Plant Growth Regul (2015) 75:383–389
DOI 10.1007/s10725-014-9927-7

BRIEF COMMUNICATION

Growth responses, antioxidant enzyme activities and lead accumulation of *Sophora japonica* and *Platycladus orientalis* seedlings under Pb and water stress

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Received: 27 February 2014 / Accepted: 17 April 2014 / Published online: 26 April 2014

Abstract The effects of lead were investigated in forest trees (*Sophora japonica* and *Platycladus orientalis*) grown in soil and exposed to $Pb(CH_3COO)_2 \cdot 3H_2O$ (0, 300, 500, 1,000 mg kg^{-1}) with different levels of water stress (100, 80, 60, 40 % soil relative water content, SRW). The results showed that, in the presence of Pb, the ground diameter, height and dry weight were greater than the control for *S. japonica* and *P. orientalis*. The proportions of biomass allocation of *S. japonica* were root > stem > leaf, and of *P. orientalis* leaf > stem > root except for 40 % SRW. SOD (superoxide dismutase) and POD (peroxidase) activities in leaves were activated by soil Pb for *P. orientalis*, while SOD activities increased but POD activities decreased compared with control under Pb stress for *S. japonica*. Water stress increased SOD and POD activities under different Pb concentrations, also increased MDA (malondialdehyde) content significantly. For *S. japonica*, the Pb concentration in the root was up to 91.9 mg kg^{-1}, while the Pb concentration in the aboveground part was 37.5 mg kg^{-1}. The Translocation Factor (TF value) increased with the increase of water stress intensity, under the same Pb concentration. For *P. orientalis*, the Pb accumulation in the roots was significantly higher than that in the aboveground part (TF < 1.0). And the total amount of Pb accumulated in *P. orientalis* was higher than *S. japonica*. On the basis of this study, it could be concluded that *P. orientalis* was more suitable for usage in the mining areas of northwest China to accumulate heavy metals, compared with *S. japonica*.

Keywords Antioxidant enzyme · Growth · Lead translocation · Phytoremediation · Water stress

Abbreviations

SOD	Superoxide dismutase
POD	Peroxidase
MDA	Malondialdehyde

Introduction

The problem of soil pollution by heavy metals has attracted public attention in recent decades, because they may be toxic to plants and animals (Broyer et al. 1972). Lead is probably one of the most frequently encountered heavy metals in polluted environments (Xiong 1998). Numerous investigations show that lead can be accumulated by plants via root and shoot, and the lead concentration in plant tissues is significantly related to the lead concentration in the environment (Rotkittikhun et al. 2006; Liu et al. 2009). Excessive lead accumulated in plants can be toxic to most plants, leading to inhibition of growth, biomass production, chlorophyll biosynthesis as well as chromosome lesions (Brennan and Shelley 1999; Wang et al. 2003; Hadi et al. 2010; Lamhamdi et al. 2011; Huang et al. 2011). Lead may generate excessive reactive oxygen species (ROS), also result in unbalance of essential trace metals and cellular redox status (Yang et al. 2010; Wang et al. 2010). In order to defend the harm induced by ROS, plants have developed antioxidative enzymes [such as SOD (superoxide

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dismutase), POD (peroxidase)], and non-enzymatic low molecular mass antioxidants to protect organs and minimize tissue injury (Mittler 2002). SOD is essential for catalyzing the dismutation of superoxide ($O_2^{\bullet -}$) into oxygen (O_2) and hydrogen peroxide (H_2O_2) (Jiang et al. 2010). POD is a key enzyme acts as a protector against peroxidation (Qureshi et al. 2007).

Due to the toxicity of lead to human health and living organisms and its widespread distribution, lead is ranked second of all hazardous substances by the Agency for Toxic Substances and Disease (ATSDR 2007; Manousaki and Kalogerakis 2009; Maraghni et al. 2010; Phang et al. 2011). Observations have investigated the plant growth, change of heavy metal concentration and the interaction in mining sites in environmental science. We have been interested in how plants, such as crops, grasses and trees act, and what they do during the period of growth and development during exposure to lead over the years (Broyer et al. 1972; Lamhamdi et al. 2011). In order to remove the Pb from soils, many methods are used, including excavation, thermal treatment, acid leaching, electro-reclamation and land fill, but the most effective one is phytoremediation (Kambhampati et al. 2003). So it is crucial to select suitable plant species which produce large biomass and accumulate as much lead as possible.

