Environ Sci Pollut Res
DOI 10.1007/s11356-015-5153-8

RESEARCH ARTICLE

Effects of Ni stress on the uptake and translocation of Ni and other mineral nutrition elements in mature wheat grown in sierozems from northwest of China

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Received: 3 June 2015 / Accepted: 3 August 2015

Abstract Effects of heavy metal on uptake of mineral nutrition elements in plants have attracted widespread interest and been widely explored. This paper reports the translocation and accumulation behaviors of Ni in the organs of mature wheat plants by means of pot experiment using the sierozem collected from northwestern China as experimental soil. Effect of Ni on accumulation of Cu, Mn, Ca, and Mg is also demonstrated. It was found that influence of Ni on wheat plants differed greatly at different Ni levels. Ni content in the organs of wheat plants increased with the increase in Ni level, and the increasing rate decreased when the Ni level was higher than 400 mg/kg. Ni was mainly accumulated in the roots and less distributed in the shoots, shells, and grains. When the Ni level was lower than 400 mg/kg, the bioconcentration factor (BCF) of the roots was higher than 1, suggesting that Ni was taken in against a concentration gradient. The average translocation factor (TF) of wheat plants was 0.221, indicating the weak ability of wheat plants in translocating Ni toward the aboveground parts. Since Ni is readily accumulated in the grains of wheat plants at lower Ni level, concerns in health risks might be raised. Excess Ni in wheat plants could inhibit the transfer of Cu, Mn, and Mg to grains, leading to the accumulation of Ca, Mg, and Mn in the shoots and shells of wheat plants. The increase in Ni content can disturb the uptake and distribution of mineral nutrition elements in the organs of plants, resulting in the toxic effect of Ni on wheat plants. Results from this study provide a scientific support to prevent or control heavy metal pollution in an arid region.

Keywords Wheat · Nickel · Sierozem · Mineral nutrition · Translocation · Accumulation

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Introduction

Ni is one of the main nonferrous metal minerals in Gansu Province, northwest China. Rapid development in exploitation, smelting, and processing industry of Ni in Gansu over the last several decades has greatly promoted the economic development and social progress. However, Ni industry also has caused serious environmental problems (Nan et al. 2011). Located in arid and semi-arid regions, it has been a long history in Gansu Province to employ industrial and domestic wastewater to irrigate or partially irrigate croplands due to the shortage of irrigation water (Wang et al. 2009). Previous research has shown that the average Ni content is 226.30 mg/kg in the farmlands in suburbs of Jinchang City in Gansu Province. The maximum content of Ni was as high as 1,000 mg/kg, considerably higher than the background value of Ni level (35.2 mg/kg) in Gansu Province (Ding et al. 2008; CNEMC 1990). Therefore, the accumulation and bioavailability of Ni in crop plants has attracted great attention in recent years because of the food safety issues and potential health risks (Yusuf 2011).

Ni is an essential element in the growth and development of plants (Marschner 1995). An appropriate amount of Ni can facilitate the growth of plants. On the other hand, an inhibition effect and toxic effect on the growth of plants may occur if Ni

Published online: 18 August 2015

level exceeds a certain level (Rahman et al. 2005; Sreekanth et al. 2013). Although much research has been devoted to the influence of Ni on plants, the mechanism of the toxicity of Ni is not completely understood. It has been confirmed that Ni can affect the metabolic processes of plants by disturbing the balance of plant mineral nutrition (Sabir et al. 2014), inhibiting transpiration and photosynthesis of plants (Carlson et al. 1975; Shafeeq et al. 2012), and influencing the common cell responses which aim at the detoxification of heavy metals (Seregin and Kozhevnikova 2006).

