ISSN 1392-3196
Zemdirbyste-Agriculture, vol. 96, No. 2 (2009), p. 111–124
UDK 633.16“321”:631.416.8:581.132

THE EFFECT OF HEAVY METALS ON SPRING BARLEY (*Hordeum vulgare* L.)

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Abstract

Comparative toxicity of most heavy metals changes with the increase of impact (concentration) and only cadmium occurred to be most toxic in the entire range of investigated concentrations. In the case of relatively low concentrations, toxicity of investigated heavy metals decreased in the following order: Cd>Cr>Ni>Cu>Pb>Zn, and in the case of relatively high impact: Cd>Cu> Ni>Cr>Zn>Pb. More severe impact on the root growth at the comparatively low and medium concentrations, and more severe inhibition of shoot growth at higher concentrations of all investigated metals were detected. Stimulation of chlorophylls and carotenoids at lower concentrations is characteristic feature for the impact of metals. For most metals (Cu, Cr, Ni, Cd) maximal content of chlorophylls was registered in the range of concentrations between 1 and 3 μM.

Key words: spring barley, heavy metals, concentrations, biomass, photosynthetic pigments, accumulation, tolerance and inhibition.

Introduction

In the strict chemical sense, the term of heavy metals can be addressed only to the elements with density above 5 g cm^{-3} /Seregin, Ivanov, 2001; Dučič, Polle, 2005/. However, in biological classification heavy metals are usually considered as the elements with relative atomic mass above 40 /Antanaitis, 2001/. Regarding the character of interaction with biota, heavy metals are classified as essential and non-essential /Punz, Sieghardt, 1993/.

Essential heavy metals, such as copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), are required by plants as structural and catalytic components of proteins and as cofactors of enzymes, and usually are named as microelements. Non-essential heavy metals, such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr) do not play any metabolic role and are considered as toxic elements. A common feature of essential and non-essential heavy metals is that at higher concentrations all of them are highly phytotoxic /Lanaras et al., 1993; Prasad, 2004; Panda, Choudhury, 2005/.

There are different natural or anthropogenic sources for heavy metals in the environment. Natural sources are weathering of the bedrock and volcanic activity /Schutzendubel, Polle, 2001/. Natural amounts of heavy metals usually do not cause negative impact on plants and other components of biota. However, because of increasing anthropogenic emissions of heavy metals from agriculture (fertilizers and pesticides), metallurgy (mining and foundry works), energy production and fuel burning, microelectronic production and waste disposal, heavy metals have become one of the most serious anthropogenic stressors for plants ant other living organisms /Antanaitis, 2001; Seregin, Ivanov, 2001/.

The most important targets of heavy metals (HM) are proteins and enzymes. The toxic impact of heavy metals may also result from interaction with other biomolecules – phospholipids, DNA and displacement of essential elements in biomolecules. Inhibition of biomass accumulation and damage of photosynthetic apparatus are the general phenomena associated with the impact of heavy metals. The visible symptoms of HM impact, such as chlorosis and necrosis, are mainly resulted by heavy metals caused deficiency of the elements, that are essential for plant growth and development /Rout, Das, 2003; Prasad, 2004; Dučič, Polle, 2005/.

Relatively new concept of heavy metals toxicity is oxidative stress /Prasad, 2004/. Heavy metals can cause oxidative stress in two ways – they can take part in the formation of reactive oxygen species (ROS), such as superoxide (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radical (HO) or cause damages of antioxidative system and inhibition of ROS removal or scavenging /Prasad, 2004/.

Redox-active metals, such as copper, iron, and according to some authors chromium, vanadium and cobalt, are involved in the formation of hydrogen peroxide and most toxic hydroxyl radical via Haber-Weiss and Fenton reactions /Okamoto et al., 2001; Valko et al., 2005; Sharma, Dietz, 2008/. Metals without redox capacity, such as cadmium, lead, mercury, nickel, zinc, cause depletion of antioxidant glutathione pool and antioxidative enzymes (catalases, superoxide dismutase, ascorbate peroxidase, etc.), thus increasing the amount of reactive oxygen species /Okamoto et al., 2001; Schutzendubel, Polle, 2001; Prasad, 2004/.

In order to control the level of ROS and protect cells from oxidative injury, plant have developed a complex antioxidant defense system to scavenge the surplus of ROS. The antioxidants include various enzymes and non-enzymes, which may also play a significant role in ROS signaling in plants /Panda, Choudhury, 2005/.

The toxicity of heavy metals is species dependent, furthermore, sequence of heavy metals toxicity depends on the soil properties, acidity of soil solution, etc. /Punz, Sieghardt, 1993; Athar, Ahmad, 2002; Ivanov et al., 2003; Prasad, 2004/. For *Hordeum vulgare* L. the following sequence of toxicity was determined Hg>Pb>Cu>Cd>Cr>Ni>Zn /Prasad, 2004; Seregin, Kozhevnikova, 2006/, for *Zea mays* L. – Ti>Cu>Ag>Hg>Cd>Zn>Pb>Co /Seregin, Ivanov, 2001/, for *Ceratophyllum demersum* L. – Cd>Cu>Ni>Zn>Pb>Cr /Athar, Ahmad, 2002/.