Lead mine reserves in the northwest of China occupy 44 % of the whole reserves of the western mines in China. And in northwest China, more than 95 % of the lead mining area belongs to arid or semi-arid regions. Therefore, water is a determinant in this region for phytoremediation. There have been many reports on Pb or water deficit in plants, but little is known about the interaction of water stress and Pb.

Platycladus orientalis is one of the main afforestation tree species for fragile ecological environment reconstruction and mining area ecological environment restoration in western China, because of its strong resistance to cold, drought and saline-alkaline soil. Moreover, it has a certain resistance to lead. *Sophora japonica* can grow well in barren land and on soil with water deficit, and most important, it has a strong resistance to smoke poison. So we chose the two species, to investigate their growth responses and lead accumulation ability under Pb and water stress. The results can provide scientific methods for phytoremediation in lead mines in the northwest of China.

Materials and methods

Soil samples and treatments

The Pb treatments were designed according to the National Soil-Environmental Quality Standard of China (NSEQSC, GB15618, 1995) (Xia 1996) and the results of the preliminary experiment by the soil-culture method. There were four treatments with Pb concentrations of 0, 300, 500 and 1,000 mg kg^{-1} respectively, as $Pb(CH_3COO)_2 \cdot 3H_2O$. The soil samples were collected by the Northwest A&F University. They were sieved and then mixed with the appropriate amount of $Pb(CH_3COO)_2 \cdot 3H_2O$ and equilibrated completely for one month. Water stress treatments with 100, 80, 60 and 40 % soil relative water content (SRW) were prepared (Hsiao 1973). So all the treatments were as following: 0 + 100 % (control), 300 + 100 %, 500 + 100 %, 1,000 + 100 %, 300 + 80 %, 500 + 80 %, 1,000 + 80 %, 300 + 60 %, 500 + 60 %, 1,000 + 60 %, 300 + 40 %, 500 + 40 %, 1,000 + 40 %.

Soil-culture experiment

The prepared soil samples were filled into plastic pots. Into each pot one *S. japonica* or two *P. orientalis* seedlings, 1 years old and with similar biomass, were transplanted in March of 2011. Then the soil surface was covered with 2 kg grit to reduce evaporation of water. One month later, when the seedlings had recovered from transplanting and showed normal growth, water stress treatments were implemented, according to the levels of the experimental design. The experiment was carried out in the artificial shed of the College of Resources and Environment, Northwest A&F University, to prevent rainwater. In the whole culture process, natural illumination was used, and the soil samples always kept natural fertility. The plants were harvested in September of 2011. The number of seedlings for each treatment was kept equal, and all treatments were replicated three times to minimize experimental errors.

Growth parameters and Pb determination

All the seedlings of each treatment were sampled. Height and ground diameter were measured. The plants were divided into roots, stems and leaves. Then they were carefully washed with deionized water after rinsing with tap water, dried at 105 °C for 30 min and then at 70 °C in an oven until completely dried. The dried plant samples were ground to powder after their dry weights had been determined, then were sieved through a 0.149 mm sieve (Wei and Zhou 2004). The plant samples were digested in HNO_3–HF–$HClO_4$ solution. The concentrations of Pb were determined using the atomic absorption spectrophotometer (AAS).

Enzyme assay

The fresh leaves from each treatment were homogenized in a pestle and mortar with 0.05 M sodium phosphate buffer

Table 1 The effect of Pb and water stress on growth parameters (ground diameter, height and dry weight) of *Sophora japonica* and *Platycladus orientalis*