Previous findings have shown that 200 mM Ni could inhibit the shoot growth of wheat plants, decrease the relative water content (RWC) and chlorophyll content, cause accumulation of proline, and exert toxic effects on wheat plants. The activities of superoxide dismutase (SOD) and catalase (CAT) were decreased after the treatment of 200 mM Ni. Conversely, the activities of peroxidase (POD) and glutathione *S*-transferase (GST) were enhanced (Gajewska et al. 2006). Higher Ni levels in wheat seedlings can lead to the modification of fatty acid profile and increase electrolyte leakage, which are related to the lipid peroxidation and damage of cells (Gajewska et al. 2012). High concentration of Ni can disrupt the uptake balance of nutrient elements in plants. For example, high Ni levels can inhibit the uptake of Mn and Cu in sprouted corn, thereby interfering with Cu regulation and causing nickel toxicity by disrupting root-to-shoot Fe translocation in *Alyssum inflatum* (Ghasemi et al. 2009; Sabir et al. 2011). Moreover, high concentration of Ni in rice can promote the uptake of Ca in order to reduce the toxic effects of Ni (Aziz et al. 2015). Ni has different effects on the uptake of mineral nutrition elements in plants because the varieties of plant, the physical and chemical properties of soil, and the natural environment of the growing region of plants are different.

However, few researchers have studied the effects of Ni on the uptake of mineral nutrition elements in wheat plants, and previous research mainly focused on Ni uptake during wheat seedlings (Page and Feller 2005; Sabir et al. 2014; Gajewska et al. 2014). Different from other non-essential metals, Ni can easily be moved to the parts which have prosperous vitality, such as newly formed parts of shoot and root system (Page and Feller 2005), and it can be readily accumulated in grains at the mature stage of wheat plants (Bose and Bhattacharyya 2008). Therefore, there is an urgent need to conduct some experimental studies to discriminate the effects of Ni on mature wheat plants, especially in the arid area of northwest China with major Ni industries. In this study, the sierozem collected from the northwestern districts was employed as the experimental soil, and pot experiments were carried out to investigate the translocation and accumulation of Ni in the organs of mature wheat. Effects of Ni stress on mineral nutrition elements in the aboveground organs of wheat plants were also studied. The objective of this study aims at providing scientific basis for the prevention and control of the heavy metal pollution in the arid environment in China.

Materials and methods

Soil sampling and pot experiment design

In this experiment, wheat was used as the model crops. Wheat seeds in the experiment were purchased from the seed companies in Yuzhong County in Gansu Province, China. The experimental soil was the sierozem collected from a crop field in Yuzhong County. The typical properties of the soil are pH 8.54, carbonate content 12.74 %, organic matter content 2.15 %, and cation exchange capacity 5.27 cmol/kg. Background levels of Ni, Cu, Mn, Ca, and Mg in the experimental soil were 28.5 mg/kg, 28.9 mg/kg, 587 mg/kg, 49.2 g/kg, and 17.1 g/kg, respectively.

Eight groups of pot experiments were carried out under open air conditions. Experimental soil (5 kg) was added to each pot, and the soil was treated with the solution of nickel nitrate with different concentrations (Table 1). The group without amended nickel nitrate was used as a control (CK). After keeping soil samples for 15 days to equilibrate, 5 g sheep manure, which was applied as basal fertilizer, was added to each pot. Local groundwater was utilized to make the soil moisture content at about 60 % of the field water holding capacity. Thirty seeds were sown to each pot. During the experimental period, tap water was added to the pots to offset the water lost from evaporation and transpiration process. In this way, the soil moisture content was maintained at approximately 60 % of the field water holding capacity. The management for the growth of wheat plants followed the same way as the wheat planted in field. The wheat plants were harvested after they were cultivated for 110 days. In this experiment, each group had three samples for the investigation.

Soil and plant analysis

The ripened wheat plants were harvested and washed with deionized water carefully thoroughly to eliminate soil particles and other impurities. The wheat plants were cut into root parts, shoot parts, shell parts, and grains parts with a pair of scissors. The different parts of the wheat samples were dried at 70 °C for 48 h. After drying, the dry weight of each part was recorded. The plant samples were then ground and homogenized in a mill and digested in a diacid mixture (HNO_3 + $HClO_4$) (Lu 2000).

