J. Elem. s. 795–810 DOI: 10.5601/jelem.2014.19.3.448

INFLUENCE OF CADMIUM DOSE AND FORM ON THE YIELD OF OAT (*AVENA SATIVA* L.) AND THE METAL DISTRIBUTION IN THE PLANT*

Jiri Tuma[1], Milan Skalicky[2], Lenka Tumova[3], Jan Flidr[1]

[1]Department of Biology
University of Hradec Kralove, Czech Republic
[2]Department of Botany and Plant Physiology
Czech University of Life Sciences Prague, Czech Republic
[3]Faculty of Pharmacy, Hradec Kralove
Charles University in Prague, Czech Republic

Abstract

The influence of two levels of artificial Cd soil contamination (2 and 20 mg Cd kg^{-1} of soil) on the weight of oat plants, chlorophyll content in leaves, rate of photosynthesis, stomatal conductivity and transpiration rate was researched in a pot experiments with *Avena sativa* L. Another objective was to detect the effect of cadmium contamination of soil on the content of cadmium in the dry mass of oat panicles, stems, upper green and bottom yellow leaves and roots. The soil contamination was applied in the forms of nitrate $Cd(NO_3)_2$, chloride $CdCl_2$ and sulphate $CdSO_4^{2-}$.

High correlation was found between the measured levels of photosynthesis rate, stomatal conductivity and transpiration rates, but no correlation occurred between these levels and the cadmium content in leaves. In the variants with Cd contamination, insignificantly higher levels of photosynthesis rates were observed in the measurements than in the zero variant. A 10-fold higher Cd application dose significantly manifested itself by a higher content of Cd in all the analyzed parts of plants, including generative organs. A several-fold higher Cd level was found in the roots than in other parts of the plant, whereas the lowest Cd content was observed in panicles.

However, the results obtained by measuring the cadmium content in stems and green leaves were not significant. In most treatments, a notably higher Cd content was determined in bottom yellow leaves than in upper green leaves. This indicates Cd accumulation in senescent tissues and its difficult reutilization. The highest variance was discovered in treatments with the accompanying SO_4^{2-} anion. While estimating the effect of accompanying anions on the Cd content, significant differences were observed only under the higher level of Cd contamination.

dr Milan Skalicky, Department of Botany and Plant Physiology, Czech University of Life Sciences Prague, Kamycka 129, 165 21 Prague, Czech Republic, e-mail: skalicky@af.czu.cz
* This study was supported by Particular Research Program, University of Hradec Kralove, No. 2119/2011.

The increase in the Cd content in bottom yellow leaves after $CdSO_4$ application was significant when compared with the treatment in which $Cd(NO_3)_2$ was applied and insignificant versus the variant with $CdCl_2$. On the other hand, a higher and more significant content of Cd in phtosynthetically active green leaves was measured in the treatment with $CdCl_2$ than with $Cd(NO_3)_2$.

Key words: cadmium, photosynthesis rate, translocation, interaction, oat.

WPŁYW DAWKI I FORMY KADMU NA PLON I DYSTRYBUCJĘ METALU W OWSIE (*AVENA SATIVA* L.)

Abstrakt

W eksperymentach z *Avena sativa* L. zbadano wpływ 2 poziomów sztucznego zanieczyszczenia gleby Cd (2 i 20 mg Cd kg^{-1} gleby) w postaci $Cd(NO_3)_2$, $CdCl_2$ i $CdSO_4^{2-}$ na masę roślin owsa, zawartość chlorofilu w liściach, tempo fotosyntezy, przewodność szparkową i szybkość parowania, a także na zawartość kadmu w suchej masie wiechy, łodyg, górnych i dolnych zielonych i żółtych liści oraz korzeni. Wysoki poziom korelacji stwierdzono między mierzonymi poziomami intensywności fotosyntezy, przewodności szparkowej i szybkości transpiracji, nie wykazano jednak korelacji między tymi poziomami i zawartością kadmu w liściach. W wariantach z zanieczyszczeniem Cd zaobserwowano nieznacznie wyższy poziom fotosyntezy w pomiarach w porównaniu z wariantem zerowym. W przypadku 10-krotnie większej intensywności stosowania kadmu wykazano istotnie większą zawartość Cd we wszystkich monitorowanych częściach roślin, w tym w organach generatywnych. Kilkakrotnie wyższy poziom Cd niż w innych częściach rośliny stwierdzono w korzeniach, a najmniejszy w wiechach, jednak dane uzyskane podczas pomiaru zawartości kadmu w łodygach i zielonych liściach nie były znaczące. W porównaniu z górnymi liśćmi, zauważalnie większą zawartość Cd w większości poddanych eksperymentowi roślin stwierdzono w dolnych żółtych liściach. Wskazuje to na akumulację Cd w starzejących się tkankach i trudności z jego przetworzeniem. Największą różnicę wykazano w próbkach z anionem towarzyszącym SO_4^{2-}. Podczas ewaluacji wpływu anionów towarzyszących na zawartość Cd istotne różnice wystąpiły jedynie w przypadku wyższego poziomu zanieczyszczenia Cd. Znaczący wzrost zawartości Cd po zastosowaniu $CdSO_4$ zaobserwowano w dolnych żółtych liściach, w porównaniu z próbkami, w których zastosowano $Cd(NO_3)_2$ natomiast nieznaczny – w porównaniu z próbkami, w których użyto $CdCl_2$. Zdecydowanie największą zawartość Cd w zielonych liściach o aktywnej fotosyntezie stwierdzono w roślinach poddanych działaniu $CdCl_2$ w porównaniu z tymi, w przypadku których użyto $Cd(NO_3)_2$.