Despite the fact, that a lot of experiments demonstrated the impact of heavy metals on different plant species, there is still a lot of indeterminations and contradictions in this field. The aim of our study is to investigate the tolerance of one of the most widespread crops in Lithuania – spring barley (*Hordeum vulgare* L. cv ʽAura DS'), to the impact of different heavy metals (Cu, Zn, Cr, Ni, Cd, Pb). Inhibition of growth and assimilation of photosynthetic pigments, along with metal ions accumulation were measured to investigate the impact of different heavy metals on spring barley.

Materials and methods

Lithuanian cultivar ʻAura DS’ of spring barley (*Hordeum vulgare* L.) was chosen as a research object, because of its high sensitivity to the impact of heavy metals /Blažytė, 2005/. Experiments were carried out in a vegetation room with controlled environment: photoperiod – 14 hours, average temperature – +22 ^oC, relative humidity – 65%. “Philips Master Green Power CG T” 600W lamps, light intensity at the level of plants 14000 Lx, provided light.

The plants, after seed sterilization and germination were grown for five days in an aerated nutrient solution (0,4 mM $CaCl_2$, 0,65 mM KNO_3, 0,25 mM $MgCl_2 \cdot 6H_2O$, 0,01 mM $(NH_4)_2SO_4$, 0,04 mM NH_4NO_3 /Aniol, 1997; Ramaškevičienė et al., 2001/ supplemented with different amount of heavy metals salts (Figure 1).

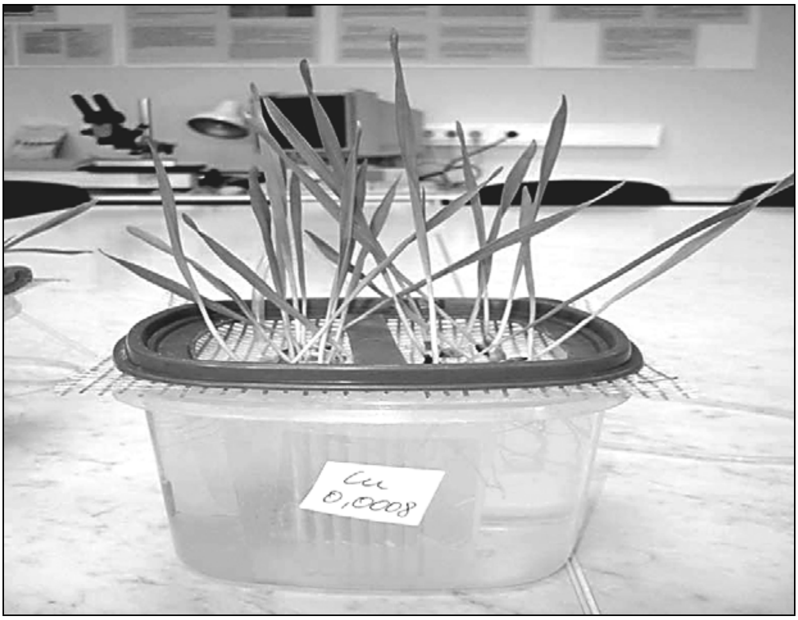

Figure 1. Spring barley (cultivar ʻAura DS’) grown in aerated nutrient medium
1 paveikslas. *Vasariniai miežiai (veislė ʻAura DS’) aeruojamoje mitybinėje terpėje*

For reference treatment, plants were grown in nutrient solution without addition of heavy metals. 24 germinated seeds were planted in each vegetation vessel and three replicate vessels per treatment were used.

Six heavy metals – copper (Cu), zinc (Zn), chromium (Cr), nickel (Ni), lead (Pb) and cadmium (Cd) were chosen for this study. Three of them (Cu, Zn and Ni) are considered as an essential, and other three (Cd, Pb and Cr) as not-essential for plant metabolism. Taking into account that bivalent metals are considered as most toxic to the plants /Kovacevic et al., 1999; Pandey, Sharma, 2002/, the following salts were used for experiments – $CuSO_4 \cdot 5H_2O$, $CdSO_4 \cdot 8/3H_2O$, $Pb SO_4$, $Ni SO_4 \cdot 6H_2O$, $Cr_2(SO_4)_3 \cdot H_2O$, $Zn SO_4 \cdot 7H_2O$. Chromium sulfate is only an exception in this list and chromium is trivalent in the investigated compound. Trivalent chromium is toxic to plants even at low concentration and has been reported to cause severe oxidative damage to plant cells /Panda, Choudhury, 2005/. Six different concentrations of element were investigated for Cu, Zn, Ni, Pb, Cd. In the case of Cr seventh concentration was added in order to reach strong growth inhibition (70–80%) (Figure 2).

The following indices were determined at the end of experiments (11–12 BBCH) – dry biomass of shoots and roots, content of chlorophyll *a* and *b*, and carotenoids in the leaves, accumulation of heavy metals in the roots and shoots. The content of chlorophylls and carotenoids was measured spectrophotometrically with a spectrophotometer DU 800 (company "Beckman Coulter") in 100% acetone extraction according to the method of Ditter von Wettstein /Brazaitytė, 1998/.