Soil samples were taken out from the pots. The crop debris and other foreign substance were removed. The soil was then

Table 1 The concentrations of the Ni added to soil

Treatments	CK	1	2	3	4	5	6	7
Heavy metal addition (mg/kg)	0	50	100	200	400	600	800	1,000

air-dried at room temperature and subsequently ground. After being passed through a 100-mesh (φ=0.149 mm) nylon sieve, the as-obtained soil samples were collected for further experiment. The physicochemical properties of the soil were investigated according to the routine analysis method of soil in agricultural chemistry. The total Ni in soil was extracted using an acid digestion mixture (HNO_3-HF-$HClO_4$) in an open system (MEP 1997; MEP 2004).

According to the standard method, clear solutions were obtained after the digestion, filtration, and reconstitution of the solution volume to a desired value. The content of Ni, Cu, Mn, Ca, and Mg in soil and wheat was analyzed by atomic absorption spectrometer (AAS, M6MK2, Thermo Electron Corporation, USA).

Quality control

Certified reference samples, GSS-8 (GBW-07408) and GSV-2 (GBW-07603), were employed in quality control. All measurement results were within the range of certified value of nickel. Total nickel content in soil, wheat plants, and extractions was triplicate. Before using, all the glassware and plastic containers must be soaked in 20 % (*v*/*v*) HNO_3 for at least 12 h and thoroughly rinsed initially with tap water and subsequently with deionized water.

Statistical analysis

Statistical analysis was performed using SPSS 13.0 software. The significance of the differences between the means of the treatments was evaluated by one-way analysis of variance (ANOVA) followed by Duncan tests.

Results and discussion

Distribution of Ni in different parts of wheat plants

Figure 1 shows the Ni concentrations in different parts of the wheat plants cultivated in the artificially contaminated arid sierozem spiked with different doses of Ni. It can be observed that the concentrations of Ni in different parts of wheat plants increased significantly with the concentration of Ni added to soil. The content of Ni in different parts of wheat plants increased rapidly at lower Ni level. When Ni levels were higher than 400 mg/kg, the increasing rate of Ni content slowed down evidently and then tended to remain uniform. Concentration of Ni varied widely in different parts of wheat plant. When the concentrations of Ni added to soil were lower than 200 mg/kg, the sequence of Ni concentrations in different parts of wheat plant was roots > shoots > grains > shells. However, when the Ni level was higher than 200 mg/kg, the sequence of Ni concentrations in different parts of wheat plant changed to roots > shoots > shells > grains. It was obvious that Ni was mainly accumulated in the wheat roots in which the content of Ni increased fastest.

The translocation and accumulation mechanism of heavy metals in plants were affected significantly by soil properties, plant species, concentrations of available metals, and coexisting heavy metals in soils. Moreover, the absorption and distribution characteristics of an element varied widely in different parts of plants (Zhu et al. 2007). For most plants, especially the plants growing in the heavy metal-enriched areas, the concentration of Ni in the roots of plants is higher than that in the aboveground parts of plants (Wang et al. 2009). Results obtained in this experiment have shown that the uptake rate of Ni in the roots of wheat plants decreased obviously when the Ni level was higher than 400 mg/kg, indicating to the appearance in the wheat plants the protective mechanisms against the translocation of nickel ions into the plant. The selective permeability of plasma membrane and the root exudates led to a decrease of the uptake effectiveness for metal ions into the plant. As a result, the Ni content in different parts of wheat plants decreased (Dai 2006).

