The effect of elevated cadmium content in soil on the uptake of nitrogen by plants

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ABSTRACT

The aim of this study was to determine the effect of cadmium (10, 20, 30 and 40 mg Cd/kg of soil) contamination in soil with the application of different substances (compost, brown coal, lime and bentonite) on the intake of nitrogen by some plants. The correlations between the nitrogen content in the plants and the cadmium concentration in the soil, as well as the plant yield and the content of micro- and macroelements in the plants were determined. Plant species and cadmium dose determined the effects of soil contamination with cadmium on the content of nitrogen. Large doses of cadmium caused an increase in nitrogen content in the *Avena sativa* straw and roots and in the *Zea mays* roots. Soil contamination with cadmium resulted in a decrease of nitrogen content in the *Avena sativa* grain, in above-ground parts and roots of the *Lupinus luteus*, in the above-ground parts of the *Zea mays* and in the above-ground parts and roots of *Phacelia tanacaetifolia*. Among the experimental different substances, the application of bentonite had the strongest and a usually negative effect on the nitrogen content in plants. The greatest effect of bentonite was on *Avena sativa* grain, above-ground parts *Zea mays* and *Lupinus luteus* and *Phacelia tanacaetifolia*. The content of nitrogen in the plants was generally positively correlated with the content of the macroelements and some of the microelements, regardless of the substances added to the soil.

Keywords: cadmium soil contamination; compost; brown coal; lime; bentonite; plant yield; nitrogen content; macro- and microelement content

Extensive industrial production causes the emission of a wide variety of contaminants to the environment. Heavy metals are one of the most dangerous of these contaminants. They accumulate in the soil, ground, and bottom sediment of seas and oceans and have a long-term effect on the biotic factors of the environment. Soil contaminated by heavy metals reduced the quality of the cultivated plants, which often limits and sometimes disqualifies the soil from the production of quality food products or animal feed (Frossard 1993, Obata and Umebayashi 1997, Kabata-Pendias and Pendias 2001). When analyzing the quality of plants harvested from fields contaminated with heavy metals, an examination for heavy metals content is carried out and the concentrations of other chemical elements are omitted. Cadmium is a very mobile heavy metal in the environment. It is easily taken up by plants and transferred to their particular organs (Kabata-Pendias and Pendias 2001). Cadmium can have a destructive effect on the cell membrane plasma in the roots of sensitive plants, limiting the uptake of water and macro-elements. This effect is determined by the plant species. Obata et al. (1996) claimed that the activity of H^+-ATPase in the cell membrane plasma of the roots of papilionaceous plants is significantly lower than in the cucurbitaceous plants, which are quite tolerant to cadmium in the soil. H^+-ATPase also participates in the uptake of elements by roots (Serrano 1989). Cadmium has an effect on the components of phospholipides and the cell membrane proteins, other than ATPase, by being toxic to the uptake of elements, and consequently, on root development (Obata and Umebayashi 1997). Research of cadmium effects on the macro-element content in plants is relatively scarce and the mechanism of its effect on uptake of macro-elements has not yet been sufficiently explained.

The aim of the experiment was to determine the effect of cadmium on the nitrogen uptake by plants. Moreover, the correlations between the nitrogen content in plants and the cadmium concentration in soil, plant yield and the content of macro- and microelements in the plants were determined.

MATERIAL AND METHODS

To investigate this mechanism, five pot experiments were carried out in a vegetation hall.

Table 1. Some physicochemical properties of the soils used in the experiments

Plant	Type (kind) of soil	pH_{KCl}	Hh [mmol(+)/kg of soil]	Cd content (mg/kg)	Content of available forms (mg/kg)			
					C	P	K	Mg
Avena sativa L. *Zea mays* L. *Lupinus luteus* L.	Eutric Cambisol (light loamy sand)	4.50	32.6	0.17	5.30	10.77	11.10	3.51
Raphanus sativus L.	Eutric Cambisol (light loamy sand)	4.07	27.4	0.07	5.62	12.60	14.73	2.93
Phacelia tanacaetifolia Bench.	Eutric Cambisol (light loamy sand)	5.91	19.5	0.00	5.01	11.92	13.80	3.44

C – organic carbon content, Hh – hydrolytic acidity

Increasing cadmium doses were applied in the experiment: 10, 20, 30 and 40 mg Cd/kg of soil as $CdCl_2$. The effect of artificial soil contamination with cadmium on *Avena sativa* L., *Zea mays* L., *Lupinus luteus* L., *Raphanus sativus* L. and *Phacelia tanacaetifolia* Bentch. was observed. The following supplements to the soil were used to immobilize cadmium: in the cultivation of *Avena sativa*: compost, brown coal and lime and in the cultivation of the remaining plants: the same as for *Avena sativa* plus bentonite. The experiment was carried out on acidic Eutric Cambisol soil with a granulometric composition of light loamy sand in polyethylene pots (Table 1). Before the experiment was established, the soil was mixed with mineral fertilisers and with cadmium chloride and different substances where required. The post was filled with 9 or 10 kg of soil. The compost and brown coal were added in the amount of 4%, bentonite in the amount of 2% of the soil mass and lime was added in an amount corresponding to 1 hydrolytic acidity (experiment with: *Avena sativa* – 1.51 g Ca/kg, *Zea mays* and *Lupinus luteus* – 0.91 g Ca/kg, *Raphanus sativus* – 1.15 g Ca/kg and *Phacelia tanacaetifolia* – 0.82 g Ca/kg of soil). Some physicochemical properties applied substances are in Table 2. In all pots, the soil was enriched with the following amounts of macro-elements necessary for the proper growth and development of plants (quantities expressed in mg/kg of soil): N – 100 (50 – in experiment with *Lupinus luteus*) as $CO(NH_2)_2$, P – 43.6 as $Ca(H_2PO_4)_2 + H_3PO_4 + CaSO_4$, K – 96 as KCl. For the whole vegetation period, the soil moisture was maintained at a fixed level of 60% of the capillary water holding capacity. The plants harvest was realized in the following phases of vegetation: *Avena sativa* – in phase of full maturity, *Lupinus luteus* – in flowering phase, *Zea mays* – after cobs formation, *Raphanus sativus* – in phase of full maturity and *Phacelia tanacaetifolia* – in flowering phase.