For determination of dry weight, shoots and roots were dried in an electric oven at +70 ºC for 24 hours. After dry weight determination, samples were used for determining the concentrations of heavy metals. This procedure was performed at the Agrochemical Research Centre of the Lithuanian Institute of Agriculture. Shoots and roots were mineralized in "Multiwave 3000" (company "Anton Paar"). Extraction of heavy metals was made with a mixture of concentrated HNO_3 and HCl. Spectrometry was accomplished with Perkin Elmer atomic absorption spectrometer "Optima 2100 DV" /Lubytė, 2001/.

Software *Statistica 6* was applied for statistical analysis and presentation of data. Data on the means of investigated indicators with confidence limits (±SE) are presented in the figures.

Results and discussion

Dry biomass, including both – shoots and roots of spring barley plants at different concentrations of investigated heavy metals is presented in Figure 2.

An essential reduction in spring barley biomass is characteristic of all heavy metals – essential or non-essential for their metabolism. As it was mentioned by different investigators, growth inhibition is a general phenomenon associated with the impact of heavy metals and even essential heavy metals, which are usually referred to as micro-elements (Cu, Zn, Mn, Fe), are required only in traces /Seregin, Ivanov, 2001; Rout, Das, 2003; Prasad, 2004/.

As it is seen from Figure 2, even the lowest investigated concentrations of heavy metals caused statistically significant ($P < 0.05$) decrease in dry biomass of spring barley. It is noteworthy that some essential metals (copper) caused more severe inhibition of spring barley growth than some metals, which are considered as a toxic element without any metabolic significance (lead). For more exact comparison of toxicity of investigated heavy metals, losses in dry biomass at different concentrations as compared to reference treatment (zero concentration of heavy metals) are presented in Figure 3. Taking into account logarithmic character of "doze – effect" relations /Ivanov et al., 2003/, concentrations of investigated heavy metals are presented on logarithmic scale.

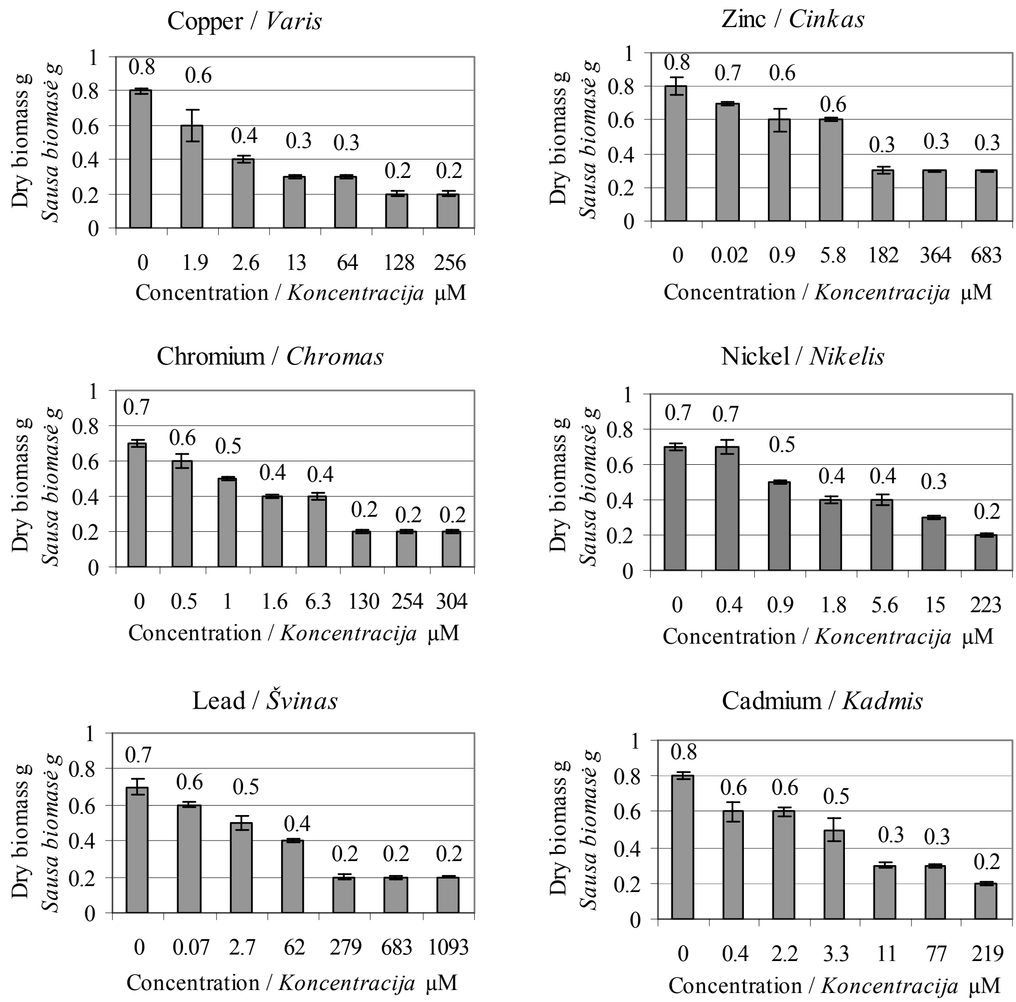

Figure 2. Dry biomass of spring barley (cultivar 'Aura DS') shoots and roots (mean ± SE) at different concentrations of investigated heavy metals
2 paveikslas. *Vasarinių miežių (veislė 'Aura DS') šaknų ir daigų sausa biomasė (vidurkis ± standartinė paklaida) esant įvairioms tirtų sunkiųjų metalų koncentracijoms*