The content of heavy metals in edible parts of plant has been a focus of a great deal of research in recent years. The understanding to the uptake, translocation, and distribution of heavy metals in plants could be helpful for the selection of suitable plant species which can grow in highly heavy metal-contaminated soils. Ni can be accumulated in plant parts with growth ability and regeneration capacity of plants and translocate within these parts (Seregin et al. 2007). According to the results in this study, in the aboveground parts of wheat plants, Ni mainly distributed in the grains at low Ni level (0–100 mg/kg). The distribution of Ni in different parts of wheat plants is closely related to the stages of plant development. At the vigorous growth stage of wheat plants, Ni is mainly accumulated in leaves. However, most Ni would be eventually transferred to seeds after the senescence of leaves (Page and Feller 2005). Because there were no criteria for limiting the concentration of Ni in crops, the standard content of Ni (1 mg/kg) in China national standards for food safety inspection were used as criteria. The results showed that the Ni distributed in the grains of wheat plants exceeded the standard. As a result, we could conclude that wheat plants were not suitable for cultivating in Ni heavily contaminated soils in the arid areas, northwest China.

Bioconcentration factor and translocation factor of Ni

Bioconcentration factor (BCF) and translocation factor (TF) are important parameters in the study of heavy metal uptake. BCF is the ratio of metal concentration in plant tissues to metal concentration in their rooted soil. The BCF measures the efficiency of heavy metal uptake by plants. TF, defined as the ratio of metal concentration in other parts of plants to the

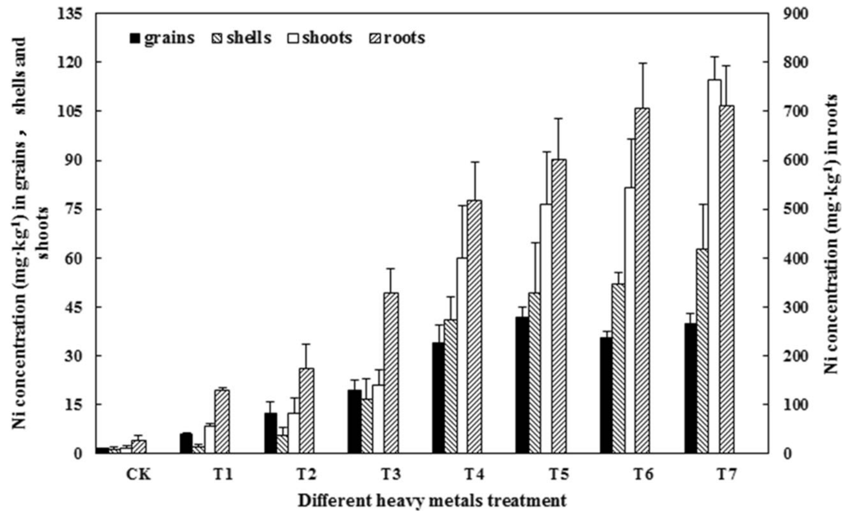

Fig. 1 Ni concentrations in parts of wheat plants at different Ni level (mean±SD, *n*=3)

concentration in roots, is a reflection of the translocation abilities of heavy metals in plants. The metals are easily transported from root to other parts of wheat plants when the value of TF is higher.

Table 2 shows the BCF and TF of Ni in different parts of wheat plants. As the Ni level increases, the BCF of Ni in different parts of wheat plants increased firstly and then decreased subsequently when the concentrations of Ni added to soil were higher than 400 mg/kg. The sequences of the average BCF of Ni in wheat plants were roots > shoots > grains > shells. The BCF of Ni in the roots of wheat plants was greater than 1 when the Ni level was lower than 400 mg/kg. This suggests that the uptake of Ni in wheat plants was inverse to concentration gradients and fairly efficient (Parida et al. 2003). When the Ni level was higher than 400 mg/kg, Ni becomes toxic to wheat plants, leading to the significant decrease of BCF of Ni in the roots of wheat plants. This suggests that in wheat plants, the protection mechanisms are formed against excessive uptake of metal into the plant. The average BCF of Ni in the grains of wheat plants was 0.067 in this study. The average BCF of Ni in the grains of wheat growing in the fields in Jinchang County of Gansu Province was 0.013 (Wang et al. 2009). Likewise, the average BCF of Ni was 0.092 in the grains of wheat growing in the artificially contaminated oasis soils spiked with different doses of Ni in arid area of Hexi Corridor, Gansu Province (Bai et al. 2014).