During the harvest, samples of the above-ground parts and roots of plants were taken, then disintegrated, dried and ground. Such prepared plant material was analysed for nitrogen content with the Kjeldahl method (Bremner 1965), for macro- and microelement content with atomic spectrometry absorption (ASA) with the use of the Unicam 939 Solar spectrometer (Calvell 1955, Szyszko 1982). While preparing the analyses of nitrogen, 1 g of plant dry matter was ashed in 25 cm^3 concentrated H_2SO_4 with the addition of 5 cm^3 hydrogen peroxide as a catalysing agent. Statistical calculations (Pearson's simple correlation coefficients) were

Table 2. Content of cadmium and macroelements in applied substances

Substance	Cd content (mg/kg)	Content (g/kg dry matter)			
		P	K	Mg	Ca
Compost	0.39	2.41	1.58	1.56	16.00
Brown coal	0.04	0.13	0.19	4.63	31.52
Lime	0.27	0.10	0.77	2.65	347.99
Bentonite	0.27	0.47	2.43	5.03	26.72

carried out with the use of the Statistica software package, version 6 (StatSoft Inc. 2001).

RESULTS AND DISCUSSION

Soil contamination with heavy metals has an effect on the properties of the soil directly surrounding the roots by modifying the plant intake of chemical elements essential for their proper growth and development. This effect is determined by both the degree of soil contamination and the plant species and their organs, which have different resistance to toxic heavy metals (Frossard 1993, Novozamsky et al. 1993, Gussarsson 1994, Obata and Umebayashi 1997, Tlustoš et al. 1998, Fargašová 2001). It seems, however, that plant species is an important factor (Obata and Umebayashi 1997, Kabata-Pendias and Pendias 2001). In our experiments, the effects of artificial soil contamination with cadmium depended mainly on the plant species and organ and on the material supplemented to the soil. The experiments involved an analysis of the effect of the factors on the above-ground organs and roots of *Avena sativa*, *Zea mays*, *Lupinus luteus*, *Raphanus sativus* and *Phacelia tanacaetifolia* (Figures 1–6). A high concentration of cadmium in the soil caused a significant decrease in yield of the above-ground parts of all the plants' and roots of *Lupinus luteus*, *Raphanus sativus* and *Phacelia tanacaetifolia* (Figure 1). In the roots of *Avena sativa* and *Zea mays* there was an opposite correlation. The application of compost, brown coal, lime and bentonite reduced the negative influence of cadmium on the plants yield. In *Avena sativa* cultivated without application substances, the highest cadmium dose (40 mg Cd/kg of soil) caused a high increase in nitrogen content (r = 0.67) in the roots and (r = 0.84) in the straw (Figure 2). In *Avena sativa* grain highest cadmium doses decreased nitrogen content (r = –0.75) at the application of 40 mg Cd/kg of soil in relation to the control series (without Cd). This decrease in *Avena sativa* grain was even higher in the pots supplemented with compost (r = –0.97) and lime (r = –0.86). On the other hand, soil contamination with cadmium and supplemented with compost and brown coal caused an increase in nitrogen content in the *Avena sativa* straw and roots. In straw it was clearly lower and in roots higher than in the series with no soil supplements. Moreover the mean nitrogen content was the higher in the *Avena sativa* grain than straw and roots.

In the experiments with *Zea mays* cultivated with no supplements, soil contamination with cadmium caused relatively small changes in the nitrogen content in the above-ground parts and a high, almost twice the increase (r = 0.76) of its concentration, in the roots (Figure 3). After the application of the neutralizing matter to the pots with compost, the nitrogen content indicated a tendency to increase (r = 0.41) and in the series with bentonite it indicated a tendency to decrease (r = –0.92). In the pots with brown coal and lime, the cadmium effect was relatively low and multidirectional. In the roots of *Zea mays* cultivated with different substances, the highest cadmium dose (40 mg Cd/kg of soil) resulted in an increase of the nitrogen content in the series with compost (r = 0.71), brown coal (r = 0.67) and bentonite (r = 0.78). Moreover, the mean nitrogen content in the pots with supplements was lower in the above-ground parts and it was higher in the roots of plants cultivated without supplements.

Massive contamination of soil with cadmium had a completely different effect on the nitrogen content in *Lupinus luteus* (Figure 4). In the pots without supplements, the nitrogen content decreased in the above-ground parts and in the roots. The nitrogen content analysis was carried out only in the two initial experimental pots. The root mass obtained in the combinations with 20, 30 and 40 mg Cd/kg of soil was insufficient to complete such analysis. In the pots with soil supplemented with the different substances, soil contamination with cadmium resulted in a decrease in nitrogen content in the above-ground parts of *Lupinus luteus* by 8–20%. The nitrogen content decreased in the roots of lupine cultivated with compost (r = –0.72) and brown coal (r = –0.78) and small increased in the roots of lupine cultivated in lime (r = 0.51) and bentonite (r = 0.82) supplemented soil. The mean nitrogen content in the pots with bentonite was considerably lower than in other experimental series. However, the mean nitrogen content in the roots of lupine cultivated in the pots with compost and brown coal was lower than in the remaining experimental combinations.