Słowa kluczowe: kadm, tempo fotosyntezy, translokacja, interakcja, owies.

INTRODUCTION

Plants absorb cadmium from soil mainly in the form of Cd^{2+} cations. The bioavailability of soil-borne Cd can be affected by its total content, the form of chemical bond and other factors, such as the type of soil, CEC (cation exchange capacity), pH, temperature, organic material content, soil redox potential and effects of other ions (Adriano 2001, Clemens et al. 2002, Hasan et al. 2009, Kacalkova et al. 2009). During the cadmium uptake by plant roots, competition occurs between heavy metals and certain mineral nutrients that have similar chemical characteristics (Tlustos et al. 2006).

The kinetics of Cd^{2+} uptake indicates the presence of two transport mechanisms – lower and higher Cd^{2+} activity in the solution (Costa, Morel 1993). Absorption may occur in complex inorganic forms of $CdCl^+$, $CdCl_2$ and $CdSO_4$, or in the form of an organic phytometalophore complex (McLaughlin et al. 1996).

The Cd root uptake in plants mainly proceeds through Ca^{2+}, Fe^{2+} and Zn^{2+} transporters (Clemens 2006). The nonspecific ZIP IRT transporter, which is involved in the ferrum uptake, has been mentioned. By contrast, higher specificity to Fe was expressed in other transporters (Plaza et al. 2007).

The transport of cadmium through plasma membranes of root cells depends on the Cd concentration in a nutrient medium. The saturated character of Cd absorption indicates that the uptake is achieved through a carrier-mediated system (Hart et al. 1998). Duarte et al. (2007) used *Halimione portulacoides* as a citric acid chelator in their experiments. At a dose of 25 μM, both the uptake of cadmium and its translocation increased; at 50 μM, a further increase of Cd uptake by roots was apparent.

In as much as Cd can make use of other transporters, its uptake can be blocked on one side of the cell wall. On the other hand, Cd can block the uptake of other cations. Cadmium uptake from soil increases at a higher Cd content in soil and a low pH value. Such ions as Ca^{2+} and, in some cases, Zn^{2+} can occupy sorption spaces better than Cd^{2+} and displace them in the soil solution. Interactions between Cd and Zn have often been described in the literature (McKenna et al. 1993, Welch 1995).

At high concentration levels, the results of determinations of Cd in a nutrient medium demonstrated a marked reduction in the concentrations of Mg, P, K, Mn, Cu and Zn in plant tissues (Abu-Muriefah 2008, Kikuchi et al. 2009). After experimental Cd contamination of soil, less potassium was determined in grains of oat and in aerial organs and roots of yellow lupine and radish. A contrary effect was also noted, with higher K concentrations in oat straw and roots, as well as in roots of maize (Ciecko et al. 2004). Lower K, Ca and Mg content in tissues with a high Cd concentration in a nutrient medium was noted in cucumbers and tomato plants (Burzynski 1988) and in maize (Walker et al. 1977).

The uptake of Cd may also be influenced by anions. Phosphates may affect Cd uptake by the formation of stable complexes, particularly at higher pH (Bolan et al. 2003). Regarding mobile anions, these are mainly Cl^- and SO_4^{2-}. Results by Zhao et al. (2004) confirmed an increased uptake after the application of KCl, along with K_2SO_4. Chlorides and sulphates created complexes with Cd^{2+} and, in this way, increased the Cd^{2+} uptake by plants. Nitrogen fertilization increased the Cd content in oats, especially at high nitrogen doses (160 kg N ha^{-1}) (Eurola et al. 2003).

Cadmium penetrates through the epidermis into the cortex of roots. It can move within the cortex through the apoplast or symplast. At the endoderm level, cadmium enters the symplast and conductive tissues, where it flows through elements of the xylem. Here, for example, it creates complexes with ligands, organic acids and phytochelatins. But most Cd (60-80%) remains in roots (MENCH et al. 1989). Therefore, the transport of Cd from the roots to aerial parts of a plant is limited (CATALDO et al. 1983). GUO, MARSCHNER (1995) present results indicating that phytochelatins may also be involved in the translocation of Cd to aerial plant organs. This suggests a relationship between higher concentrations of cadmium and Cd-bound phytochelatins in the roots of maize and other plant species.

As mentioned above, roots are the main organ for the accumulation of Cd. Cadmium can accumulate in the vacuoles of root cells and, through the tonoplast, it is transported by several mechanisms, for example the Cd^{2+}/H^{+} antiport or *via* a phytochelatin-Cd transporter (HART et al. 1998), which may be Mg-ATP dependent (SALT, RAUSER 1995). Phytochelatins are obviously also involved in the detoxication of heavy metals through chelation into vacuoles. Zinc phytates were found in cells of the root extension zones, where small vacuoles are located, but Cd bound with phytine acid was not indicated (VANSTEVENINCK et al. 1992). Cadmium ions can create complexes with soluble compounds, such as organic acids. Phytochelatines are degraded in vacuoles by hydrolases, or they are transported back into cytosol (LEOPOLD et al. 1999).

The most common symptoms of the toxic effect of Cd include the browning of root hairs, root tips and necrotic spots on leaves. Thus, Cd influences the structure of leaves and brings about many physiological changes. This is related to the negative effect of Cd on the production of chlorophyll, carotenoids and the activity and reduction of the regeneration of enzymes which participate in the fixation of CO_2 (DE FILIPPIS, ZIEGLER 1993, GOUIA et al. 2003, EKMEKCI et al. 2008). Consequently, a decrease in the gas exchange parameters also occurs, the degree of stomata opening is reduced and the transpiration and photosynthetic rates are decreased (DI TOPPI, GABBRIELLI 1999). At the same time, with these diminishing life parameters, the synthesis of defensive and reparation proteins is increased. This is true, for example, about glutathione, which is connected with the onset of the plant's adaptation to cadmium (HALL 2002).