The TF of Ni in different parts of wheat plants increased with the Ni levels, which indicated the translocation of Ni from root to other parts of wheat plants was enhanced. A possible explanation for this result is that, in order to reduce or avoid the disturbance and damage of Ni to the functional parts and normal metabolism of plants, Ni was transferred from root to the aboveground parts and distributed in the non-metabolic active tissues. Sabir et al. (2014) have investigated the TF of Ni of two different wheat cultivars (Sehar-2006 and LU-26) which cultivated in the soil that artificially spiked with different doses of Ni. Their results showed that the average TF of Ni of the Sehar-2006 and LU-26 were 0.2872

Table 2 Bioconcentration factor (BCF) and translocation factor (TF) of Ni in wheat plants

Treatment	Bioconcentration factor of Ni in different parts of wheat plants				Translocation factor
	Roots	Shoots	Shells	Grains	
CK	0.937±0.420ab	0.064±0.034a	0.041±0.022ab	0.052±0.011ab	0.185±0.062ab
50	1.607±0.109d	0.105±0.011ab	0.028±0.009a	0.074±0.007bc	0.129±0.010a
100	1.284±0.357bcd	0.092±0.031ab	0.040±0.017ab	0.091±0.027c	0.174±0.009ab
200	1.448±0.172d	0.092±0.019ab	0.073±0.025bc	0.086±0.014c	0.173±0.021ab
400	1.427±0.299 cd	0.147±0.038b	0.101±0.020c	0.083±0.015c	0.233±0.011bc
600	0.987±0.151abc	0.126±0.029b	0.081±0.027c	0.069±0.006bc	0.281±0.058 cd
800	0.864±0.130ab	0.126±0.048b	0.064±0.004abc	0.043±0.002a	0.268±0.023 cd
1,000	0.701±0.069a	0.113±0.007ab	0.076±0.027bc	0.039±0.003a	0.327±0.044d
Average	1.157±0.322	0.108±0.032	0.063±0.025	0.067±0.019	0.221±0.070

In each column, means with similar letters are not significantly different at 0.05 level according to the Duncan test

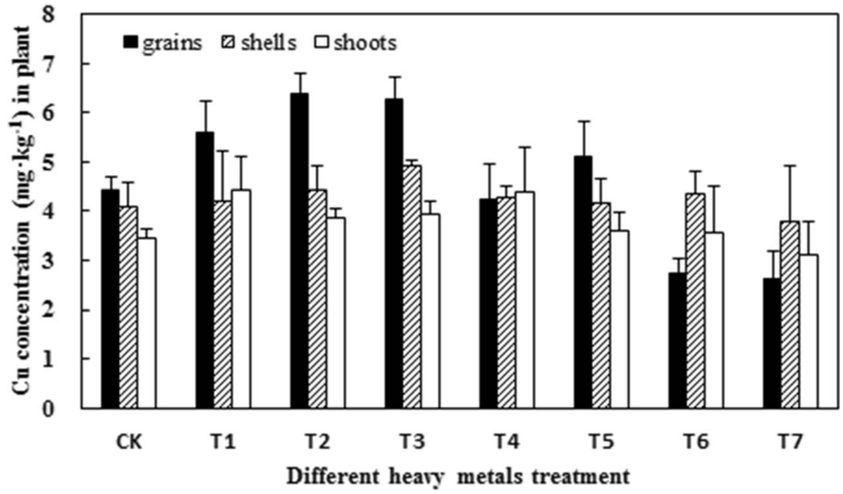

Fig. 2 Cu concentration in the aboveground organs of wheat plants at different Ni level (mean ±SD, n=3)

and 0.2066, respectively (Sabir et al. 2014). Whereas the average TF of Ni in wheat plants growing in the artificially contaminated oasis soil spiked with different Ni in arid area of Hexi Corridor, Gansu Province was 0.65 (Bai et al. 2014), the average TF of the wheat plants in this research was 0.221, indicating that the translocation ability of Ni from the roots to the aboveground parts was poor.