Species	Treatment	Ground diameter (mm)	Height (cm)	Dry weight (g plant^{-1})
Sophora japonica	0 + 100 (CK)	15.23 ± 2.41ab	157.0 ± 7.0ab	141.83 ± 7.43d
	300 + 100	15.45 ± 1.45a	157.5 ± 4.5ab	159.22 ± 9.09c
	300 + 80	12.41 ± 1.98ab	141.3 ± 8.3b	89.43 ± 8.38g
	300 + 60	11.96 ± 0.33b	141.3 ± 10.4b	56.95 ± 8.03i
	300 + 40	11.63 ± 3.36b	143.0 ± 9.9b	41.08 ± 3.06k
	500 + 100	15.65 ± 2.30a	165.7 ± 4.2a	221.96 ± 8.67a
	500 + 80	14.17 ± 0.70ab	140.0 ± 2.9b	125.33 ± 8.64e
	500 + 60	11.67 ± 0.96b	131.7 ± 7.4b	62.93 ± 6.45h
	500 + 40	10.52 ± 1.06b	129.1 ± 5.4b	44.13 ± 3.93j
	1,000 + 100	15.50 ± 2.28a	163.3 ± 11.9a	179.73 ± 3.22b
	1,000 + 80	13.77 ± 0.77ab	144.0 ± 12.0b	108.95 ± 4.82f
	1,000 + 60	11.02 ± 0.85b	140.5 ± 0.5b	61.97 ± 2.13h
	1,000 + 40	9.40 ± 0.26b	131.3 ± 4.2b	37.87 ± 2.24l
Platycladus orientalis	0 + 100 (CK)	4.88 ± 0.17bc	56.5 ± 4.9b	7.86 + 0.52e
	300 + 100	6.78 ± 0.18a	56.0 ± 5.7b	11.94 + 0.04b
	300 + 80	4.30 ± 0.26c	36.0 ± 1.4d	6.29 + 0.90i
	300 + 60	3.57 ± 0.31cd	33.0 ± 1.4d	3.52 + 0.14j
	300 + 40	3.81 ± 0.47c	31.0 ± 0.0d	1.97 + 0.06l
	500 + 100	5.67 ± 0.18b	58.0 ± 8.5b	11.73 + 3.02c
	500 + 80	5.96 ± 2.38ab	58.0 ± 7.1b	8.89 + 0.82f
	500 + 60	4.90 ± 0.53bc	43.5 ± 3.5c	6.90 + 0.62h
	500 + 40	3.06 ± 1.24d	23.0 ± 7.1e	1.37 + 0.01m
	1,000 + 100	7.05 ± 0.01a	66.0 ± 1.4a	11.24 + 2.87b
	1,000 + 80	6.43 ± 0.11ab	63.0 ± 2.8a	14.35 + 2.46a
	1,000 + 60	5.36 ± 0.05b	49.5 ± 0.7c	9.08 + 1.19c
	1,000 + 40	3.84 ± 1.01c	26.0 ± 9.9e	2.48 + 0.02f

Values are the mean ± SD of three replicates. The values followed by the different letter show statistically significant differences at $P < 0.05$, the same below

(pH 7.5). The homogenate was centrifuged at 10,000 rpm for 20 min and the supernatant was used for analyzing SOD, POD and MDA (malondialdehyde) content. The above steps were carried out at 4 °C (Shu et al. 2012). SOD, POD enzyme activities were determined according by the method of Li et al. (2000). MDA content was measured following the method of shu et al. (2012).

Statistical analysis

All analyses were done on a completely randomized design. All data were statistically processed using Excel XP, SPSS 11.0, and analyzed by one-way ANOVAs with the lowest standard deviations (LSD) test at a 0.05 level.

Results

After growing in pots for 6 months, the presence of Pb in the soil caused visible changes in the development of the two species. Pb promoted growth of *S. japonica* seedlings to some extent, especially under 500 + 100 % treatment. The growth responses of *S. japonica* seedlings without water stress did not differ significantly among treatments ($P > 0.05$), although the ground diameter and height were slightly higher than that of control. However, the dry weight of seedlings under Pb stress increased significantly compared with the control ($P < 0.05$), especially for 500 mg kg^{-1}, the dry weight reached 1.56 times as much as that of control. The results showed that Pb had stronger influence on growth of *P. orientalis*. The ground diameter, height and dry weight increased under Pb treatments; The maximums of ground diameter and height were 1.44, 1.17 times of control at 1,000 mg kg^{-1}, both increased significantly ($P < 0.05$); the dry weight increased significantly at 300 mg kg^{-1}, reached 1.52 times of the control ($P < 0.05$) (Table 1).