High cadmium concentrations in the soil did not have a significant effect on the nitrogen content in the above-ground parts of *Raphanus sativus* in the series with application compost, brown coal, lime and bentonite and in the roots in the series with brown coal and bentonite (Figure 5). However, the nitrogen concentration increased in the above-ground parts of *Raphanus sativus* in the series without additions and in the roots cultivated with compost (r = 0.79) and lime (r = 0.80). The mean nitrogen content in the above-ground parts and roots of *Raphanus sativus* cultivated with the supplements was a lower, than in the pots with no supplements.

Soil contamination with cadmium had a rather negative effect on the nitrogen content in *Phacelia tanacaetifolia* (Figure 6). In the series without supplements, the nitrogen content decreased by 13% in the above-ground parts and by 48% in the roots.

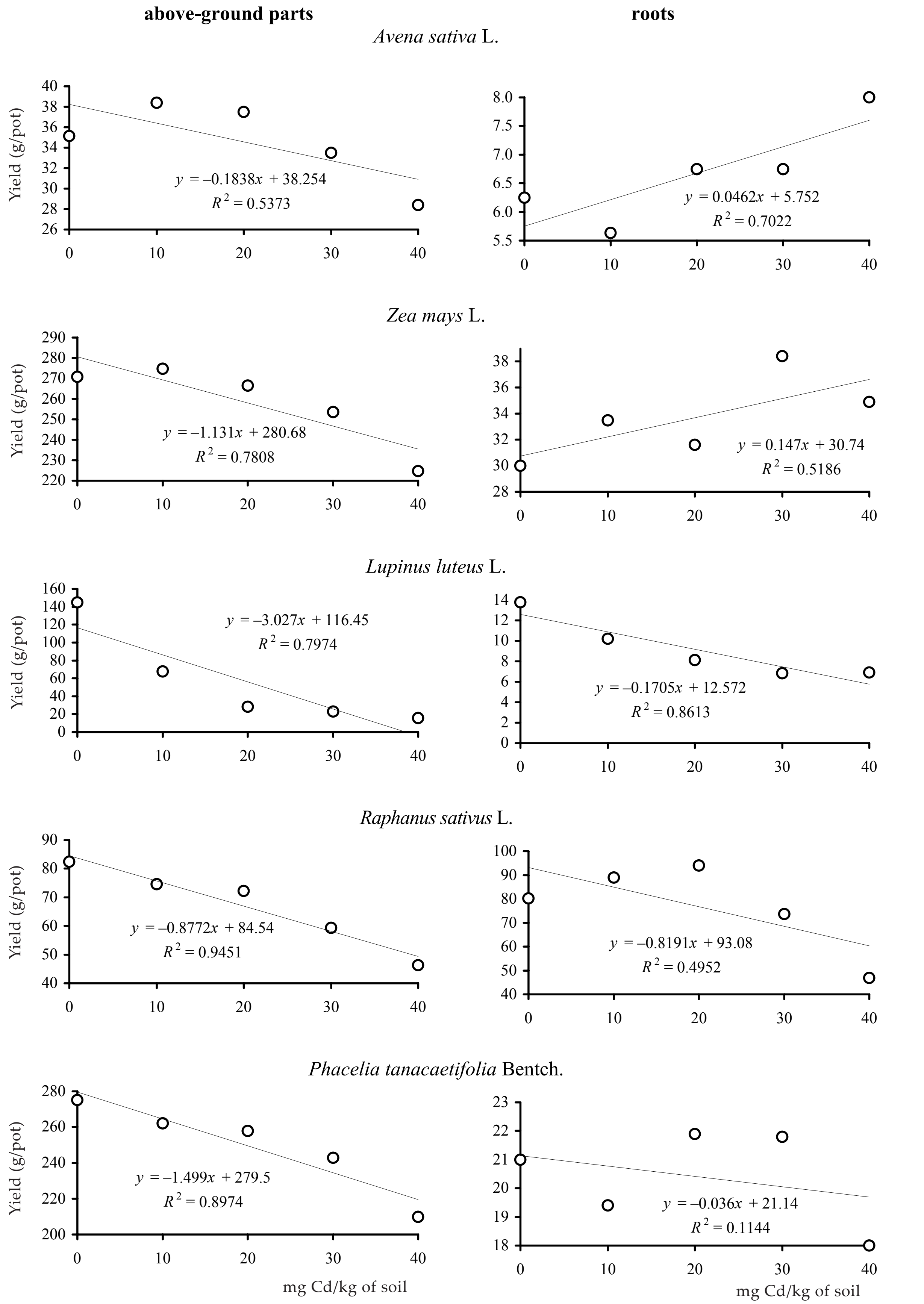

Figure 1. Relationship between the content of cadmium in soil and yield of plants