The average content of cadmium equal 0.26 mg kg^{-1} of soil (median 0.18 mg kg^{-1}) was established, based on the results of monitoring agricultural soils in the Czech Republic. Minimum and maximum values ranged between 0.18 - 4.56 mg kg^{-1} of soil (all in a total solution of aqua regia) (POLAKOVA et al. 2010). According to the Regulation of the Ministry of Environment of the Czech Republic, number 13/1994 Coll., the maximum permissible amount of cadmium in soils is 1 mg kg^{-1}.

The goal of this study was to study the translocation of cadmium to the aerial parts of oat plants and its impact on selected physiological parameters.

Cadmium was applied in the nitrate, chloride and sulphate forms, in dosages of 2 and 20 mg kg^{-1} of soil. The lower dose of cadmium is double the maximum permissible content in soil. The higher dose was established based on a preliminary experiment, during which notable visual symptoms of phytotoxicity in oat plants were absent. Cadmium content was also evaluated in individual parts of oat plants: roots, stem, lower yellowing leaves, upper photosynthetically active leaves and panicles. Differences in the cadmium content of yellowing leaves and the green, photosynthetically active leaves indicates a possibility of the reutilization of Cd.

Another objective was to investigate the phytotoxicity of Cd, particularly its impact on yield, chlorophyll content and the physiological characteristics: photosynthetic rates (P_N), transpiration rates (E) and gas conductivity (g_s).

MATERIAL AND METHODS

The research was carried out as a pot experiment in an outdoor environment. The experiment took place in Černožice (a region of Hradec Kralove, the Czech Republic), situated at the altitude of 255 m above sea level. The experimental crop was the common oat (*Avena sativa* L.), Atego variety. Oat was grown in alluvial soil, which was clay loamy in texture. The agricultural and chemical characteristics of the soil medium were as follows: pH/KCl – 6.20; content of available P 30.0 mg kg^{-1}, K 382.2 mg kg^{-1}, Mg 166.2 mg kg^{-1}, Ca 6700.0 mg kg^{-1} (in the Mehlich III. leach), CEC 211.5 mmol kg^{-1}. The total heavy metal content in *aqua regia* was Cd <0.5; Ni 16.1; As 9.9; Cr 30.6; Pb 42.8; Hg 0.179; Zn 182.0 mg kg^{-1}. Thus, the soil was characterized by a high content of potassium, at the K/Mg ratio 2.29, and a low phosphorus content. The high potassium content may influence the absorption of Cd and other cations. On the other hand, the effect of accompanying anions on Cd absorption may be more obvious. The soil placed in pots for the trials was air-dried, homogenized and sieved through a 10-mm stainless-steel sieve.

The experimental pots were 10-L plastic pots with perforated bottoms (pot dimensions: height 0.28 m; top diameter 0.25 m; bottom diameter 0.21 m). Each pot was placed in a polyethylene bowl, with a diameter of 26 mm m and a depth of 40 mm. A 10-kg batch of air-dried and sieved (≤10 mm) soil was put into each 10-L plastic pot. Seven variants of cadmium treatment were started in the experiment, with three replications. The scheme of the experiment and doses of chemicals per experimental pot are given in Table 1. Except for the control variant, the nitrogen dose in all variants was levelled by means of NH_4NO_3. In order to provide a nutrient supply, a weighed amount of chemicals was dissolved in 300 ml of distilled water (1 day) and the solution was evenly applied to the soil in the experimental pots. Phosphorus or potassium nutrition was not performed.

Subsequently, thirty grains of oat (*Avena sativa* L.) were sown into each pot in May. Normally developed plants were singled out in June, i.e., twenty

Table 1

Scheme of the experiment

Variant No.	Concentration Cd mg kg^{-1}/ accompanying anion	Chemicals (g^{-1} / pot)			
		$Cd(NO_3)_2.4H_2O$	$CdCl_2.2.5H_2O$	$CdSO_4.8H_2O$	NH_4NO_3
I.	control	-	-	-	-
II.	Cd 2 / NO_3^-	0.055	-	-	1.130
III.	Cd 20 / NO_3^-	0.549	-	-	1.001
IV.	Cd 2 / Cl^-	-	0.041	-	1.144
V.	Cd 20 / Cl^-	-	0.405	-	1.144
VI.	Cd 2 / SO_4^{2-}	-	-	0.046	1.144
VII.	Cd 20 / SO_4^{2-}	-	-	0.456	1.144

-five best-developed plants remained in each pot. The pots were placed outdoors, on an experimental plot of land. Individual pots were spaced at 0.15 m from each other and their position within the group at the site was regularly changed. Plants were grown under standard light and temperature conditions. Soil moisture was kept at ~60% of WHC by watering with distilled water. The average daily temperature levels for individual ten-day periods and months at the Hradec Kralove site, located approximately 4 km away, are given in Table 2.

Plants were harvested on 5 of August 2009, at the phase of milky ripeness (75 DC). Twenty whole plants were harvested from each experimental pot and their panicles, stems, upper green leaves and lower yellowing leaves were collected separately. The individual samples were placed into paper bags and immediately dried in a drying apparatus (Venticell 707; Ilabo, Borsovska, Kyjov, CZ) at a temperature of 65°C until they reached constant mass (*ca* 48 hours). The experimental pots were turned upside down and the roots of the harvested plants were also taken. The roots were washed three times in distilled water and also dried at 65°C. The dried parts of the plants were then ground in a laboratory mill into fine powder.