Water stress restrained the growth of *S. japonica*. Under water stress, the *S. japonica* seedlings showed inhibition of ground diameter, height and decrease in dry weight in Pb contaminated soil, especially for 40 % SRW. The value of ground diameter, height and dry weight was 61.7, 83.6 and 26.7 % of control respectively, when exposed to 1,000 mg kg^{-1}. And the sequence of the inhibition ratio

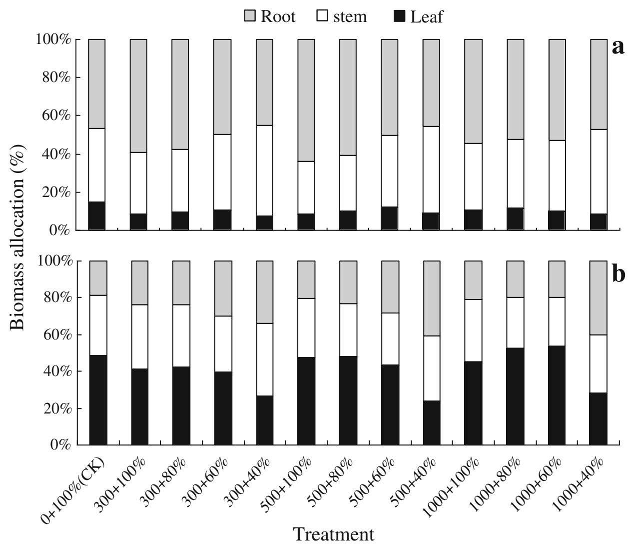

Fig. 1 Biomass allocation of *Sophora japonica* and *Platycladus orientalis* under Pb and water stress. **a** *Sophora japonica*; **b** *Platycladus orientalis*

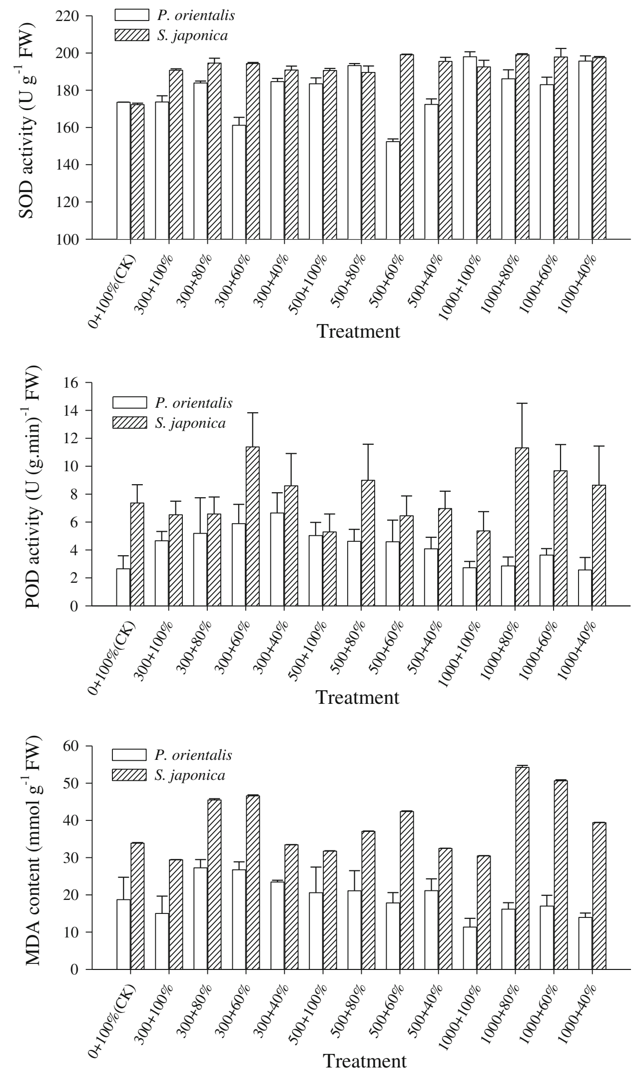

Fig. 2 Changes of superoxide dismutase (SOD), guaiacol peroxidase (POD) activities and MDA content in *Sophora japonica* and *Platycladus orientalis* under Pb and water stress

was dry weight > ground diameter > height. Water stress with a SRW of 80 % could promote plant growth when the Pb concentration was ≥500 mg kg^{-1}, while an SRW of 60 % when the Pb concentration was 1,000 mg kg^{-1} for *P. orientalis*. The growth of *P. orientalis* seedlings was also affected, the reduction of growth was significant in Pb contaminated soil, under water stress treatment of 40 % SRW ($P < 0.05$) (Table 1).