The influence of Ni stress on the mineral nutrition elements

Cu concentration in the aboveground organs of wheat plants

As shown in Fig. 2, the influence of Ni stress on the content of Cu in different organs of wheat plants was explored. With the increase in the concentrations of Ni added to soil, the content of Cu in the aboveground organs of wheat plants increased firstly and then decreased. Cu was mainly distributed in the grains of wheat plants when Ni level was lower than 200 mg/kg. As Ni level was higher than 200 mg/kg and increased gradually, an inhibition effect on the translocation of Cu from other parts to the grains took place. The concentration of Cu in the grains of wheat plants was 61.5 % of that in control groups when the Ni level was 800 mg/kg and 59 % of that in control groups when the Ni level was 1,000 mg/kg. It has been reported that the content of Cu in the barley malt decreased with the increase in Ni level (0, 1.0, 10, and 100 μM) in growth medium (Rahman et al. 2005). Cu is a kind of indispensable microelement in plants and plays an important role in the growth and development of plants. It is the structure component and catalytic active component of enzyme which participates in the electron transfer and oxidation reaction in plants (Yruela 2005). In this study, during the period that adding Ni could promote the growth of wheat plants, the plants grow vigorously and the demand for micronutrient elements was enhanced, resulting in an increasing trend of Cu concentration in the organs of wheat plants. As the Ni stress was enhanced, the antagonism between Ni and Cu was increasing, resulting in the inhibition of Cu uptake in wheat plants. Therefore, the metabolic disorder in wheat

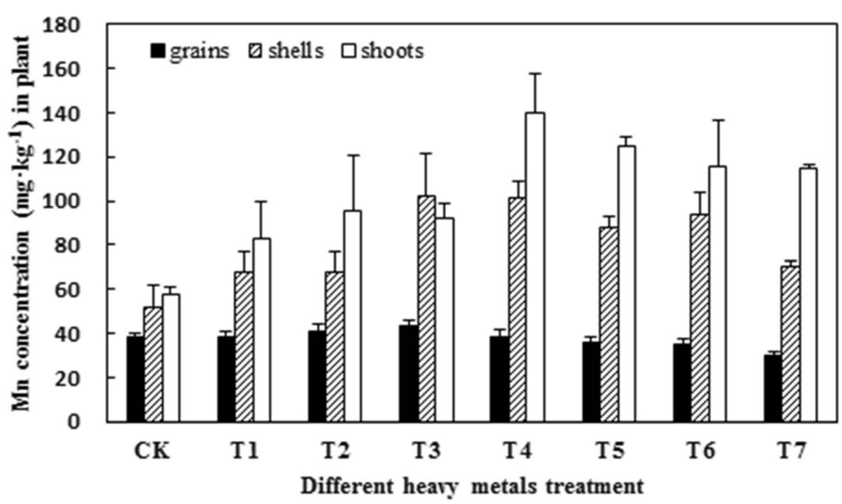

Fig. 3 Mn concentration in the aboveground organs of wheat plants at different Ni level (mean ±SD, n=3)

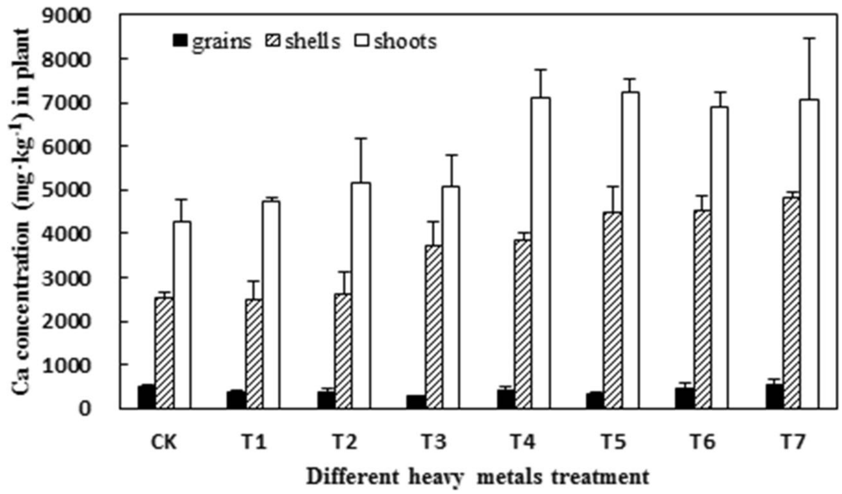

Fig. 4 Ca concentration in the aboveground organs of wheat plants at different Ni level (mean ±SD, n=3)

