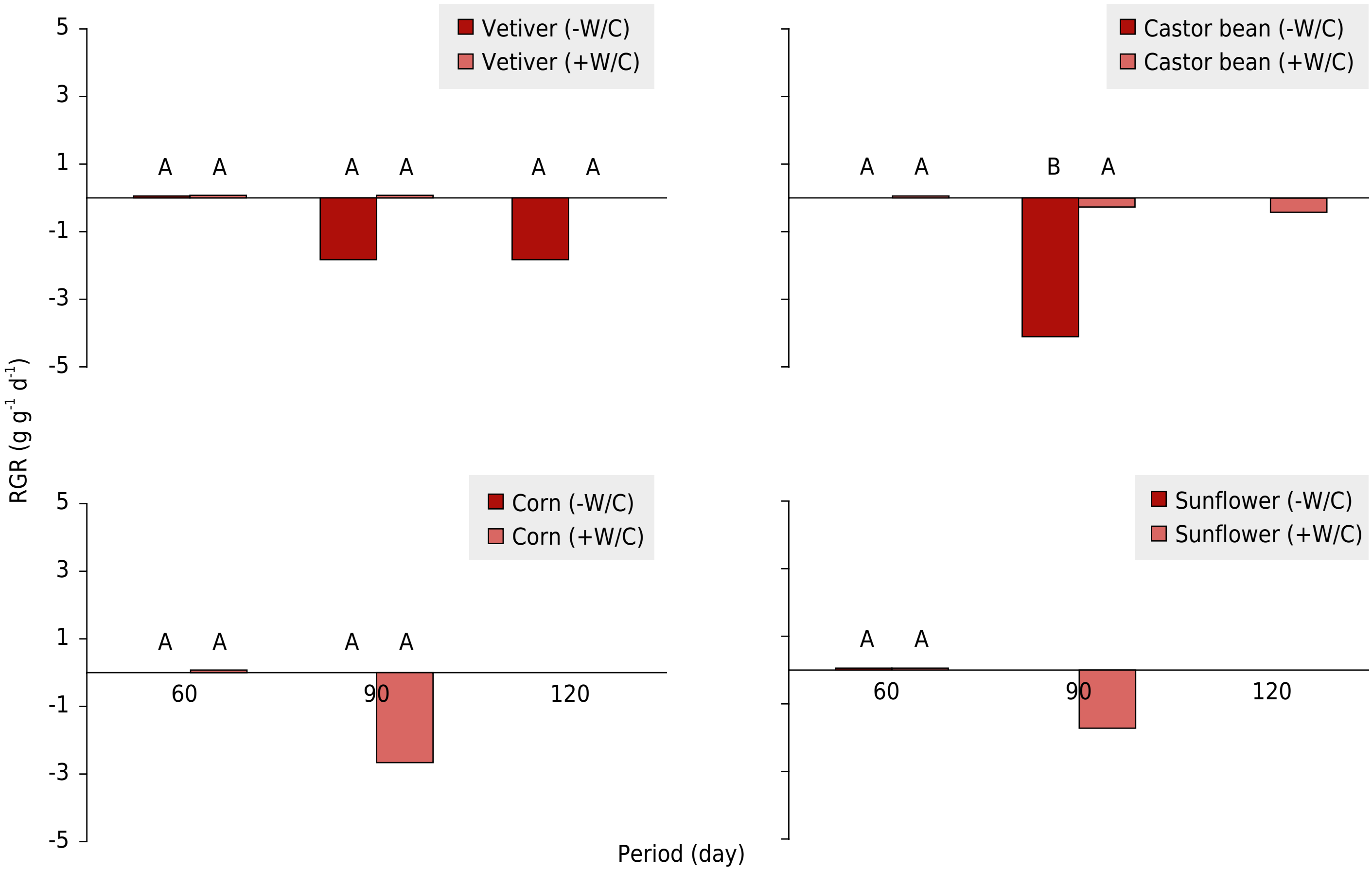

Figure 1. Relative growth rate (RGR) in vetiver, castor bean, corn, and sunflower plants conducted in soil contaminated with lead, without (-W/C) and with (+W/C) correction of soil pH, at 60, 90, and 120 days after planting (DAP). Means followed by the same letter, within each period, do not differ among themselves.