The relative biomass allocation of *S. japonica* was root > stem > leaf, the root proportion reached its maximum at 500 + 100 % treatment, and decreased with the increase of water stress intensity, under the same Pb concentration. In contrast, the trend of the stem proportion was just the opposite. The proportion of leaf biomass was very small, less than 20 %. In addition, the leaf proportion of all the treatments was less than the control. The relative biomass allocation of *P. orientalis* was leaf > stem > root, except under the 40 % treatments. The root proportion of *P. orientalis* increased with the increase of water stress intensity, and reached a significant difference at 40 % SRW ($P < 0.05$). On the contrary, the trend for proportion of leaf biomass decreased with the increase of water stress intensity (Fig. 1).

The SOD activities increased with increasing Pb concentrations both for *S. japonica* and *P. orientalis*. The water stress increased SOD activities in *S. japonica*, under the same Pb concentration. However, SRW 60 % decreased the SOD activities in *P. orientalis* when existed with Pb (Fig. 2). POD activities in *S. japonica* treated with different Pb concentrations decreased compared with control, while increased firstly, reached the maximum at 500 mg kg^{-1} and then decreased lower than the control at 1,000 mg kg^{-1} in *P. orientalis*. The POD activities in *S. japonica* and *P. orientalis* under water stress and Pb stress were higher than that under single Pb stress. The MDA contents under different Pb concentrations were lower than that of control, both for *S. japonica* and *P. orientalis*. Moreover, the MDA contents increased under the combined treatments Pb and water stress, and degree of increasing was more obvious in *S. japonica* than *P. orientalis*.

The Pb concentrations in different parts of the plants were shown in Table 2. For *S. japonica*, the Pb concentration in the roots was higher than that in other parts in all the treatments, reaching 91.85 mg kg^{-1} under 1,000 + 100 % treatment. And under the same Pb concentration in the soil, the Pb concentration in the root decreased with the increase of water stress intensity. The Pb in the stem reached a

Table 2 Pb concentration (mg kg^{-1}) in different parts, TF of *Sophora japonica* and *Platycladus orientalis*

Species	Treatment	Pb concentration (mg kg^{-1})			TF
		Root	Stem	Leaf	
Sophora japonica	0 + 100 (CK)	1.77 ± 0.10e	0.73 ± 0.12d	1.05 ± 0.36g	1.00 ± 0.05a
	300 + 100	45.63 ± 6.54cd	4.75 ± 0.15c	13.06 ± 1.25f	0.39 ± 0.01h
	300 + 80	35.39 ± 1.28cd	4.74 ± 0.60c	13.55 ± 2.33f	0.52 ± 0.04f
	300 + 60	35.00 ± 0.83cd	8.27 ± 0.11bc	14.27 ± 0.99ef	0.64 ± 0.03d
	300 + 40	34.15 ± 1.05d	10.21 ± 1.02b	17.89 ± 3.68d	0.82 ± 0.06c
	500 + 100	58.60 ± 4.36b	5.94 ± 0.66c	24.89 ± 2.94bc	0.53 ± 0.06f
	500 + 80	45.74 ± 8.12cd	9.45 ± 0.45bc	17.60 ± 1.59de	0.59 ± 0.03e
	500 + 60	34.69 ± 2.03cd	9.45 ± 1.27bc	18.43 ± 2.43d	0.80 ± 0.05c
	500 + 40	30.60 ± 3.03d	8.34 ± 0.99bc	16.26 ± 5.45e	0.80 ± 0.03c
	1,000 + 100	91.85 ± 2.91a	11.36 ± 3.45b	26.13 ± 3.07b	0.41 ± 0.02gh
	1,000 + 80	87.51 ± 4.47a	15.03 ± 2.08a	21.61 ± 3.74c	0.42 ± 0.04gh
	1,000 + 60	80.56 ± 7.09a	11.39 ± 1.76ab	22.95 ± 1.28c	0.43 ± 0.01g
	1,000 + 40	46.42 ± 3.04c	13.58 ± 0.98ab	30.57 ± 1.40a	0.95 ± 0.04b
Platycladus orientalis	0 + 100 (CK)	1.45 ± 0.00d	1.41 ± 0.00f	1.43 ± 0.01e	1.96 ± 0.12a
	300 + 100	114.25 ± 14.82c	15.76 ± 2.43c	24.11 ± 0.84b	0.35 ± 0.01c
	300 + 80	103.69 ± 10.91c	14.77 ± 3.11c	14.17 ± 2.10d	0.28 ± 0.04e
	300 + 60	80.95 ± 6.74cd	19.45 ± 2.31b	17.32 ± 1.36cd	0.45 ± 0.08b
	300 + 40	85.44 ± 8.21cd	13.86 ± 1.08cd	18.57 ± 1.24c	0.38 ± 0.02c
	500 + 100	144.84 ± 10.00bc	18.34 ± 1.12bc	28.50 ± 0.92a	0.32 ± 0.01d
	500 + 80	119.15 ± 9.17c	18.01 ± 0.99e	17.44 ± 2.57cd	0.30 ± 0.04de
	500 + 60	104.95 ± 10.24c	6.65 ± 0.81d	21.83 ± 4.21bc	0.27 ± 0.05e
	500 + 40	96.41 ± 5.89c	11.43 ± 2.94d	21.84 ± 3.15bc	0.35 ± 0.02cd
	1,000 + 100	328.01 ± 1.22a	12.11 ± 1.09d	28.21 ± 1.72a	0.12 ± 0.01g
	1,000 + 80	269.17 ± 4.97ab	11.37 ± 1.99d	27.54 ± 1.93ab	0.14 ± 0.01g
	1,000 + 60	220.68 ± 21.36b	23.43 ± 3.51a	15.32 ± 2.56cd	0.18 ± 0.03f
	1,000 + 40	104.12 ± 13.45c	18.20 ± 2.47bc	25.89 ± 4.28ab	0.42 ± 0.01b