plants was one of the main reasons causing inhibition in the growth and development of wheat plants and wheat plant contamination.

Mn concentration in the aboveground organs of wheat plants

The influence of Ni stress on the content of Mn in different organs of wheat plants was shown in Fig. 3. The content of Mn in the aboveground organs of wheat plants increased firstly and then decreased with the increase in Ni level. Mn content in the shoots of wheat plants increased quickly at a lower Ni level and decreased slightly when the Ni level was higher than 400 mg/kg. However, even though Ni level was up to 1,000 mg/kg, the content of Mn in the shoots of wheat plants was still twice as high as that in control groups. When the concentration of Ni added to soils reached 200 mg/kg, the maximum Mn concentration in the grains of wheat plants was 43 mg/kg which was 1.13 times of that in control groups. However, the concentration of Mn in the grains of wheat plants was 30 mg/kg, 79 % of Mn concentration in control groups as the Ni level reached 1,000 mg/kg. It was reported that Mn added in *Phytolacca americana* could decrease the uptake amount of Cd and reduce the inhibition effect of Cd on the growth of *P. americana* (Peng et al. 2008). In this research, Ni stress could potentially enable wheat plants to uptake a large amount of Mn which mainly was distributed in the non-reproductive organs, in order to reduce the toxicity of Ni.

Ca concentration in the aboveground organs of wheat plants

It can be seen from Fig. 4 that Ni stress could also influence the concentration of Ca in the aboveground organs of wheat plants. With the increase in concentration of Ni added in soil, the content of Ca in the shoots and shells of wheat plants increased. For Ni level below 400 mg/kg, Ca content increased in the shoots and shells. However, the concentration of Ca in shoots and shells had no obvious change when the Ni level was higher than 400 mg/kg. In the aboveground organs of wheat plants, Ca was mainly distributed and accumulated in shoots and shells in which mean Ca concentrations were 14.6 times and 8.9 times of that in the grains, respectively. More importantly, Ca

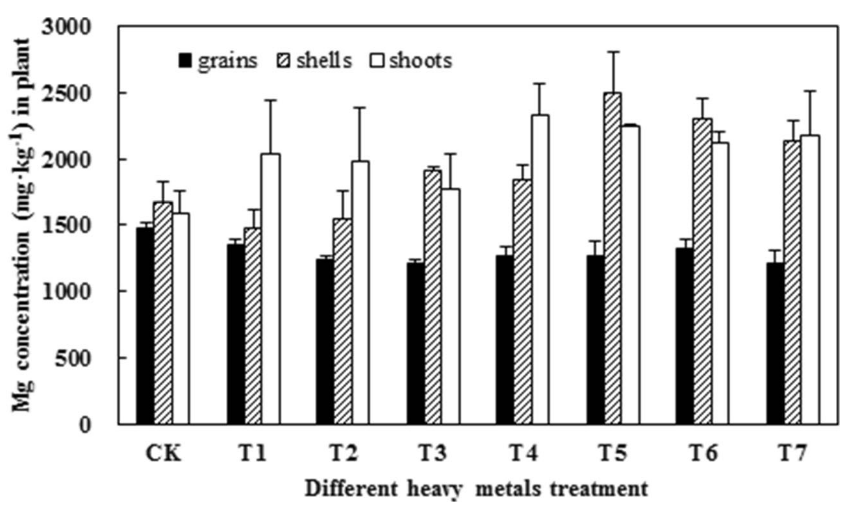

Fig. 5 Mg concentration in the aboveground organs of wheat plants at different Ni level (mean ±SD, n=3)