Table 2

Average daily temperatures in 2009 at the Hradec Kralove (the Czech Republic) site in °C

Month	1st decade (mean)	2nd decade (mean)	3rd decade (mean)
May	-	19.0	13.8
June	14.4	19.4	15.2
July	18.6	17.6	21.0
August	16.6	-	-

Source: Czech Hydrometeorological Institute

The measurement of physiological characteristics, i.e. photosynthesis rate (P_N), transpiration rate (E) and gas conductance (g_s), took place at the stage of 71 DC, by means of an infra-red gas analyser LCpro+ (ADC Bio-Scientific Ltd., UK). The chlorophyll content was measured by a chlorophyll -meter CCM 200 (OptiScience, USA).

Mineralization of the dried and ground samples was carried out by the dry combustion method in a combustion muffle furnace (CALOR SN 305; MIWY, Lipnik n. Becvou, CZ). A portion of each sample in a quartz cup was 0.2-1 g. The maximum incineration temperature was 450°C. While it was still warm after combustion, the ash was dissolved in a 5% solution of nitric acid on a heating plate, qualitatively transferred into a calibrated test-tube and replenished with de-mineralized water up to the mark line. The actual determination of the cadmium content was carried out by atomic absorption spectrometry (Atomic Absorption Spectrometer SOLAAR M5; Thermo Electron Spectroscopy Ltd., Solaar House, Cambridge, UK). The identifiable limit of atom absorption of cadmium was 0.050 mg l^{-1}. A mixed-model procedure, with a repeated statement for variants, was used to analyse the content of cadmium in the oat plants. Data from each plant part was tested separately. Analysis of variance (the Wilks' lambda, $P < 0.05$) was used to determine significant differences. All statistical tests presented in this study were performed using a Statistica 9.1 (StatSoft Inc., Tulsa, OK, U.S.A.) software package.

RESULTS AND DISCUSSION

During the experiment, the growth, development and health of the plants were recorded. No incidence of diseases or pests was identified and no symptoms of deficiency or damage resulting from higher doses of cadmium were observed in any of the groups. In groups II - VII, no statistically significant differences in the weight of dry matter of aerial parts of the plants were observed (Table 3). Any larger decrease in the plant weight in the variants with Cd contamination may have also been partly prevented by the dose of nitrogen. No significant decrease of the chlorophyll content was observed and no correlation between the Cd content and chlorophyll content in leaves was identified. In the experiments carried out by Lagriffoul et al. (1998) and Cheng et al. (2002), a decrease in the chlorophyll content was

Table 3

Weight of the dry matter (g)/pot of the aerial parts of oat plants

Variants	I	II	III	IV	V	VI	VII
Mean	175.39	163.44	172.95	160.96	167.1233	157.3567	155.21
SD (n = 3)	5.99	5.99	5.991	5.99	5.99	5.99	5.99

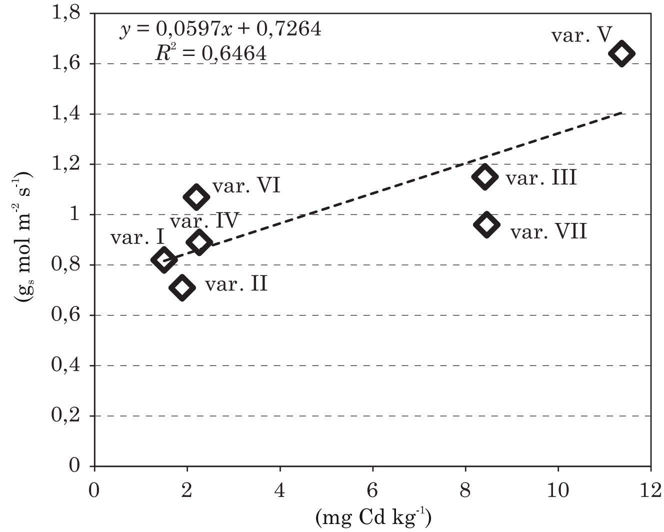

Fig. 1. Relationship between Cd content in green leaves (axis *x*) and gas conductance (g_s, axis *y*)

observed only at the highest levels of Cd contamination. Figure 1 shows the relation between the Cd content in green leaves and gas conductance (g_s).

In the variants with the Cd nutrition, insignificantly higher levels of photosynthesis rates were identified in the measurements as compared with the control variant. The initial response of plants to stress can be the intensification of metabolic processes. Our results imply that oat is fairly tolerant and adaptable to stresses induced by higher Cd^{2+} ion content. For comparison, VASSILEV et al. (2004) reported the following findings for barley: the maximal shoot Cd concentration of 41 ± 8 mg Cd kg^{-1} DW without any visual toxicity symptoms on the shoots occurred at 28 mg Cd kg^{-1} of sand. However, at the highest contamination level (42 mg Cd kg^{-1} of sand), reduced leaf gas exchange, photosynthetic pigments content and electron transport activity, but not altered lipid peroxidation status of thylakoids were found.

Table 4 gives data on Cd content in particular treatments of the experiment. Statistically significant differences in the content of Cd, at $p \geq 0.05$, are evident in the individual parts of the oat plant, i.e. panicles, stems, upper green leaves, lower yellow leaves and roots. Significantly, as is seen in Table 4, the highest content of cadmium was observed in roots. A higher content of Cd in roots than in the other parts of plant was indicated in all the treatments where Cd was applied (II-VII.).