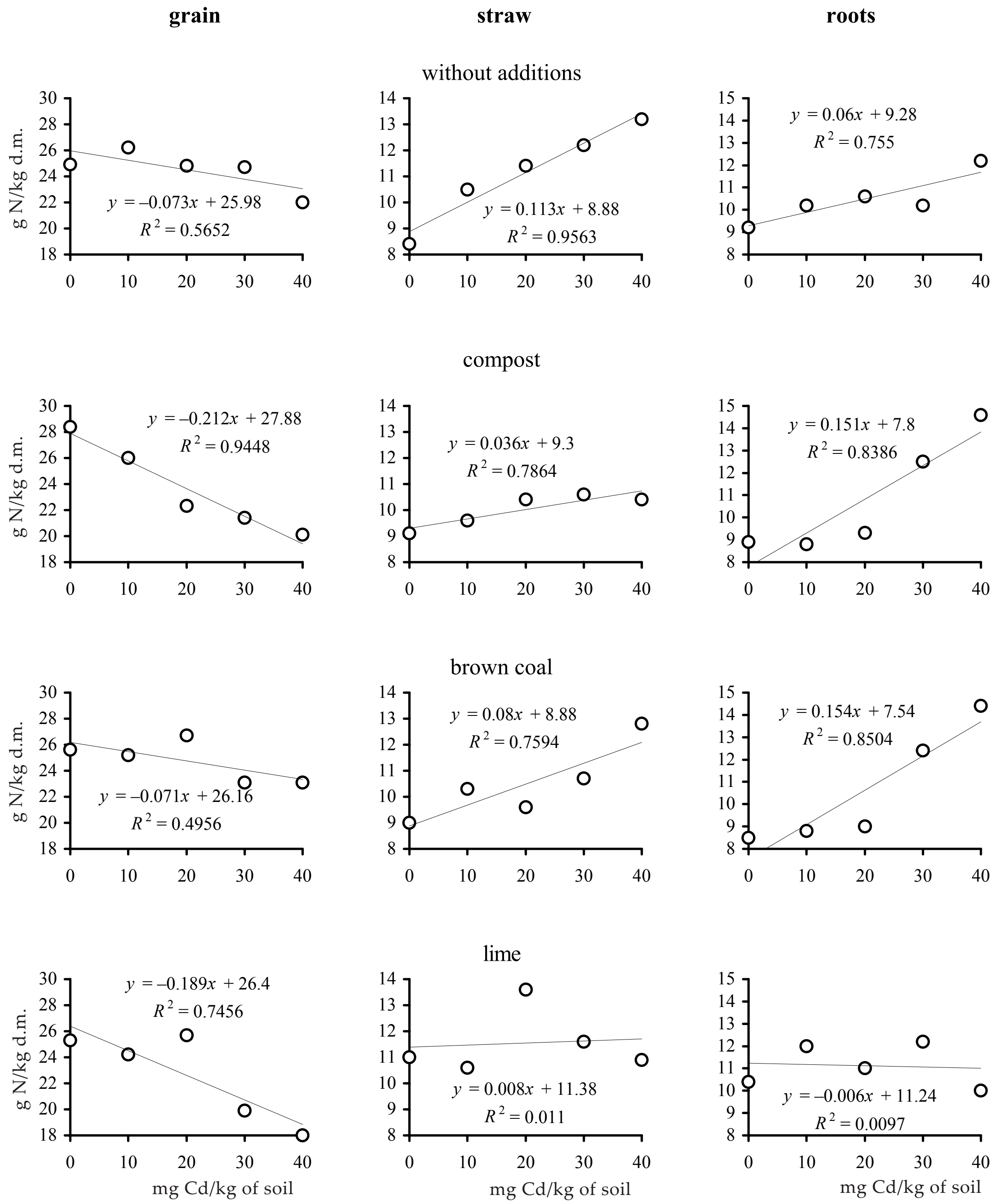

Figure 2. Nitrogen content in *Avena sativa* L. (g/kg of dry matter)

The decrease in the nitrogen content in the aboveground parts of *Phacelia tanacaetifolia* in the pots with the supplements was similar to that in the pots without the neutralizing matter and was between a few and a dozen per cent. On the other hand, this decrease was clearly greater in the pots with compost. A great increase in the nitrogen content was observed in the roots of *Phacelia tanacaetifolia* cultivated with the application of bentonite to the soil contaminated Cd ($r = 0.82$).

The nitrogen concentration in the plants was correlated with the plant yields (Figure 7). Both the regression equations and the R^2 coefficient indicate a high correlation degree between the analysed factors. For the majority of the analysed plant organs, greater nitrogen contents meant higher