Dry matter production of the roots and shoots was also influenced by soil pH correction (Figure 3) for vetiver, castor bean, corn, and sunflower species in all the periods analyzed. Very acidic and contaminated soils, such as those from the area studied, make it harder to establish plants due to the high concentration of Mn and Al in the soil solution (Pedron et al., 2009; González-Alcaraz et al., 2011), low nutrient availability, and an increase in heavy metal solubility. In extreme cases, Pb phytotoxicity may even result in plant death (Boonyapookana et al., 2005), as observed for sunflower at 90 DAP without soil acidity correction (Figure 3).

Soil pH correction allowed the highest values of dry matter production from the corn and vetiver shoots, while the highest dry matter production of the roots was observed for vetiver. In this regard, comparing the values of total dry matter production (Figure 3) obtained in this study with those obtained by Meers et al. (2010) for corn (12 Mg ha^{-1}) and Zhuang et al. (2007) for vetiver (30 Mg ha^{-1}), it can be observed that the production was much lower in terms of total dry matter. The higher values of dry matter production may be related to smaller concentrations of exchangeable Pb in the soil used by those authors, which were approximately 200 mg kg^{-1}.

Differences in values of biomass production among the species studied can be attributed to differentiated responses shown by different species regarding response to Pb exposure (Alves et al., 2008; Fässler et al., 2010), expressed by their growth. Fellet et al. (2007) attributed this behavior to different ecophysiological aspects of the plants, which can occur even between their tissues (Alves et al., 2008).

Regarding Pb contents in plants, no significant effect from soil pH correction on Pb uptake was observed for vetiver and corn species (Figure 4). There was a decrease in