It is necessary to note (Figure 3) that comparative toxicity of the most investigated heavy metals changes with the increase of impact (concentration) and only cadmium should be considered as the most toxic in the entire range of investigated concentrations. Evaluation which was made on the basis of data presented in Figure 2, showed that in the case of relatively low impact (growth inhibition – 20%) toxicity of investigated heavy metals decreased (concentration necessary to reach 20% growth inhibition increased) in the following order: Cd>Cr>Ni>Cu>Pb>Zn. In the case of relatively high impact (growth inhibition 60%) toxicity of investigated heavy metals decreased as follows: Cd>Cu> Ni>Cr>Zn>Pb. It can be seen that comparative toxicity of copper increased most essentially and from the forth rank in the case of low impact it moved to the second rank in the case of high impact. Increase in rank of toxicity along with increase of impact (concentration) is characteristic of other microelement – zinc as well. At the same time rank of chromium and lead toxicity decreased along with increase of impact.

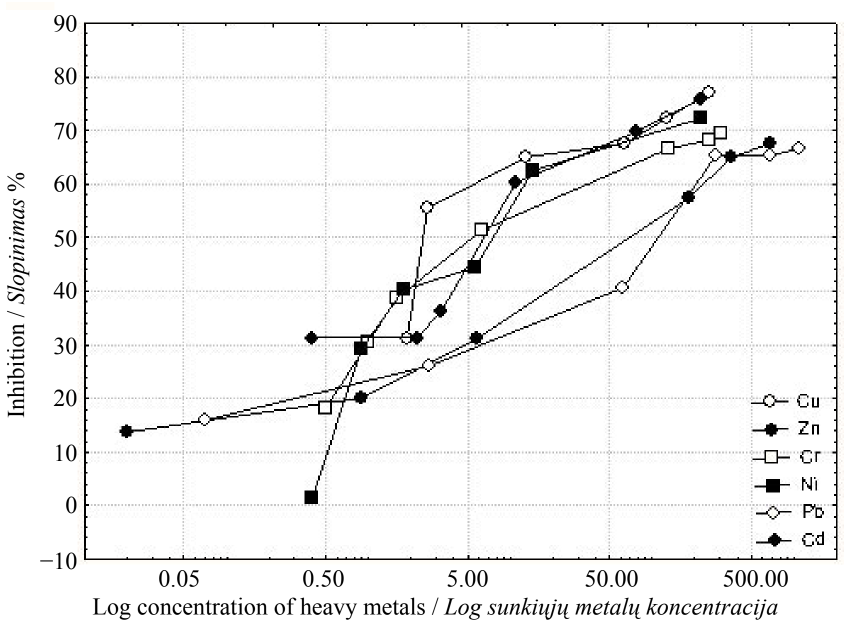

Figure 3. Inhibition of spring barley (cultivar 'Aura DS'*)* growth by different heavy metals

3 paveikslas. *Įvairių metalų koncentracijos sąlygojamas vasarinių miežių (veislė 'Aura DS') augimo slopinimas*

According to the results of other investigations, the following sequences in decrease of heavy metals toxicity was presented: Hg>Cd>Ni>Zn>Cr>Pb /Antanaitis, 2001/, Cd>Cu>Ni>Zn>Pb>Cr /Athar, Ahmad, 2002/, Ti>Cu>Ag>Hg>Cd>Zn>Pb>Co /Ivanov et al., 2003/. As different authors emphasized, relative toxicity of different heavy metals is species specific /Lanaras et al., 1993; Prasad, 2004/ and depends on soil fertility, acidity and presence of other toxic substances /Athar, Ahmad, 2002/. Our investigations showed that relative toxicity of heavy metals depends on the severity of impact as well.