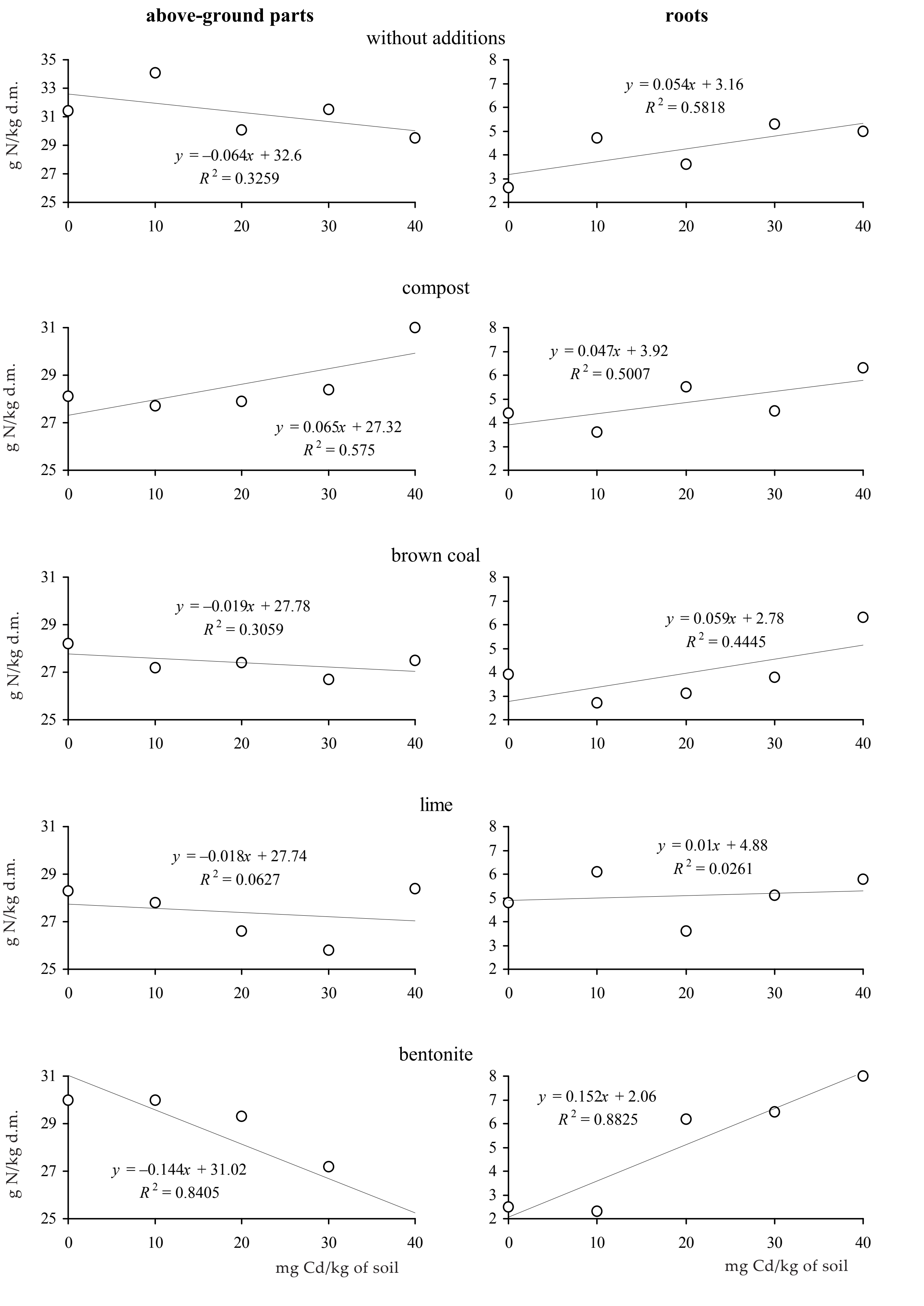

Figure 3. Nitrogen content in *Zea mays* L. (g/kg of dry matter)

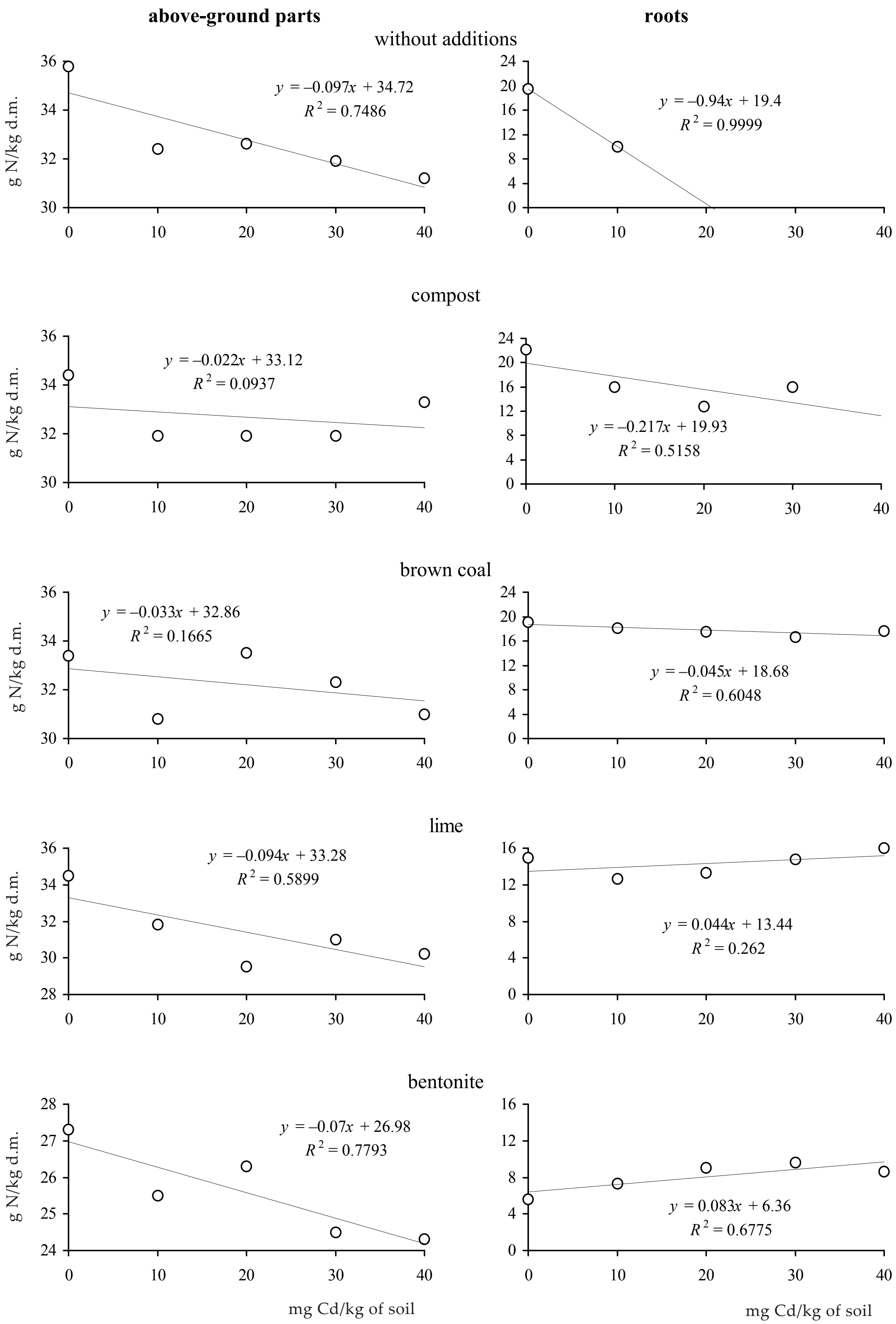

Figure 4. Nitrogen content in *Lupinus luteus* L. (g/kg of dry matter)