These results are confirmed by numerous sources in the literature, which document high content of Cd in roots relative to the comparatively simple uptake from the soil environment and difficult translocation of Cd from roots to aerial parts of a plant. OBATA, UMEBAYASHI (1993) mention that over 50% of cadmium intake remains in roots. The same results (60-80 % in roots) were

Table 4

Changes in the cadmium content (mg kg^{-1}) in all the analyzed parts of oat plants relative to different variants of cadmium nutrition and accompanying anions nutrition

Specification	Var. I		Var. II		Var. III		Var. IV		Var. V		Var. VI		Var. VII	
	av.	SD	av.	SD	av.	SD	av.	SD	av.	SD	av.	SD	av.	SD
Panicles	0.12^{a}	0.01	$1,59^{a}$	0.28	5.88^{a}	0.50	2.31^{a}	0.46	5.98^{a}	0.20	2.47^{a}	0.65	5.85^{a}	0.68
Stalks	1.56^{b}	0.20	3.68^{a}	0.43	18.17^{a}	1.53	3.72^{a}	1.17	19.37^{ab}	1.76	3.98^{ab}	0.54	17.37^{a}	0.81
Green leaves	1.50^{b}	0.25	1.89^{a}	0.14	8.42^{a}	1.11	2.26^{a}	0.58	11.37^{ab}	1.60	2.19^{a}	0.43	8.47^{a}	1.04
Yellow leaves	1.37^{b}	0.30	8.34^{a}	1.65	44.63^{b}	5.25	9.93^{b}	0.12	55.97^{b}	5.64	11.63^{b}	1.18	62.70^{b}	10.62
Roots	1.82^{b}	0.26	31.4^{b}	3.95	194.67^{c}	20.0	40.90^{c}	3.79	235.33^{c}	23.38	42.20^{c}	4.05	219.33^{c}	18.41

NB: Statistically significant difference between parts of plant *a*, *b*, *c*, *d* - $P < 0.05$; av. = average; SD = standard deviation further documented by Cataldo et al. (1983) or Mench et al. (1989). By contrast, the lowest content of Cd was indicated in panicles, which did not significantly vary from the content of Cd in stems and green leaves. It is generally understood that the concentration of Cd in plants decreases in the sequence of root> leaves> fruit> seeds (Sharma et al. 2006).

A significantly higher content of Cd in lower yellowed leaves than in green leaves was determined in most of the treatments, except treatments I, II and V. That suggests the accumulation of Cd in senescent tissues and its difficult reutilization. The biggest difference was detected in the treatment with accompanying SO_4^{2-} (treatment VII). Higher doses of sulphate could be predicted to cause higher accumulation Cd in yellow leaves and lower reutilization in other parts of the plant. Our earlier experiments, in which the translocation of zinc (Tuma et al. 2008) and nickel (Tuma et al. 2010) were examined, provided similar results.

These findings may confirm the important role of sulphur in the synthesis of phytochelatins, with which cadmium creates complexes. These complexes, of low and medium molecular weight, are bound to unstable acid sulphides (S^{2-}), which in turn are stabilized by complexes. These complexes obviously play an important role in the detoxication of cadmium (Nocito et al. 2007, Khan et al. 2008), after which they are transported into vacuoles, where they are dissociated and Cd creates complexes with acids (Di Toppi, Gabbrielli 1999).

Statistical significances between individual treatment variants are shown in Figure 2, in contrast to Table 4. Evidently, a 10-fold higher supply of cadmium (III, V and VII) was significantly linked to higher Cd content in all parts of plants, including generative organs, in which (see above) the lowest content of Cd was detected. This is related to the simple uptake of Cd through the root system. Thus, the amount of Cd absorbed by plants depends on its concentration in the nutrient medium (Holm et al. 1995). Most of the Cd which remains accumulated in roots is transported into all aerial parts of the plant when the degree of soil contamination increases.

Page, Feller (2005) suggested that, in this case, Cd was released more slowly from the roots to the leaves and subsequently redistributed only at trace levels in the phloem to the youngest leaves. Hart et al. (1998) mention that results indicate that excess Cd accumulation in durum wheat grain is not correlated with the seedling-root influx rates or root-to-shoot translocation, but may be related to phloem-mediated Cd transport to the grain.

The influence of the accompanying mobile anions (NO_3^-, Cl^-, SO_4^{2-}) on the content of Cd in roots was not significant. A significant increase in the content of Cd appeared in leaves, but only at lager cadmium loading.

A significant increase in the content of Cd in bottom yellow leaves was indicated in treatment VII, after the application of $CdSO_4$, relative to treatment III ($Cd(NO_3)_2$); the said increase was insignificant compared with treatment VI ($CdCl_2$). On the other hand, the highest cadmium content in photo-