TF: Pb concentration ratio of shoots to roots

maximum of 15.03 mg kg^{-1} in the 1,000 + 80 % treatment and a maximum of 30.57 mg kg^{-1} in the leave at the 1,000 + 40 % treatment. The TF values were lower than 1.0 in all the treatments except 300 + 60 % and 300 + 40 %. However, the TF value increased significantly with the increase of water stress intensity, under the same Pb concentration ($P < 0.05$). For *P. orientalis*, the Pb concentration in the aboveground parts was also lower than that in the roots (TF < 1.0). Furthermore, the Pb accumulation in the roots was much higher than that in *S. japonica*. The Pb concentration in the roots reached 328.01 mg kg^{-1} in the 1000 + 100 % treatment, and increased with increasing Pb concentration in the soil. In addition, there was no obvious symptom of phytotoxicity for *P. orientalis* seedlings growing in 80 % SRW. *P. orientalis* has the potential to grow in arid or semi-arid region for lead accumulation.

Discussion

Heavy metals in the soil can be absorbed by plant roots and transported to the shoots. There have been different results about the toxicity of heavy metals for plants and the possible importance of lead in the toxic effects (Keaton 1937). Many reports confirmed that lead could induce inhibitory effects on plant growth (Wang et al. 2010; Yang et al. 2010). However, Begonia et al. (1998) confirmed that lead promoted plant growth within a range of concentrations. Baumhardt and Welch (1972) reported that *Zea mays L.* was not affected by added lead in soil. Rasmussen and Henry (1963) also showed that lead stimulated the growth of some crop plants, had no effect on others, and inhibited growth of still others, at low concentrations. Our results were in agreement with these conclusions. The results of the growth parameters showed that proper concentrations of Pb could facilitate plant growth. In the presence of Pb, the ground diameter, height and dry weight were greater than that of control, for *S. japonica* and *P. orientalis*. The reason for this phenomenon may be that low concentrations of Pb increase the activities of amylase, proteinase and lipase and speed up the decomposition of endosperm (Cheng 2003), this is relative to plant species and to the growth stages of plants. Results of this study demonstrated that lead resulted in increase of SOD and POD activities in leaves of *P. orientalis*. This increase had been reported in many plants under Pb stress, such as *Cassia angustifolia* (Qureshi et al. 2007), *Zea mays* (Gupta et al. 2009). The increase of antioxidative enzymes activities under Pb stress may be one of the reasons that promoting the plant growth.