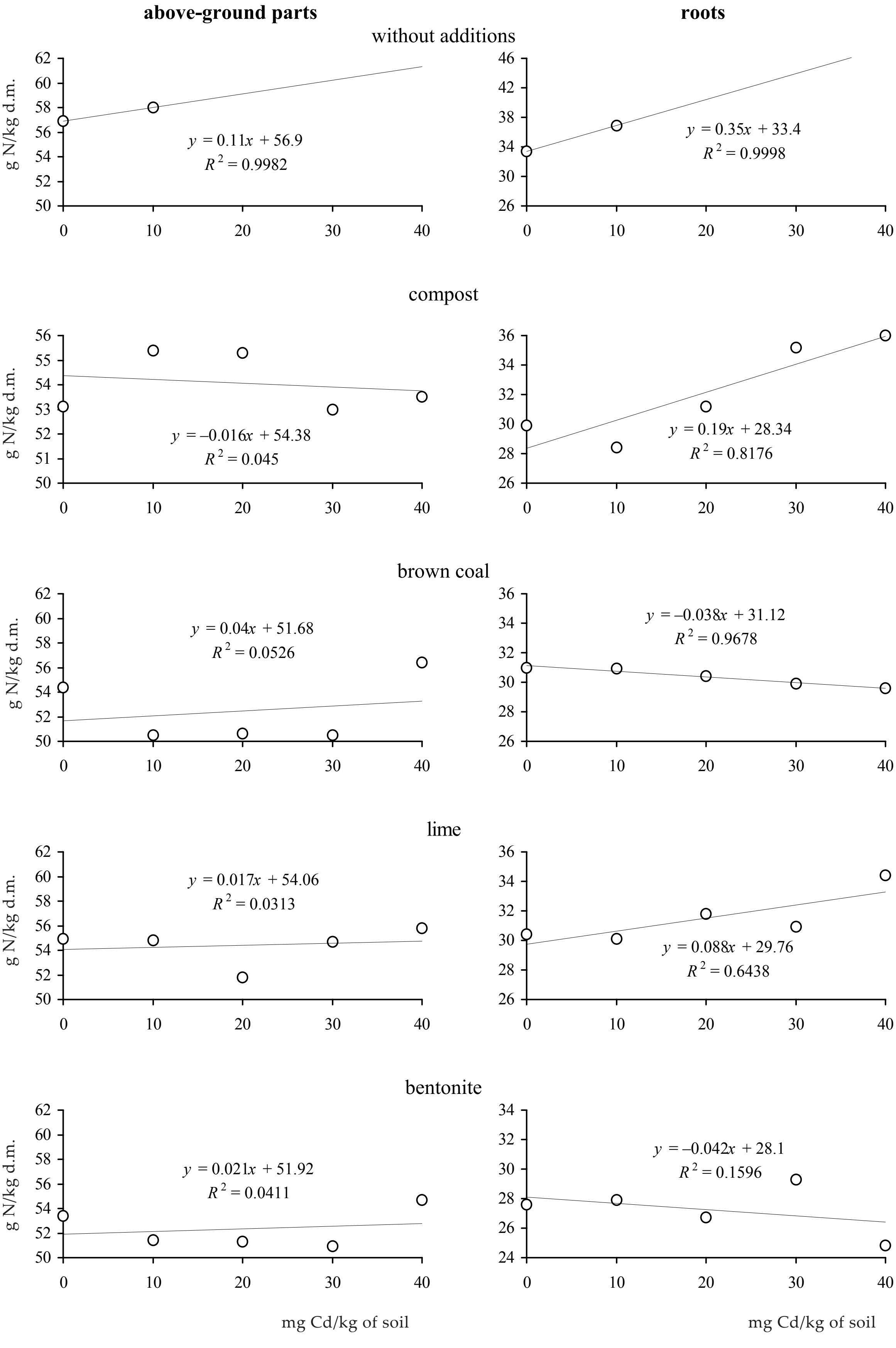

Figure 5. Nitrogen content in *Raphanus sativus* L. (g/kg of dry matter)