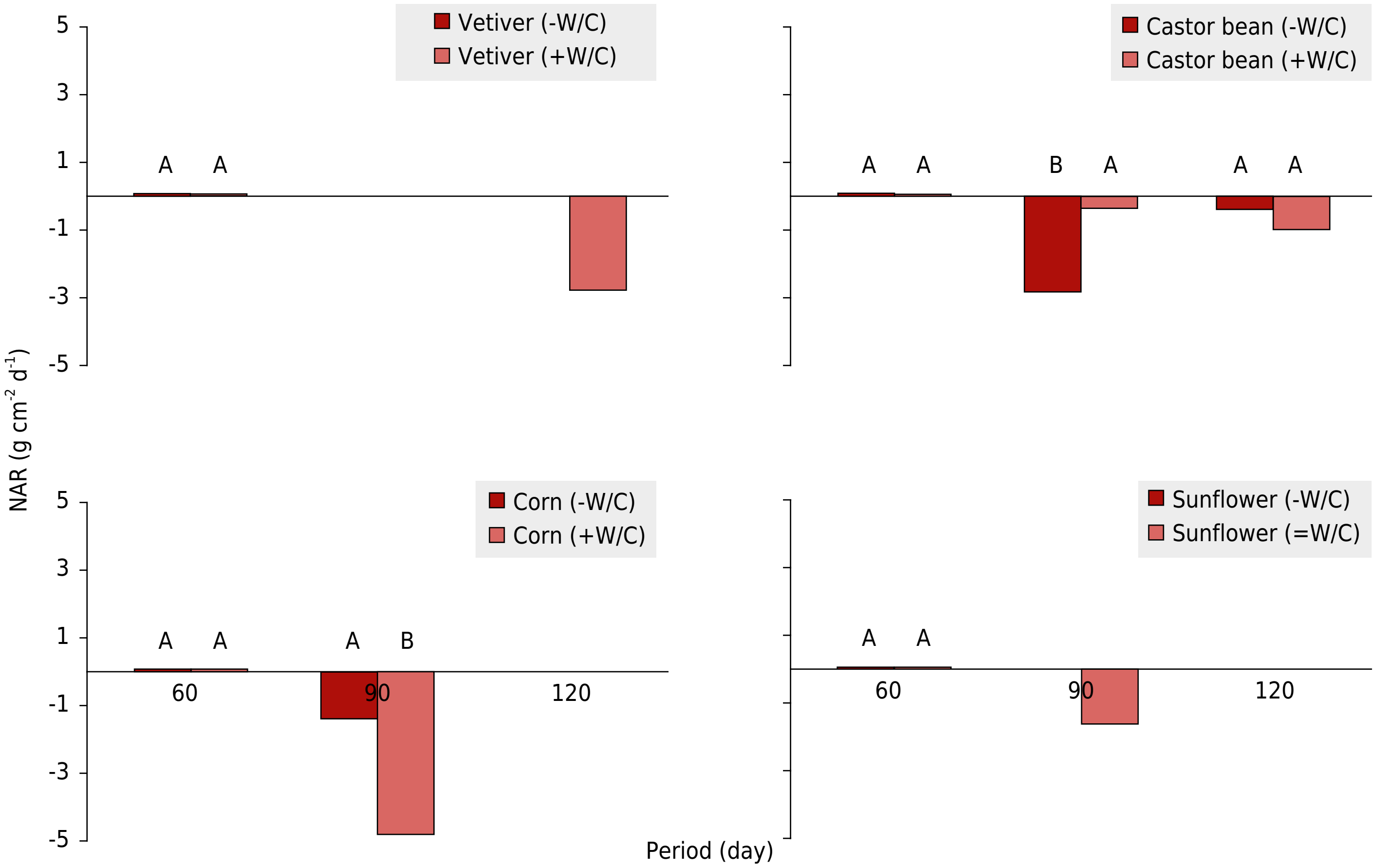

Figure 2. Net assimilatory rate (NAR) in vetiver, castor bean, corn, and sunflower plants conducted in soil contaminated with lead, without (-W/C) and with (+W/C) correction of soil pH, at 60, 90, and 120 days after planting (DAP). Means followed by the same letter, within each period, do not differ among themselves.

Pb uptake at 120 DAP for castor bean when cultivated under liming, and at 60 DAP for sunflower, in agreement with Evanko and Dzombak (1997) and González-Alcaraz et al. (2011), who reported that Pb uptake is passive, and decreases with liming and low temperatures due to the formation of precipitates with hydroxides and carbonates. Strong Pb adsorption to the soil or low solubility of its compounds results in low availability of this element to plants, limiting its uptake (Henry, 2000), making this metal one of the most difficult for application of phytoremediation techniques. However, the contents found in all the species analyzed, in the roots as well as in the shoots (Figure 4), were much higher than the toxic range (30 to 300 mg kg^{-1}) suggested by Kabata-Pendias and Pendias (2001).

For accumulated Pb (Table 2) within each period evaluated, significant differences were not observed among the species or from soil pH correction at 60 DAP; only at 90 DAP, where correction increased accumulation of Pb by the corn shoots and corn roots by about 29.7 times and 8.7 times, respectively. In this period, corn with soil pH correction accumulated 1,273.79 g ha^{-1} of Pb in the shoots and 1,543.22 g ha^{-1} total, which was significantly higher than the other species studied. These results disagree with those presented by Meers et al. (2010), who reported low Pb accumulation (28 to 46 g ha^{-1}). The soil used by Meers et al. (2010) had a Pb concentration of approximately 189 mg kg^{-1}, which probably led to a low Pb concentration in the plant, since high biomass production was verified.

Only vetiver and castor species continued accumulating Pb at 120 DAP. Vetiver with soil pH correction accumulated 130.13 and 1,235.55 g ha^{-1} of Pb by the shoots and in total, respectively, which was much greater than castor bean (Table 2). In this aspect, comparing vetiver to corn, the characteristics of vetiver, such as an