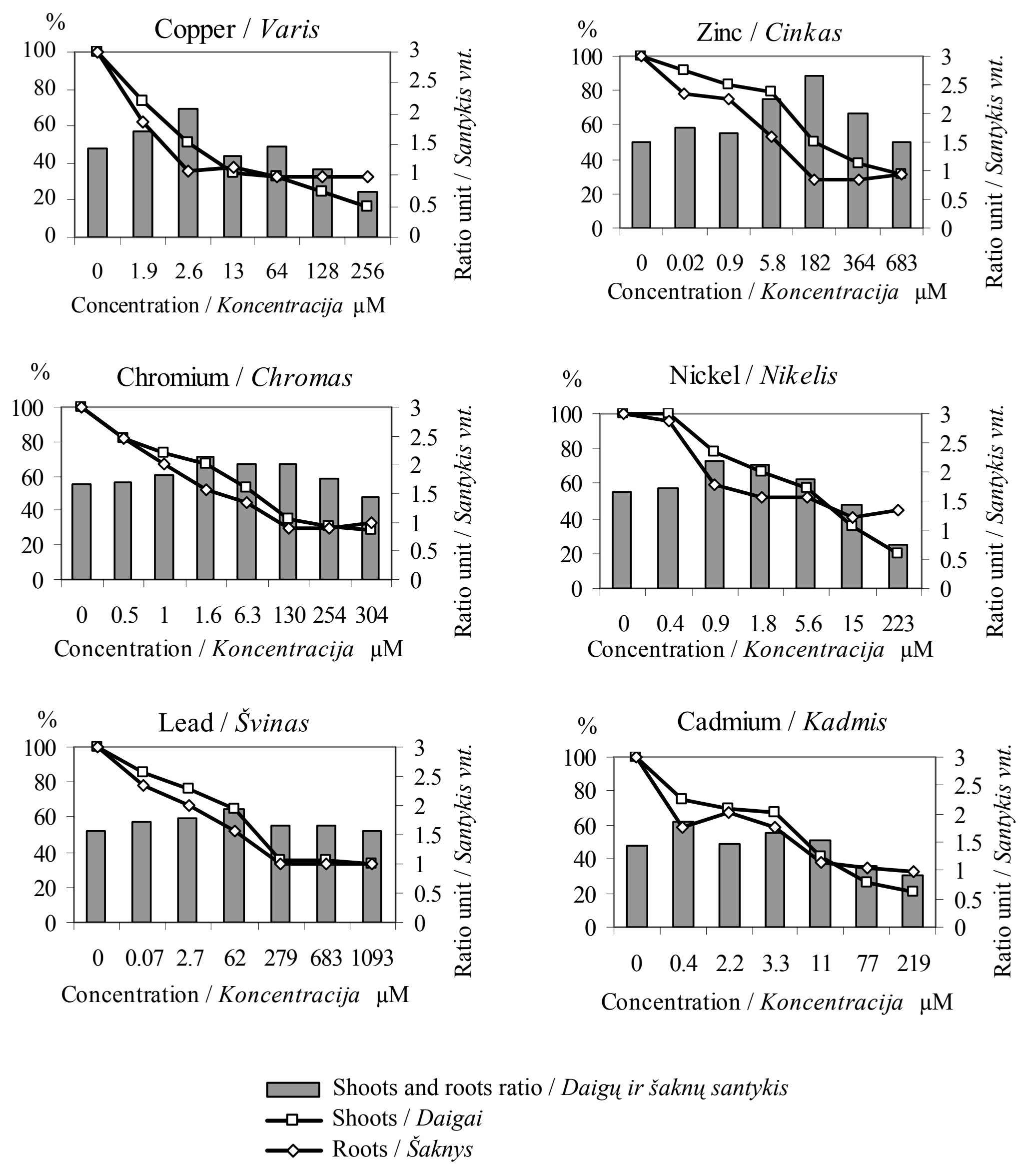

Figure 4. Dry biomass of spring barley (cultivar 'Aura DS'*)* shoots and roots (in percent from reference) at different concentrations of investigated heavy metals and ratio of shoots and roots biomass (bars)
4 paveikslas. *Vasarinių miežių (veislė 'Aura DS') daigų bei šaknų sausa biomasė (procentais, palyginti su kontroliniu variantu) esant įvairioms tirtų sunkiųjų metalų koncentracijoms ir daigų bei šaknų biomasės santykis (stulpeliai)*

According to the data of most authors root growth is more sensitive to the impact of heavy metals than shoot growth /Seregin, Ivanov, 2001; Prasad, 2004/. Roots of plants are the first barrier which detains heavy metals, therefore they are most vulnerable. Heavy metals damage meristemic tissue of roots, blocks cells development and slow down roots growth /Arduini et al., 1994; Prasad, 2004/. But there are also contrary data suggesting that organs of plants, which accumulate large amounts of heavy metals, become the most resistant to their toxic impact. Investigations of some authors /Athar, Ahmad, 2002/ has showed that under impact of some metals (cadmium, lead, zinc) biomass losses were higher for roots, and contrary, under impact of copper, nickel and chromium growth inhibition was more pronounced for shoots.

Data of our investigations on dry biomass of shoots and roots at different concentrations of investigated heavy metals are presented in Figure 4. Despite the essential difference in reaction of spring barley shoots and roots to the impact of different metals, some general features can be distinguished. First of all, characteristic feature for the impact of all investigated metals is more severe impact on the root growth at the comparatively low and medium concentrations. The next general feature is that for high concentrations inhibition of shoots growth gradually becomes more essential than that for roots.

Above mentioned general features in inhibition of shoots and roots growth under impact of different heavy metals, resulted in general pattern of changes in ratio of shoots and roots biomass along with increase of impact (concentration). As can be seen from Figure 4, shoots / roots biomass ratio as compared to reference treatment (zero concentration) increases along with increase of concentration, however after this ratio reaches maximal value, rather sharp decrease in shoots / roots biomass ratio is characteristic of all investigated heavy metals.