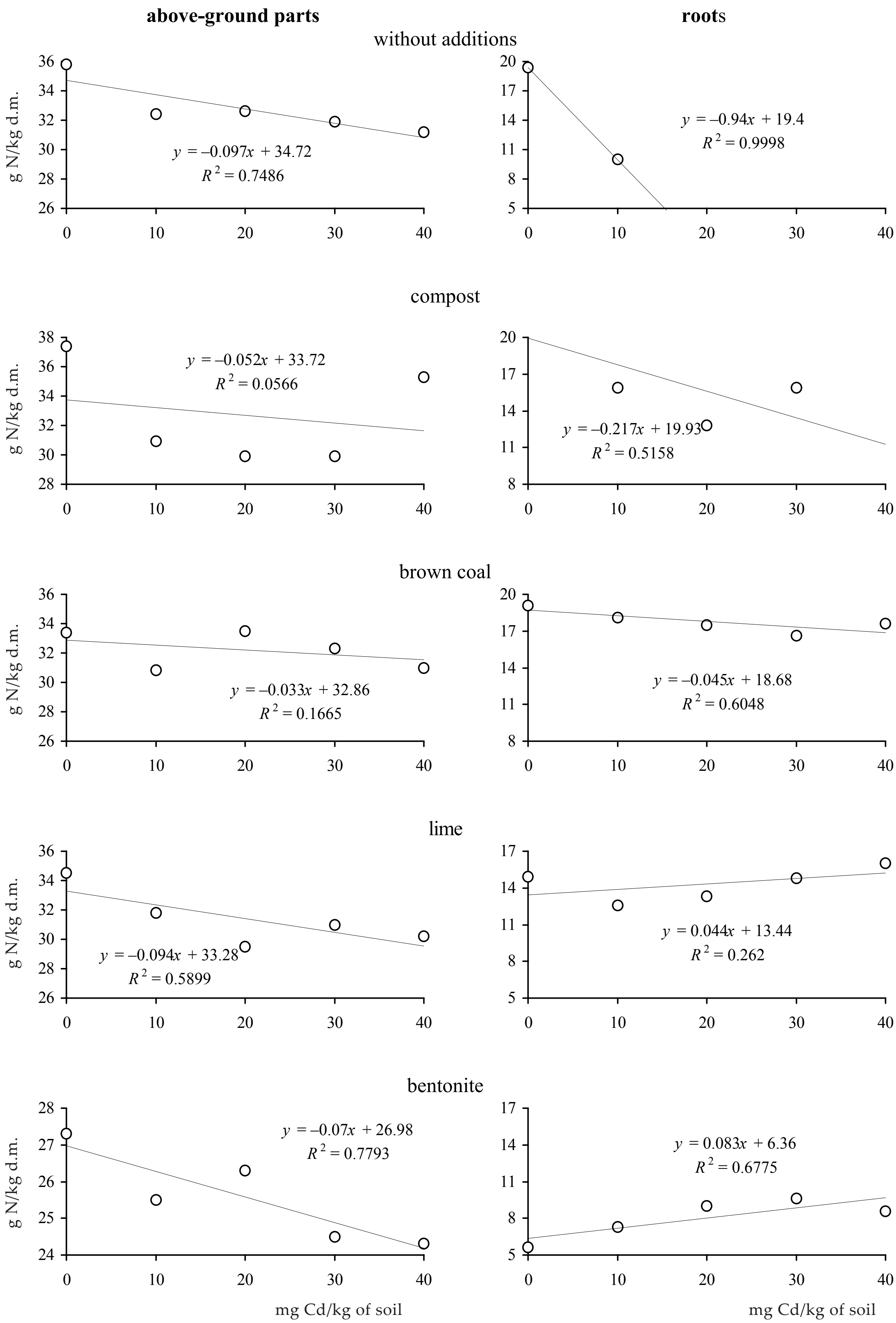

Figure 6. Nitrogen content in *Phacelia tanacaetifolia* Bentch. (g/kg of dry matter)

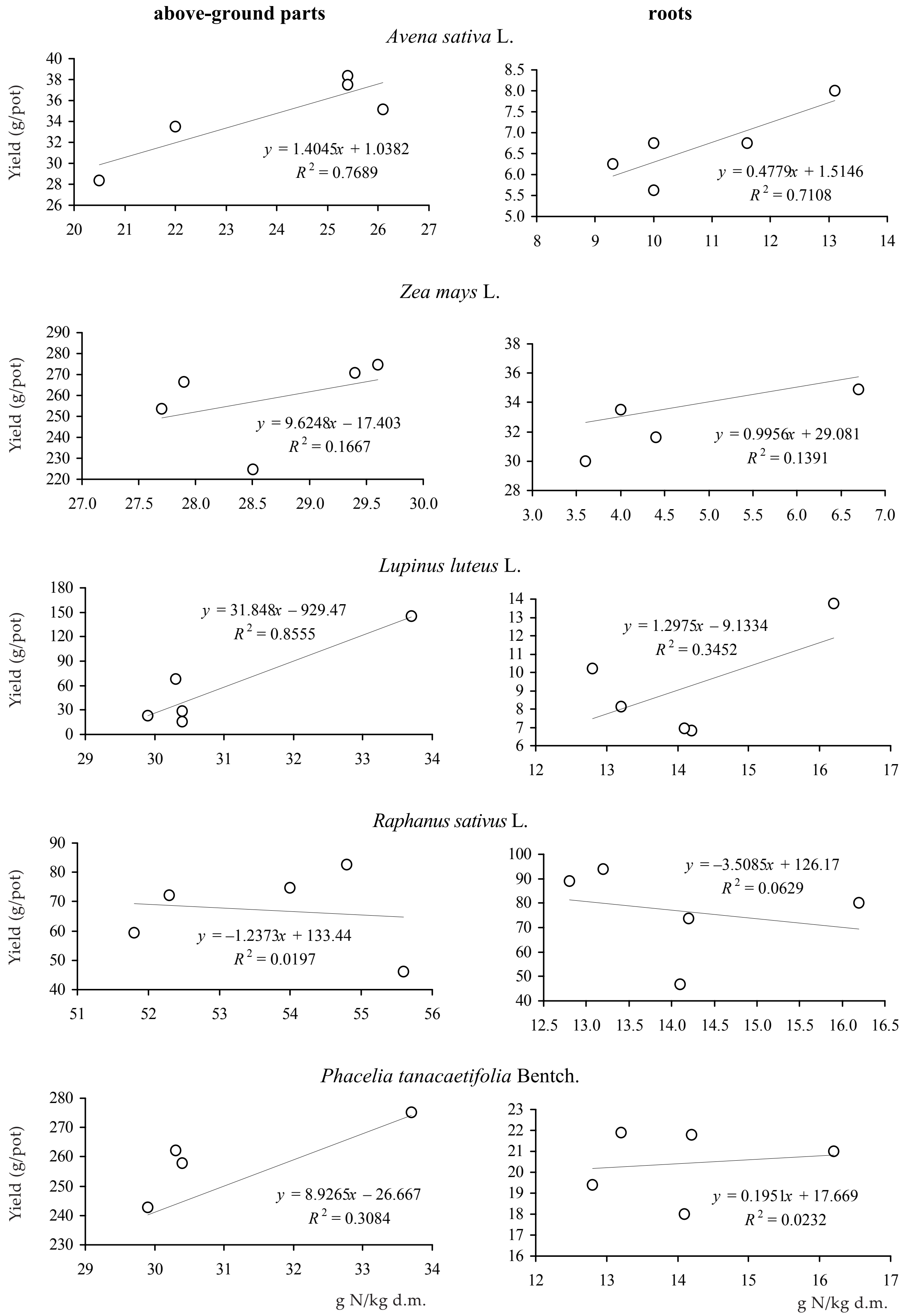

Figure 7. Relationship between the content of nitrogen and yield of plants

Table 3. Relationships (correlation coefficients *r*) between the nitrogen content versus the content of cadmium and the content of macro- and microelements in plants