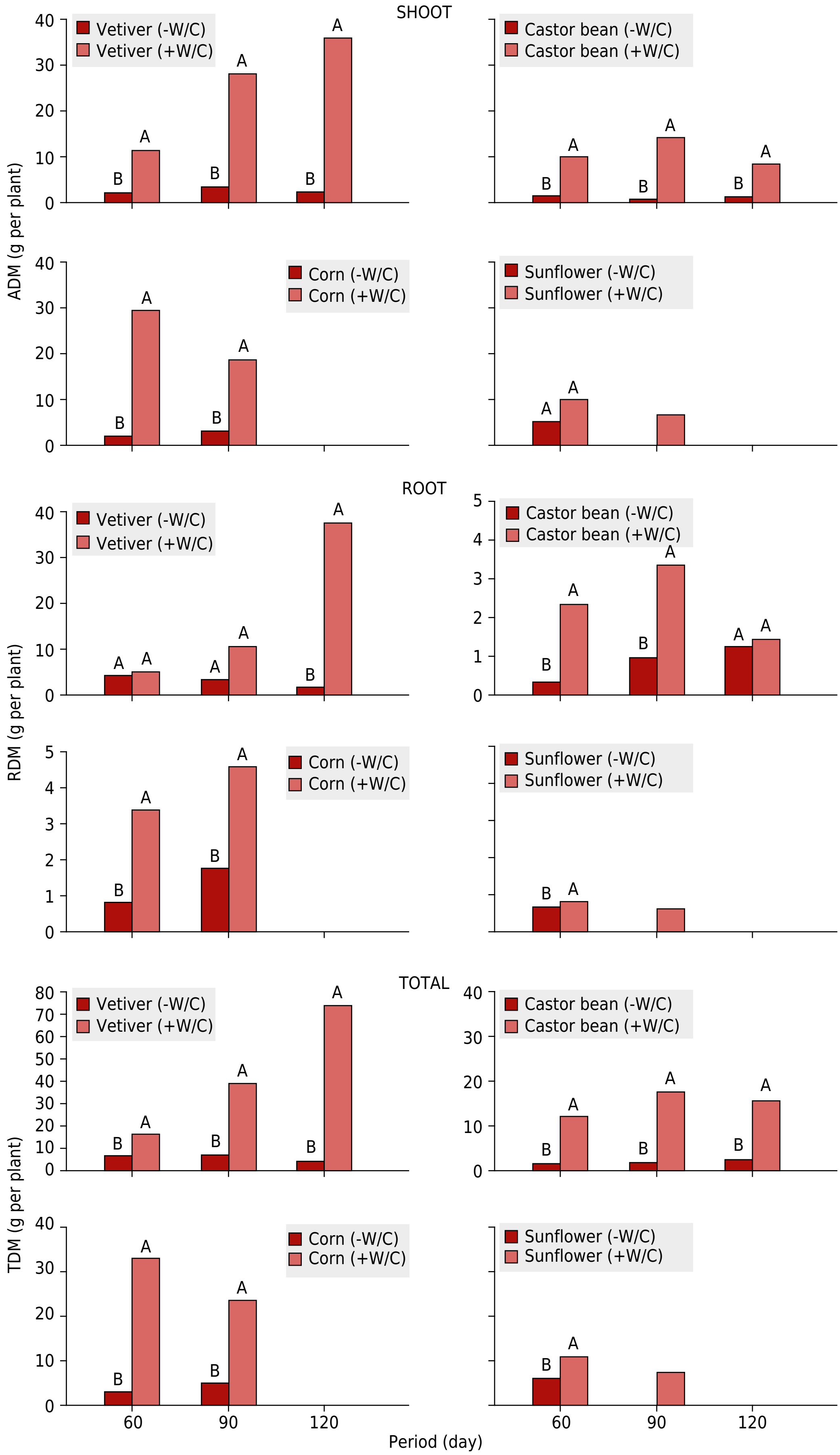

Figure 3. Dry matter contents from the shoots (ADM), roots (RDM), and total (TDM), in vetiver, castor bean, corn, and sunflower plants conducted in contaminated soil, without (-W/C) and with (+W/C)) correction of soil pH, at 60, 90, and 120 days after planting (DAP). Means followed by the same letter, within each period, do not differ among themselves.

Table 2. Lead accumulation by the shoots, roots, and total (roots + shoots) for vetiver, corn, castor bean, and sunflower species obtained in different evaluation periods, without (-W/C) and with (+W/C) correction of soil pH (mean of four replications)

Specie	Shoot		Root		Total	
	-W/C	+W/C	-W/C	+W/C	-W/C	+W/C
	g ha^{-1}					
	60 days after planting					
Vetiver	18.53 aA	85.41 aA	23.35 aA	104.28 aA	41.28 aA	189.69 aA
Corn	10.75 aA	404.16 aA	12.59 aA	63.34 aA	23.34 aA	467.70 aA
Castor bean	4.36 aA	11.72 aA	2.36 aA	4.36 aA	6.71 aA	16.11 aA
Sunflower	14.17 aA	16.59 aA	4.74 aA	9.99 aA	18.91 aA	26.58 aA
	90 days after planting					
Vetiver	25.89 aA	200.14 aB	29.34 bA	224.68 aA	55.22 aA	424.82 aB
Corn	42.96 bA	1273.79 aA	32.79 bA	269.41 aA	75.75 bA	1543.22 aA
Castor bean	0.70 aA	18.38 aB	0.62 aA	20.26 aB	1.33 aA	38.63 aB
Sunflower	-	6.48 B	-	1.28B	-	7.76B
	120 days after planting					
Vetiver	23.48 aA	130.13 aA	24.67 bA	1105.41 aA	48.14 aA	1235.55 bA
Corn	-	-	-	-	-	-
Castor bean	5.32 aA	12.46 aB	91.30 aA	15.40 aB	96.62 aA	27.86 aB
Sunflower	-	-	-	-	-	-