Water deficit negatively affected seedling development and decreased biomass by reducing carbohydrate supply for optimum growth (Singh and Singh 2006). In this study, growth diameters of *S. japonica* and *P. orientalis* were significantly reduced under water stress, when the Pb concentration was the same. This may be due to a decrease of turgor which would result in a decrease of growth and development of cells, especially in stems and leaves, caused by water stress (Kaufmann and Eckard 1971), and resulted in strong disturbances on the photochemical reactions (Tezara et al. 2005; Hura et al. 2007). The root is crucial for seedling, and species with greater drought tolerance generally show a bigger investment in root growth compared with shoot growth (Pallardy and Rhoads 1993). Abrams (1990) reported that the pattern of allocation of dry matter to roots and shoots also affected the water relations. Bongarten and Teskey (1987) found that seedlings of *Pinus taeda* grown in a dry regime allocated a greater portion of dry weight to the roots and less to the stem. In the present study, the root proportion of *S. japonica* was greater than that of the stem, and significantly greater than that of the leaf, but the proportion decreased under water stress, when the Pb concentration was the same. The reason for this symptom may be related to the leaf cuticle thickness (Oppenheimer 1951). The root proportion of *P. orientalis* increased under water stress, leaf and stem proportions decreased, but the decrease of the leaf proportion was greater than that of the stem, indicating that the allocation to the roots was at the expense of the leaves, which was in agreement with the result of Singh and Singh (2006). SOD and POD activities increased under Pb and water stress in some extent. However, the MDA content also increased significantly, demonstrating that water stress increased the oxidative stress in the two species, which may account for the inhibition of growth.

It is well know that heavy metals penetrate plants mainly through the roots (Piechalak et al. 2002; Begonia et al. 2005). Heavy metal uptake is stopped on the root surface at first, but a large portion penetrates the roots and then is bound to the cell wall forming insoluble deposits (Malecka et al. 2008). Like most plants, *S. japonica* and *P. orientalis* accumulated Pb mainly in the roots, and the amount increased with increasing Pb concentrations in the soil. Furthermore, the Pb concentration in the roots of *P. orientalis* was higher than that in *S. japonica*. The TF values of the two plants were both lower than 1.0, indicating the limited ability of transferring Pb from the roots to the aboveground parts. A higher shoot/root ratio of the heavy metal content in plants is important in phytoremediation of heavy metal contaminated soils. Extracting lead from the growth medium and concentrating it in the plant biomass depends on photosynthesis and thus on energy (Center 1995). In the present study, we demonstrated that *P. orientalis* was a relatively powerful species in extraction of lead via its root system, especially when the Pb concentration is 1,000 mg kg^{-1}. The two species *S. japonica* and *P. orientalis* could grow normally and considerable amounts of heavy metals could be extracted when they were harvested (Mertens et al. 2004; Liu et al. 2008), although they cannot be used as hyperaccumulators, Pb concentration in them was high, especially for *P. orientalis*.

For the combined treatments Pb and water stress, it was determined that the amount of accumulated Pb decreased and the proportion of Pb distributed in the roots decreased significantly under water stress for *S. japonica*. The amount of accumulated Pb also decreased under water stress, but the proportion of Pb distribution changed less obvious for *P. orientalis* compared with *S. japonica*. Metal transport to the aboveground parts probably takes place in the xylem along with transpiration, and is redistributed via the phloem. The transpiration of *S. japonica* was stronger than that of *P. orientalis*, and the casparian strips of the two species were different, so that a different amount of metal ions was able to cross the endodermis. All this may result in the changed distribution of the Pb proportions.

Water deficit is a wide-spread problem seriously influencing plant growth, crop production and quality (Sio-Se Mardeh et al. 2006; Khalid et al. 2010), especially in the arid and semi-arid regions in the northwest of China. On the basis of this study, it could be concluded that *P. orientalis* was more suitable than *S. japonica* for heavy metal accumulation in the mining areas of northwest China.

Acknowledgments This research Project was supported by National Natural Science Foundation of China (No. 31170579) and by the Specialized Research Fund for the Doctoral Program of Higher Education (No. 20110204110009). Thanks are due to the Department of Environmental Science, College of Resources and Environment, Northwest A&F University for technical guidance and help with this study.

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