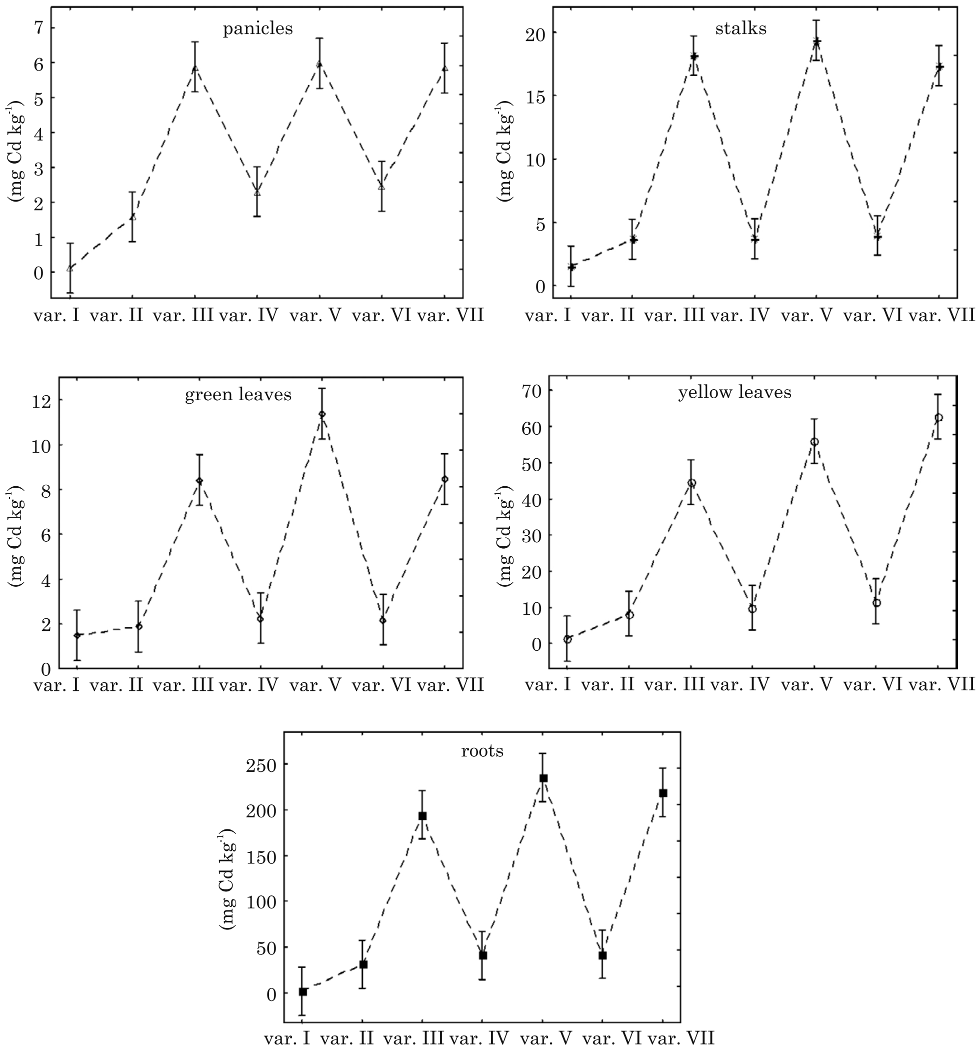

Fig. 2. Changes in the cadmium content according to the treatment variants. Error bars represent means ± SD (n = 3)

synthetically active green leaves appeared in treatment VI ($CdCl_2$). Herren, Feller (1997) state that the long distance translocation of cadmium may depend on the availability of other elements. McLaughlin et al. (1996) mention that sulphate had just a limited effect on the availability Cd for chard, especially when compared with Cl^-.

These results have been contrasted with some earlier work on the effect of Cl^- salinity on Cd availability in Swiss chard. Possible mechanisms explaining a weaker effect of SO_4^{2-} compared to Cl^- on Cd^{2+} availability have been proposed. Experiments by Zhao et al. (2004) showed that Cl^- and SO_4^{2-} anions increased Cd uptake by plants, which can be interpreted as Cl^- and SO_4^{2-} readily complexing with Cd^{2+}, thereby increasing the bioavailability of Cd^{2+} in soils. The effect of potassium itself on the plant uptake of Cd was also observed.

In our experiments, cadmium behaved somewhat differently than nickel (Tuma et al. 2010) and zinc (Tuma et al. 2008). Nickel was much more easily transported through the plant. In the treatments in which $NiSO_4$ was applied in higher doses, a significant increase in Ni content was observed in all the analyzed parts of plants, including panicles. Roots were the only exception. Zinc is less mobile in plants than nickel. Nevertheless, an increase in Zn content was found in the treatments with $ZnSO_4$, compared to treatments with the application of Zn $(NO_3)_2$. The effect was significant in stems at both lower and higher nutrition, and in upper green and bottom yellow leaves of oat plants at higher nutrition. Obviously, the mobility of Cd through the plant is substantially lower than that of Ni and lower than the mobility of Zn, so the influence of the accompanying mobile anions on the translocation of Cd was less significant (Zeller, Feller 1999, Zhu et al. 2003, Yuruk, Bozkurt 2006, Gondek 2010).

CONCLUSIONS

In all the variants with Cd contamination, the weight of aerial parts of oat plants decreased only insignificantly. No significant decrease in the chlorophyll content in leaves was observed. Based on the measured photosynthesis rate, stomatal conductivity and transpiration rate, no correlation between these characteristics and the cadmium content in leaves was proven. Oat developed fairly good tolerance to stress induced by a higher cocentration of Cd^{2+} ions.

A 10-fold higher Cd application dose manifested itself significantly by a higher content of Cd in all the analyzed parts of plants, including generative organs. A several-fold higher Cd content was determined in roots than in the other parts of the plant, whereas the lowest content of Cd was observed in panicles. However, the results obtained by measuring the content of cadmium in stems and green leaves were not significant. A notably higher content of Cd in most treatments was determined in bottom yellow leaves than in upper green leaves. This indicates the accumulation of Cd in senescent tissues and difficulties in its reutilization. The biggest difference was discovered in the treatments with the accompanying anion SO_4^{2-}. A higher sulphate application level, along with Cd, could lead to higher accumulation and deposition of Cd in yellow leaves, and to lower reutilization of the metal in other parts of the plant. The assessment of the effects of accompanying anions on Cd content revealed significant differences only at higher levels of

Cd contamination. An increase in the Cd content after $CdSO_4$ application was determined in bottom yellow leaves. It was significant versus the treatment in which $Cd(NO_3)_2$ was applied and insignificant compared with variants in which $CdCl_2$ was applied.