Plant		Cd dose	Content in plants										
			P	K	Mg	Ca	Na	S	B	Mo	Mn	Fe	Cd
Avena sativa L.	grain	–0.74**	0.21	0.30	0.09	–0.44**	0.17	0.18	–0.02	0.39*	0.27	–0.37*	–0.28
Avena sativa L.	straw	0.59**	–0.33*	0.15	0.00	0.38*	0.43**	0.43**	–0.09	0.38*	–0.31*	–0.01	0.44**
Avena sativa L.	roots	0.84**	0.17	0.53**	0.56**	0.55**	0.51**	0.53**	0.05	–0.06	0.08	–0.11	0.72**
Zea mays L.	above-ground parts	–0.22	0.61**	0.59**	–0.23	0.09	–0.08	0.04	–0.19		0.57**	–0.16	0.12
Zea mays L.	roots	0.57**	0.65**	0.22	0.39**	0.35*	0.57**	0.68**	0.11		–0.21	–0.01	0.66**
Lupinus luteus L.	above-ground parts	–0.30*	0.41**	0.72**	0.38**	0.38**	–0.84**	–0.18	0.27	–0.20	0.56**	0.12	0.19
Lupinus luteus L.	roots	–0.02	0.83**	0.93**	0.47**	0.42**	–0.48**	0.51**	0.63**	0.03	–0.84**	–0.93**	0.30
Raphanus sativus L.	above-ground parts	0.11	0.04	0.35*	–0.19	0.01	–0.25	–0.41**	–0.02	–0.30*	0.24	–0.02	0.08
Raphanus sativus L.	roots	0.26	–0.09	0.50**	0.30*	0.66**	–0.63**	0.45**	0.45**	–0.17	0.37**	–0.02	0.69**

yields. The correlations between the nitrogen content in plants and the cadmium dose and the content of other macro- and microelements, including heavy metals, is interesting (Table 3). Nitrogen content, regardless of the neutralizing matter supplemented to the soil, in the *Avena sativa* grain and the above-ground parts of *Lupinus luteus* was significantly negatively correlated and in the straw and the roots of *Avena sativa* and the roots of *Zea mays* was positively correlated with the cadmium dose. The nitrogen content in the above-ground parts and the roots of the experimental plants was generally significantly positively correlated with the concentration of phosphorus, potassium, magnesium, calcium, sodium and sulfur. The nitrogen content also indicated a significant correlation with some microelements in the above-ground parts and roots. This undoubtedly resulted from a complicated mechanism of element uptake by plants from soil, among others, from the antagonisms and synergies occurring between particular elements during their uptake by plant roots.

In previous experiments (Ciećko et al. 1998, 2001), the effect of soil contamination with cadmium on the nitrogen uptake by plants was determined by plant species as in the present experiment. In the case of spring triticale grain and straw and the above-ground mass of *Zea mays*, a high cadmium concentration in the soil had a stimulating effect and in the case of spring rape an inhibiting effect on the nitrogen accumulation in the above-ground parts of the plants. Considerably lower fluctuations of macro-element concentrations in the yield of *Avena sativa* and *Zea mays* as a consequence of soil contamination with cadmium were observed in previous experiments (Ciećko et al. 1995). However, in the experiments of Simon (1998), neither low nor high cadmium doses modified the uptake of nitrogen, phosphorus or potassium by sunflower plants. The effect of soil supplements on the nitrogen content in plants was observed in previous experiments (Ciećko et al. 1998, 2001).

In which a positive nitrogen accumulation was observed in the effect of compost (and particularly brown coal) on the nitrogen content in the grain and straw of triticale and a negative accumulation in the above-ground parts of *Zea mays*. On the other hand, the effect of lime application on the nitrogen content in the above-ground parts of triticale was negative and in the above-ground parts of *Zea mays* this effect was positive (Ciećko et al. 1998, 2001). In the present experiment, the effect of these substances on the uptake of nitrogen by the grain, straw and roots of *Avena sativa* was rather negative. Supplementation of lime into the soil caused, however, an increase in the nitrogen content in the roots, in contrary to the above-ground parts of *Zea mays* in which a decrease was observed.

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ABSTRAKT

Vliv zvýšeného obsahu kadmia v půdě na příjem dusíku různými plodinami

Byl ověřován vliv kontaminace půdy kadmiem (10, 20, 30 a 40 mg Cd/kg půdy) na příjem dusíku některými plodinami při současné aplikaci různých materiálů (kompostu, hnědého uhlí, vápna a bentonitu). Byly stanoveny závislosti mezi obsahem dusíku v jednotlivých plodinách a koncentrací kadmia v půdě, jakož i závislosti mezi výnosem plodiny a obsahem mikro- a makroprvků v plodinách. Vliv kontaminace půdy kadmiem na obsah dusíku byl dán druhem plodiny a dávkou kadmia. Vysoké dávky kadmia vedly ke zvýšení obsahu dusíku ve slámě a kořenech u druhu *Avena sativa* a v kořenech *Zea mays*. Kontaminace půdy kadmiem způsobila snížení obsahu dusíku v zrnu plodiny *Avena sativa*, v nadzemních částech a kořenech *Lupinus luteus*, v nadzemních částech *Zea mays* a v nadzemních částech a kořenech *Phacelia tanacaetifolia*. Aplikace bentonitu měla z uvedených pokusných materiálů nejvýznamnější a obvykle záporný vliv na obsah dusíku v jednotlivých plodinách. Tento vliv byl největší u zrna *Avena sativa*, nadzemních částí plodin *Zea mays* a *Lupinus luteus* a *Phacelia tanacaetifolia*. Obecně vzato jsme zjistili pozitivní korelace obsahu dusíku v jednotlivých plodinách s obsahem makroprvků a některých mikroprvků, a to bez ohledu na materiál aplikovaný do půdy.

Klíčová slova: kontaminace půdy kadmiem; kompost; hnědé uhlí; vápno; bentonit; výnos rostlin; obsah dusíku; obsah makro- a mikroprvků

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