- : dead plants. In each period, means followed by the same letter, capital letters for columns and lower case letters for lines, within characteristics evaluated for each specie, do not differ among themselves by the F test ($p<0.05$) and Tukey test ($p<0.05$).

ample and deep root system, its perennial character, fast growth, and especially its regrowth capacity and tolerance to high contents of heavy metals (Chen et al., 2000; Yang et al., 2004; Chantachon et al., 2004; Chen et al., 2004; Xu et al., 2009), make it the most efficient plant considering the number of cultivars necessary to remediate a contaminated area.

In sunflower, the absence of pH correction for contaminated soil led to the death of plants at 90 and 120 DAP, probably due to higher sensitivity to Pb exposure, together with low availability of nutrients in the soil and low pH. Similar results were found by Boonyapookana et al. (2005).

Relating these results to growth data, it can be inferred that high Pb contents in the shoots of the castor bean and sunflower species (Figure 4) caused inhibition in their development; this was also shown by negative values of RGR and NAR (Figures 1 and 2), which represent consumption of reserves to meet a higher energy demand for plant maintenance created by stress (Ferrari et al., 2008). This shows that under field conditions, such as those in this study, these species do not have the same tolerance potential as observed in a greenhouse, reported in the literature (Romeiro et al., 2006; Pereira et al., 2006; Schmidt et al., 2007; Liu et al., 2008).

An additional observation was that high Pb contents in the shoots of the castor bean and sunflower species led to toxicity symptoms, such as chlorosis and subsequent necrosis of older leaves, as well as loss of the organ in some cases. This was not observed for vetiver and corn.