It is necessary to note, that dry biomass of shoots exceeds dry biomass of roots approximately 1.5 times in the case of reference treatment. Most essential increase in shoots / roots biomass ratio was registered under impact of zinc, as a heavy metal of lowest toxicity. This ratio reached 2.6 values at comparatively high concentration (182 μM) of zinc in the solution. And contrary, lowermost increase in shoots / roots biomass ratio (1.85) is characteristic of most toxic heavy metal cadmium ant this extreme was reached at very low concentration (0.4 μM).

Data on the content of chlorophylls (*a* + *b*) and carotenoids in the leaves of spring barley at different concentrations of investigated heavy metals in the nutrient solution are presented in Figure 5. Nonspecific stimulation of chlorophylls at lower concentrations is characteristic feature for the impact of all investigated metals. For most metals (Cu, Cr, Ni, Cd) maximal content of chlorophylls was registered in the range of concentrations between 1 and 3 μM. Only for metals of lowest toxicity (Zn, Pb) maximal concentration of chlorophylls was detected at comparatively high (680 μM) concentration of metal (Figure 5).

Increase in the content of chlorophylls along with some increase in concentrations of heavy metals was reported by different authors /Karavaev et al., 2001; Blažytė, 2005; Shinha et al., 2007/. Several explanations of this phenomenon are usually presented. Some authors argue, that increase in concentration of chlorophylls and especially carotenoids can be explained as a defence reaction of plants to the oxidative stress caused by heavy metals /Yu et al., 2007/. According to other authors stimulating effect of some heavy metals can be explained as “concentrating effect”, due to stronger inhibition of plant growth and biomass formation than photosynthetic apparatus /Vassilev et al., 1995; Seregin, Ivanov, 2001/.

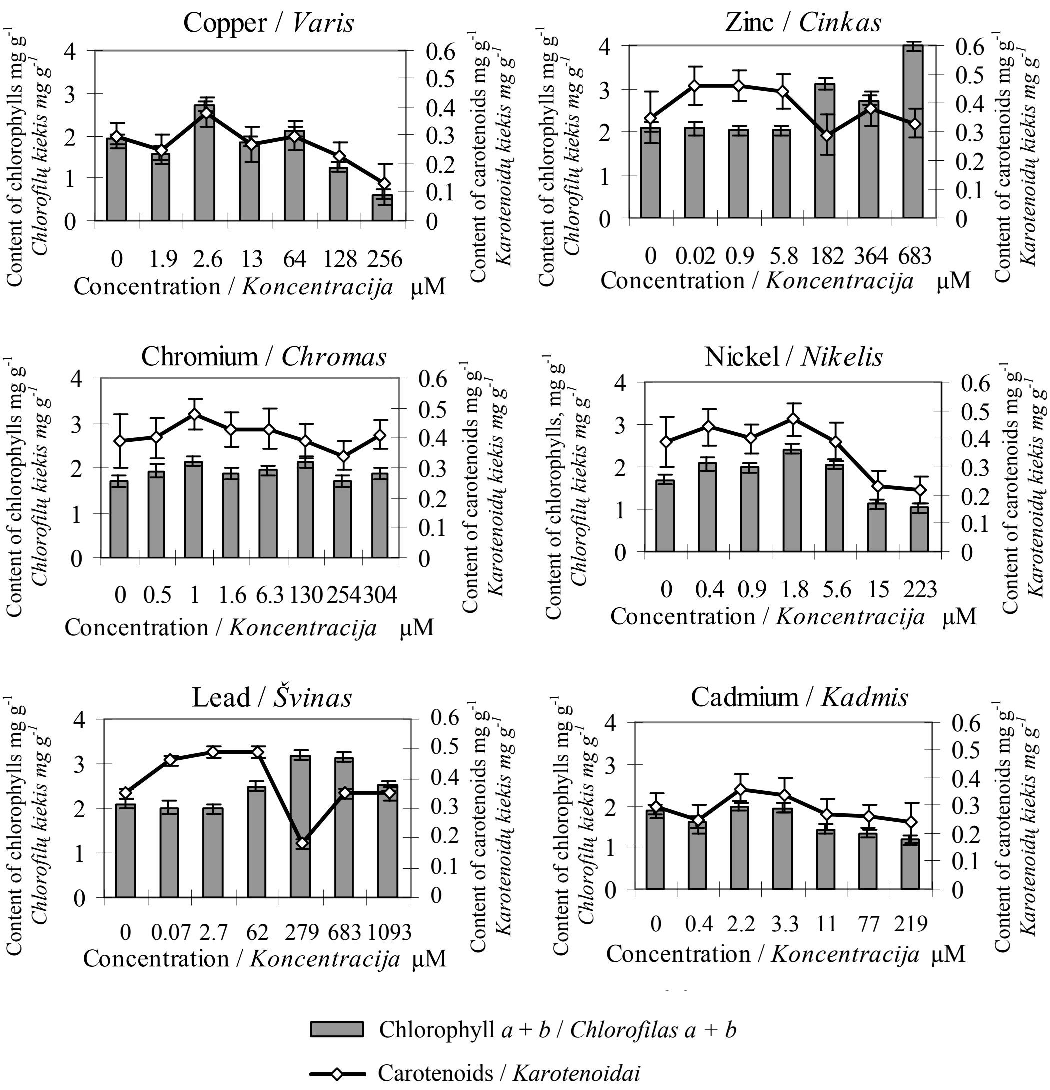

Figure 5. Content of chlorophylls (bars) and carotenoids in the leaves of spring barley *(*cultivar ‘Aura DS’) (mean ± SE) at different concentrations of investigated heavy metals