element serves as a second messenger in cells which can activate a series of physiological and biochemical processes, in addition to the major macronutrients required by plants, Ca also can stimulate a multiple resistance mechanism in plants (Issa et al. 1995). Performance and biological activity of metals can be altered by different cations such as Ca^{2+} (Antosiewicz and Hennig 2004). Ca^{2+} can facilitate anti-oxidant activity, thus limiting the peroxidation of membrane lipids, stabilizing the cell membrane, and preventing the leakage of solute (Hirschi 2004). Previous research has shown that Ca enhances photosynthesis, chlorophyll content, and stomatal conductance of plants that counteracts the toxic effects of nickel (Aziz et al. 2015).

Mg concentration in the aboveground organs of wheat plants

Figure 5 shows that Ni stress also has an effect on Mg content in the aboveground organs of wheat plants. With an increase in Ni level, the concentration of Mg increased slowly in shoots and shells and decreased slowly in grains. Ni treatment can increase the concentrations of some ions such as PO_4^{3-}, Ca^{2+}, and Mg^{2+} in oats (Hunter and Vergnano 1953). The Ni added to soils, of which the concentration range from 50 to 200 mg/kg, can result in the decrease in the contents of Cu and Mg in caryopses of wheat plants (Barsukova and Gamzikova 1999). Sufficient supply of mineral nutrients such as Ca and Mg could help reduce stressing effect and toxicity of heavy metal ions. It is possible that the Ca^{2+} and other salt ions could compete against the heavy metal ions on those uptake and transport sites. Moreover, the existence of Ca^{2+} and Mg^{2+} in plants can help cells maintain a normal osmotic system, ensuring the mineral nutrition which is less affected by the stress influence of heavy metals (An et al. 2002).

Conclusion

In this study, translocation and accumulation behaviors of Ni in the organs of mature wheat plants and the effects of Ni on accumulation and distribution of Cu, Mn, Ca, and Mg were investigated by means of pot experiment. Sierozem collected from an arid area in northwestern China was employed as experimental soil. The results showed that Ni level could affect the mineral composition of wheat plants. An increase in Ni level could lead to the increase of Ni content in the organs of wheat plants. However, the increasing rate slowed down and become relatively stable as Ni level was higher than 400 mg/kg. Ni was mainly accumulated and distributed in roots with a minor portion in shoots, shells, and grains, respectively. The BCF and TF of the tissues in wheat plants increased firstly and then decreased as the concentration of Ni added to soil increased. With Ni level higher than 400 mg/kg, root BCF was greater than 1, implying that the wheat plants had the capacity to take in Ni against the concentration gradients. The average TF of wheat plants was 0.221, indicating that wheat plants had a very poor performance in translocating Ni toward the aboveground parts. The risk of transferring Ni to the grains of wheat plants should be taken into consideration because the average BCF of the grains was 0.067. All these results have shown that Ni could disrupt the balance of mineral nutrition elements, thus influencing the normal growth and development of wheat plants. Excess Ni could reduce Cu content in the aboveground organs and inhibit the translocation of Cu, Mn, and Mg to the grains of wheat plants, respectively. Moreover, excess Ni also led to large uptake and accumulation of Mn, Ca, and Mg in the shoots and shells of wheat plants. This is likely that these minerals could protect wheat plants from the toxicity of Ni. Outcomes from our study could provide some scientific support for prevention and control of heavy metal pollution in arid region. In addition to the results and analysis shown here, the interaction between Ni and other mineral nutrition elements needs further studies. Moreover, the effects of different soils with varied properties on the growth performance and mineral status of wheat plants are also an interesting problem requiring further research.

Acknowledgments This work was supported by the Fundamental Research Funds for the Central Universities in Lanzhou University (lzujbky-2015-150), the Supervision of PhD Degree Fund of Chinese Ministry of Education (20120211110018), and the National Natural Science Foundation of China (Nos. 91025015 and 51178209).

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