On the other hand, significantly the highest content of Cd in green leaves with active photosynthesis was measured in the treatment with $CdCl_2$, compared to the treatment with $Cd(NO_3)_2$. The above results were certainly connected with the lower mobility of Cd through the plant, as compared with Ni and Zn.

REFERENCES

Abu-Muriefah S.S., 2008. *Growth parameters and elemental status of cucumber (Cucumis sativus) seedlings in response to cadmium accumulation.* Int. J. Agri. Biol., 10: 261-266.

Adriano D.C. 2001. *Trace elements in terrestrial environments.* Springer-Verlag, New York, 866 p.

Bolan N.S., Adriano D.C., Duraisamy P., Mani A. 2003. *Immobilization and phytoavailability of cadmium in variable charge soils.* III. *Effect of biosolid compost addition.* Plant Soil, 256: 231-241.

Burzynski M. 1988. *The uptake and accumulation of phosphorus and nitrates and the activity of nitrate reductase in cucumber seedlings treated with $PbCl_2$ or $CdCl_2$.* Acta Soc. Bot. Pol., 57: 349-359.

Cataldo D.A., Garland T.R., Wildung R.E. 1983. *Cadmium uptake kinetics in intact soybean plants.* Plant Physiol., 73: 844-848.

Cheng S., Ren F., Grosse W., Wu Z. 2002. *Effects of cadmium on chlorophyll content, photochemical efficiency, and photosynthetic intensity of Canna indica Linn.* Int. J. Phytoremediat., 4: 239-246.

Ciecko Z., Kalembasa S., Wyszkowski M., Rolka E. 2004. *Effect of soil contamination by cadmium on potassium uptake by plants.* Pol. J. Environ. Stud., 13: 333-337.

Clemens S. 2006. *Evolution and function of phytochelatin synthases.* J. Plant Physiol., 163: 319-332.

Clemens S., Palmgren M.G., Kramer U. 2002. *A long way ahead: understanding and engineering plant metal accumulation.* Trends Plant Sci., 7: 309-315.

Costa G., Morel J.L., 1993. *Cadmium uptake by lupinus-albus (L) – cadmium excretion, a possible mechanism of cadmium tolerance.* Plant Nutr., 16: 1921-1929.

De Filippis L.F., Ziegler H. 1993. *Effect of sublethal concentrations of zinc, cadmium and mercury on the photosynthetic carbon reduction cycle of Euglena.* J. Plant Physiol., 142: 167-172.

Di Toppi L.S., Gabbrielli R. 1999. *Response to cadmium in higher plants.* Environ. Exp. Bot., 41: 105-130.

Duarte B., Delgado M., Cacador I. 2007. *The role of citric acid in cadmium and nickel uptake and translocation, in Halimione portulacoides.* Chemosphere, 69: 836-840.

Ekmekci Y., Tanyolac D., Ayhan B., 2008. *Effects of cadmium on antioxidant enzyme and photosynthetic activities in leaves of two maize cultivars.* J. Plant Physiol., 165: 600-611.

Eurola M., Hietaniemi V., Kontturi M., Tuuri H., Pihlava J.M., Saastamoinen M., Rantanen O., Kangas A., Niskanen M. 2003. *Cadmium contents of oats (Avena sativa* L.*) in official variety, organic cultivation, and nitrogen fertilization trials during 1997-1999.* J. Agric. Food Chem., 51: 2608-2614.

Gondek K. 2010. *Zinc and cadmium accumulation in maize (Zea mays* L.*) and the concentra-*

tion of mobile forms of these metals in soil after application of farmyard manure and sewage sludge. J. Elem., 15: 639-652.

Gouia H., Suzuki A., Brulfert J., Ghorbal M.H. 2003. *Effects of cadmium on the coordination of nitrogen and carbon metabolism in bean seedlings.* J. Plant Physiol., 160: 367-376.

Guo Y., Marschner H. 1995. *Uptake, distribution and binding of cadmium and nickel in different plant species.* J. Plant Nutr., 18: 2691-2706.

Hall J.L. 2002. *Cellular mechanisms for heavy metal detoxification and tolerance.* J. Exp. Bot., 53: 1-11.

Hart J.J., Welch R.M., Norvell W.A., Sullivan L.A., Kochian L.V. 1998. *Characterization of cadmium binding, uptake, and translocation in intact seedlings of bread and durum wheat cultivars.* Plant Physiol., 116: 1413-1420.

Hasan S.A., Fariduddin Q., Ali B., Hayat S., Ahmad A. 2009. *Cadmium: toxicity and tolerance in plants.* J. Environ. Biol., 30: 165-174.

Herren T., Feller U. 1997. *Transport of cadmium via xylem and phloem in maturing wheat shoots: Comparison with the translocation of zinc, strontium and rubidium.* Ann. Bot., 80: 623-628.

Holm P.E., Christensen T.H., Tjell J.C., McGrath S.P. 1995. *Speciation of cadmium and zinc with application to soil solutions.* J. Environ. Qual., 24: 183-190.

Kacalkova L., Tlustos P., Szakova J. 2009. *Phytoextraction of cadmium, copper, zinc and mercury by selected plants.* Plant Soil Environ., 55: 295-304.

Khan N.A., Singh S., Umar S. 2008. *Sulfur assimilation and abiotic stress in plants.* Springer Verlag, Heidelberg.