5 paveikslas. *Chlorofilų (stulpeliai) ir karotenoidų kiekis vasarinių miežių (veislė 'Aura DS’) lapuose (vidurkis ± standartinė paklaida) esant įvairioms tirtų sunkiųjų metalų koncentracijoms*

However, higher concentrations of heavy metals, as a rule, result in an essential decrease in the content of photosynthetic pigments affecting both – their synthesis and degradation /Vassilev et al., 2003/. Inactivation of enzymes involved in the chlorophyll synthesis (δ-aminolaevulinate dehydrogenase, protochlorophyllide reductase) usually is considered as main reason for chlorophyll synthesis inhibition /Seregin, Ivanov, 2001; Shanker et al., 2005/. Chlorophyll degradation is mainly addressed to the increased content of reactive oxygen species, which cause damages of thylakoids membranes /Seregin, Ivanov, 2001/.

Decrease in chlorophyll content in the leaves of spring barley at higher concentrations of investigated heavy metals is very different for different metals (Figure 5). At the metal concentration above 3 μM the most remarkable reduction in chlorophyll content can be noted for the most toxic metals – cadmium and copper, and for nickel. High concentrations of nickel have been shown to decrease chlorophyll content even more remarkably than cadmium /Pahlsson, 1989; Brune et al., 1995/. Ability of Ni ions to cross-endodermal barrier and to enter the stele via the symplast, and fast translocation of nickel from roots to shoots /Gajewska, Sklodowska, 2006; Seregin, Kozhevnikova, 2006/ can be considered as a main reason for such sharp impact of Ni on chlorophyll degradation.

In the case of zinc, the highest investigated concentration did not cause chlorophyll degradation (Figure 5). According to different authors, even large concentrations of zinc stimulate chlorophyll synthesis and increase chlorophyll content /Pahlsson, 1989; Brune et al., 1995/ because Zn is necessary as micronutrient for production of chlorophyll /Deriu et al., 2007/.

Impact of trivalent chromium on chlorophyll is detected to be very weak and content of chlorophyll in the leaves of spring barley almost did not change in the entire range of investigated concentrations (Figure 5). Data of other authors concerning the impact of Cr on the photosynthetic pigments are rather controversial. Some investigators have noticed that Cr is toxic to most higher plants and inactivation of enzymes involved in the chlorophyll biosynthesis contributes to the reduction in chlorophyll content in most plants under chromium stress /Panda, Choudhury, 2005; Shanker et al., 2005/.

However, according to other authors, increased chlorophyll concentrations were detected in plants from Cr contaminated soils /Sinha et al., 2007/. As it was noticed by Yu with coauthors (2007), the positive effect of low and moderate concentrations of Cr on chlorophyll synthesis may be attributed to the increased transport of Mg^{2+}, which is an essential component of the chlorophyll molecule.

Changes in content of carotenoids in the leaves of spring barley along with increase of most investigated heavy metals concentration were rather synchronic with changes of chlorophyll content, and comparatively low concentrations of all investigated metals stimulated synthesis of carotenoids (Figure 5). Some authors reported an increase in content of carotenoids at comparatively high concentrations of metals. Carotenoids, which are important consituents of chloroplast membranes quench singlet oxygen rapidly and can therefore, help to protect chlorophyll and membranes against damage. Carotenoids act as a non-enzymatic antioxidant, and play an important role in protection of chlorophyll under stress condition /Panda, Choudhury, 2005; Brazaitytė et al., 2006; Sinha et al., 2007/. Our investigations on spring barley carotenoids content (Figure 5) showed only small increase of carotenoids content at higher concentrations of lead, chromium and zinc.

Our investigations on accumulation of heavy metals in roots and shoots of spring barley (Table), confirmed the general opinion, that the main site of accumulation of heavy metals is the roots. Nevertheless, there are big differences in translocation of metal ions from roots to shoots between the investigated heavy metals. Because of high mobility of nickel, the smallest difference between concentration in roots and shoots is characteristic namely for this metal and its concentration in shoots was only 20–30% lower of that in roots.