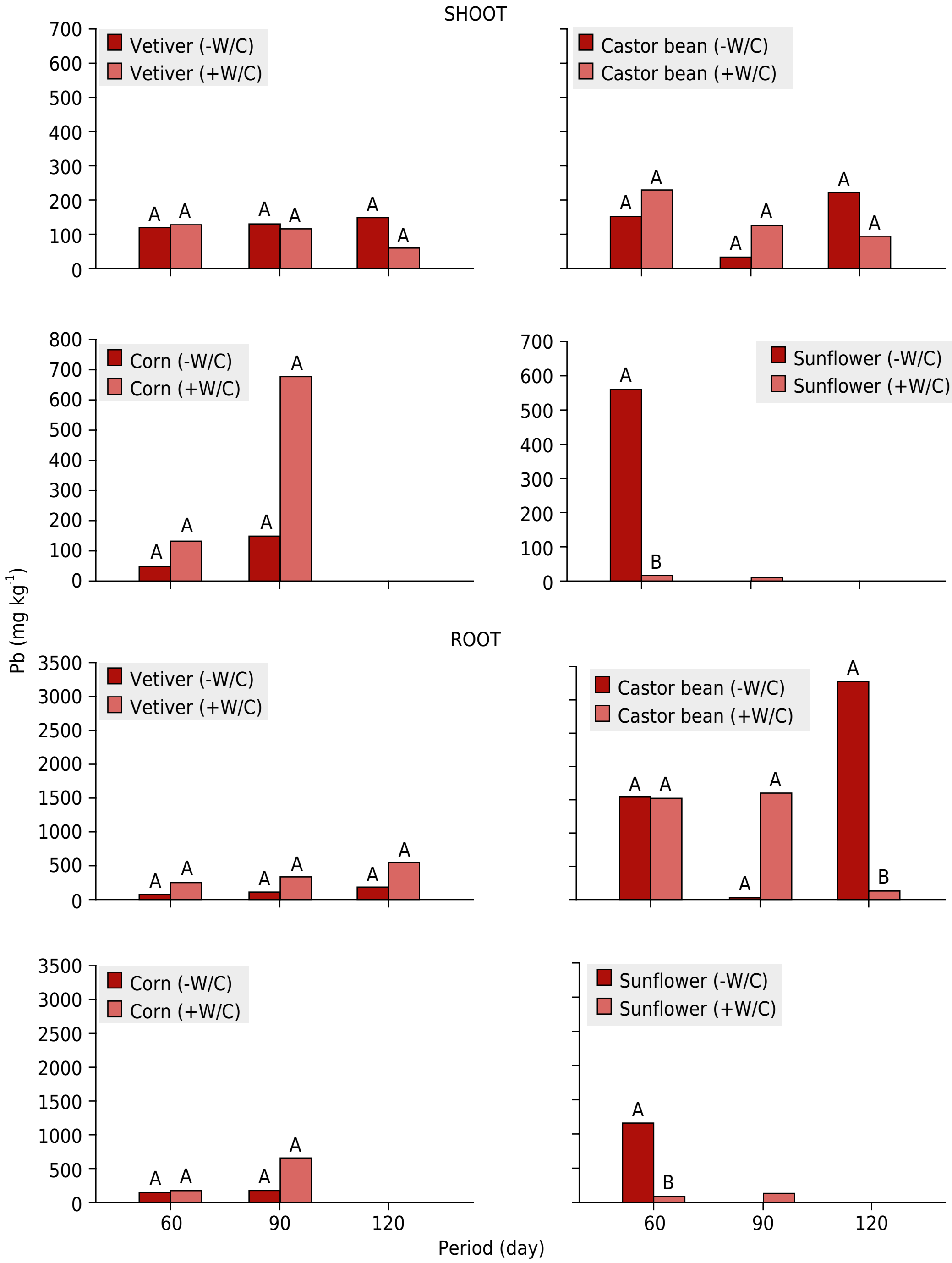

Figure 4. Lead contents in the shoots and roots in vetiver, castor bean, corn, and sunflower plants conducted in contaminated soil, without (-W/C) and with (+W/C) correction of soil pH, at 60, 90, and 120 days after planting (DAP). Means followed by the same letter, within each period, do not differ among themselves.

Regarding evaluation of phytoextraction potential of the species, there was uptake of Pb by the species, indicated by phytoextraction coefficient values (Table 3) and also shown by high Pb contents found in the roots and shoots (Figure 4), with an effect from soil pH correction only for corn at 90 DAP. Differences observed among the species is due to the degree of tolerance to Pb exposure, verified by Meers et al. (2010) and already discussed above.

As for Pb translocation, there was no effect from soil pH correction for any of the species analyzed (Table 3), observing low transfer from the roots to the shoots (less than 40 %). This can be explained by the fact that Pb preferably moves via the apoplast, and it is strongly retained to carboxyl groups of galacturonic and glucoronic acids of the cell wall,

Table 3. Phytoextraction coefficient (PC) and translocation factor (TF) for vetiver, corn, castor bean, and sunflower species obtained in different evaluation periods, without (-W/C) and with (+W/C) correction of soil pH (mean of four replications)

Period	Vetiver		Corn		Castor bean		Sunflower	
	-W/C	+W/C	-W/C	+W/C	-W/C	+W/C	-W/C	+W/C
day								
				PC				
60	0.07 A	0.07 A	0.03 A	0.07 A	0.08 A	0.12 A	0.31 A	0.01 B
90	0.07 A	0.06 A	0.08 B	0.37 A	0.02 A	0.07 A	-	0.01 A
120	0.08 A	0.03 A	-	-	0.12 A	0.05 A	-	-
				TF				
60	19.76 A	22.32 A	20.65 A	34.69 A	12.10 A	15.04 A	27.95 A	21.41 B
90	23.91 A	19.53 A	28.40 A	37.64 A	28.56 A	16.62 A	-	21.79 A
120	26.05 A	8.09 B	-	-	3.46 B	21.85 A	-	-

Mean of four replications. - : dead plants. Means followed by the same letter, within each species for each period, do not differ among themselves by the Tukey test ($p<0.05$).

which restricts this movement (Jarvis and Leung, 2001). Crops can compensate low metal translocation capacity by higher biomass production (Vamerali et al., 2010), which was particularly shown by vetiver, in association with its regrowth capacity and tolerance to high levels of heavy metals. It was the most efficient species considering the number of crop seasons necessary to remediate a contaminated area.

CONCLUSIONS

In soils with high Pb availability in the soil solution, soil correction by liming was fundamental for biomass production in all the species studied.

Castor bean and sunflower under high acidity conditions (pH < 4.0) were most affected by Pb, with low productions of biomass, even under conditions of soil correction.

Corn and vetiver exhibited the best growth rates at 90 days after planting and the highest Pb translocations to the shoots, and are thus the species most recommended for phytoremediation of the area.

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