Kikuchi T., Okazaki M., Motobayashi T. 2009. *Suppressive effect of magnesium oxide materials on cadmium accumulation in winter wheat grain cultivated in a cadmium-contaminated paddy field under annual rice-wheat rotational cultivation.* J. Hazard. Mater., 168: 89-93.

Lagriffoul A., Mocquot B., Mench M., Vangronsveld J. 1998. *Cadmium toxicity effects on growth, mineral and chlorophyll contents, and activities of stress related enzymes in young maize plants (Zea mays* L.*).* Plant Soil, 200: 241-250.

Leopold I., Gunther D., Schmidt J., Neumann D. 1999. *Phytochelatins and heavy metal tolerance.* Phytochemistry, 50: 1323-1328.

McKenna I.M., Chaney R.L., Williams F.M. 1993. *The effects of cadmium and zinc interactions on the accumulation and tissue distribution of zinc and cadmium in lettuce and spinach.* Environ. Pollut., 79: 113-120.

McLaughlin M.J., Tiller K.G., Naidu R., Stevens D.P. 1996. *Review: The behaviour and environmental impact of contaminants in fertilizers.* Aust. J. Soil Res., 34: 1-54.

Mench M., Tancogne J., Gomez A., Juste C. 1989. *Cadmium bioavailability to Nicotiana-tabacum-*L.*, Nicotiana-rustica* L.*, and Zea-mays-*L. *grown in soil amended or not amended with cadmium nitrate.* Biol. Fertil. Soils, 8: 48-53.

Nocito F.F., Lancilli C., Giacomini B., Sacchi G.A. 2007. *Sulfur metabolism and cadmium stress in higher plants.* Plant Stress, 1: 142-156.

Obata H., Umebayashi M. 1993. *Production of sh compounds in higher-plants of different tolerance to Cd.* Plant Soil, 156: 533-536.

Page V., Feller U. 2005. *Selective transport of zinc, manganese, nickel, cobalt and cadmium in the root system and transfer to the leaves in young wheat plants.* Ann. Bot., 96: 425-434.

Plaza S., Tearall S.K.L., Zhao F-J., Buchner P., McGrath S.P., Hawkesford M.J. 2007. *Expression and functional analysis of metal transporter genes in two contrasting ecotypes of the hyperaccumulator Thlaspi caerulescens.* J. Exp. Bot., 58: 1717-1728.

Polakova S., Kubik L., Nemec P., Maly S. 2010. *Bazální monitoring zemědělských půd 1992-2007.* UKZUZ, Brno, 94 p. (in Czech)

SALT D.E., RAUSER W.E. 1995. *Mgatp-dependent transport of phytochelatins across the tonoplast of oat roots*. Plant Physiol., 107: 1293-1301.

SHARMA M., GAUTAM K.H., HANDIQUE A.K. 2006. *Toxic heavy metal stress in paddy: Metalaccumulation profile and development of a novel stress protein in seed*. Ind. J. Plant Physiol., 11: 227-233.

TLUSTOS P., SZAKOVA J., KORINEK K., PAVLIKOVA D., HANC A., BALIK J. 2006. *The effect of liming on cadmium, lead, and zinc uptake reduction by spring wheat grown in contaminated soil*. Plant Soil Environ., 52: 16-24.

TUMA J., SKALICKY M., TUMOVA L., MALIR F., MATEJSKOVA D. 2008. *The translocation of zinc in Avena sativa* L. *depending on fertilisation with zinc and mobile anions*. Cereal Res. Commun., 36: 1083-1086.

TUMA J., SKALICKY M., TUMOVA L., SAFRANKOVA M. 2010. *Translocation of nickel in Avena sativa: The effect of accompanying mobile anions*. Fresn. Environ. Bull., 19: 2974-2980.

VANSTEVENINCK R.F.M., VANSTEVENINCK M.E., FERNANDO D.R. 1992. *Heavy-metal (Zn, Cd) tolerance in selected clones of duck weed (Lemna-minor)*. Plant Soil, 146: 271-280.

VASSILEV A., LIDON F.C., RAMALHO J.C., MATOS M.D., BAREIRO M.G. 2004. *Shoot cadmium accumulation and photosynthetic performance of barley plants exposed to high cadmium treatments*. J. Plant Nutr., 27: 775-795.

WALKER W.M., MILLER J.E., HASSETT J.J. 1977. *Effect of lead and cadmium upon calcium, magnesium, potassium, and phosphorus concentration in young corn plants*. Soil Sci., 124: 145-151.

WELCH R.M. 1995. *Micronutrient nutrition of plants*. Crit. Rev. Plant Sci., 14: 49-82.

YURUK A., BOZKURT M.A., 2006. *Heavy metal accumulation in different organs of plants grown under high sewage sludge doses*. Fresen. Environ. Bull., 15: 107-112.

ZELLER S., FELLER U. 1999. *Long-distance transport of cobalt and nickel in maturing wheat*. Eur. J. Agron., 10: 91-98.

ZHAO Z.Q., ZHU Y.G., LI H.Y., SMITH S.E., SMITH F.A. 2004. *Effects of forms and rates of potassium fertilizers on cadmium uptake by two cultivars of spring wheat (Triticum aestivum* L.*)*. Environ. Int., 29: 973-978.

ZHU Y.G., ZHAO Z.Q., LI H.Y., SMITH S.E., SMITH F.A. 2003. *Effect of zinc-cadmium interactions on the uptake of zinc and cadmium by winter wheat (Triticum aestivum) grown in pot culture*. Bull. Environ. Contam. Toxicol., 71: 1289-1296.