Table. Accumulation of heavy metals in roots and shoots of spring barley (cultivar 'Aura DS')
Lentelė. *Sunkiųjų metalų kaupimasis vasarinių miežių (veislė 'Aura DS') šaknyse ir daiguose*

Heavy metal *Sunkusis metalas*	Weak impact* *Silpnas poveikis** Accumulation / *Akumuliacija* mg g^{-1}		Strong impact** *Stiprus poveikis*** Accumulation / *Akumuliacija* mg g^{-1}	
	roots / *šaknys*	shoots / *daigai*	roots / *šaknys*	shoots / *daigai*
Cu	0.183	0.065	11.19	0.211
Zn	2.819	0.764	31.536	5.969
Cr	0.491	0.027	32.177	3.355
Ni	0.084	0.070	3.103	1.995
Pb	0.394	0.028	221.974	1.298
Cd	1.690	0.177	11.747	2.836

Note / *Pastaba*. * – 20% growth inhibition / *augimo slopinimas*, ** – 60% growth inhibition / *augimo slopinimas*.

Contrary to nickel, very small part of lead (Pb) was translocated from roots to shoots (Table) and it can be considered as a main reason why even at high Pb concentrations content of chlorophyll in the leaves was found to be comparatively high (Figure 5). According to Kamel (2008) lead accumulation in the roots takes places by binding with polysaccharides, complexing with organic acids, binding to the cell walls in the roots, xylem vessels and thus become immobile.

The accumulation of Cd, Cr, Zn and Cu was also considerably (5–20 times) higher in roots than in shoots of spring barley (Table). It supports conclusions of other authors that the roots of the actively growing plant provide a strict barrier that restricts the movement of heavy metals to the aboveground parts of plants /Kovacevic et al., 1999/.

Conclusions

1. Comparative toxicity of heavy metals changes with the increase of impact (concentration) and only cadmium should be considered as the most toxic in the entire range of investigated concentrations. In the case of relatively low concentrations, toxicity of investigated heavy metals decreased in the following order: Cd>Cr>Ni>Cu> Pb>Zn, and in the case of relatively high impact: Cd>Cu> Ni>Cr>Zn>Pb.

2. Characteristic feature for the impact of all investigated metals is more severe impact on the root growth at the comparatively low and medium concentrations, and more severe inhibition of shoots growth at higher concentrations of metals. Shoots / roots biomass ratio as compared to reference treatment (zero concentration) increases along with increase of concentration, however after this ratio reaches maximal value, rather sharp decrease in shoots / roots biomass ratio is characteristic for the impact of all investigated heavy metals.

3. Stimulation of chlorophylls and carotenoids at lower concentrations is characteristic feature for the impact of all investigated metals. For most metals (Cu, Cr, Ni, Cd) maximal content of chlorophylls was registered in the range of concentrations between 1 and 3 μM. The most remarkable reduction in chlorophyll content at higher concentrations is characteristic of most toxic ones – cadmium, copper, and for nickel. Impact of trivalent chromium on chlorophyll was detected to be very weak and content of chlorophyll almost did not change in the entire range of investigated concentrations. In the case of zinc, even the highest investigated concentration (680 μM) did not cause chlorophyll degradation.

4. Investigations on accumulation of heavy metals in roots and shoots of spring barley showed very high mobility of nickel and its concentration in shoots was only 20–30% lower than that in roots. Contrary to nickel, very small part of lead was translocated from roots to shoots and it can be considered as a main reason why even at high Pb concentrations content of chlorophyll in the leaves was found to be comparatively high. The accumulation of Cd, Cr, Zn and Cu was also considerably (5–20 times) higher in roots than in shoots of spring barley.

Received 02 03 2009
Accepted 28 04 2009

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ISSN 1392-3196
Žemdirbystė-Agriculture, t. 96, Nr. 2 (2009), p. 111–124
UDK 633.16“321”:631.416.8:581.132

SUNKIŲJŲ METALŲ POVEIKIS VASARINIAM MIEŽIUI (*Hordeum vulgare* L.)

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Santrauka

Didėjant sunkiųjų metalų koncentracijai, keičiasi jų santykinis toksiškumas, ir iš visų tirtų koncentracijų tik kadmis išlieka toksiškiausias. Esant sąlygiškai mažoms koncentracijoms, vasarinių miežių sunkiųjų metalų tolerancija mažėjo tokia seka: Cd > Cr > Ni > Cu >Pb > Zn, o esant sąlygiškai stipriam poveikiui – Cd > Cu > Ni > Cr > Zn >Pb. Nustatyta, kad, esant palyginti mažoms ir vidutinėms sunkiųjų metalų koncentracijoms, stipresnis poveikis pasireiškė šaknų augimui, o, esant didesnėms sunkiųjų metalų koncentracijoms, nustatytas stipresnis daigų nei šaknų augimo slopinimas. Dėl mažesnio visų tirtų metalų koncentracijų poveikio vasarinių miežių lapuose nustatytas chlorofilų ir karotenoidų kiekio padidėjimas. Dėl daugumos sunkiųjų metalų (Cu, Cr, Ni, Cd) poveikio augimo terpėje maksimalus chlorofilų kiekis nustatytas, metalų koncentracijai esant nuo 1 iki 3 μM.

Reikšminiai žodžiai: vasarinis miežis, sunkieji metalai, koncentracija, biomasė, fotosintetiniai pigmentai, akumuliacija, tolerancija ir slopinimas.