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Input of heavy metals to the forest floor as a result of Cracow urban pollution

Katarzyna Sawicka-Kapusta*, Marta Zakrzewska, Katarzyna Bajorek, Joanna Gdula-Argasińska

Department of Environmental Monitoring, Institute of Environmental Sciences, Jagiellonian University, Ingardena 6, 30-060 Cracow, Poland

Abstract

The influence of Cracow's urban pollution on small forest ecosystems was studied during 1998–2000. Seven sites located at different distances from the Cracow conurbation and from busy road were selected. Two sites were situated 26 and 31 km from Cracow town along an eastern transect, the other five—3, 8, 14, 26 and 35 km respectively, from Cracow—along a southern transect. At the beginning of September, five litter traps were set at each site. The quantity of litter fall, along with percentage composition of each species, were estimated for an area of 1 m^2. The concentration of Cd, Pb, Cu, Zn and Fe in the litter fall and the input of these metals to the forest floor were determined. The input of cadmium ranged from 84 μg m^{-2} at Kornatka in 1998 to 382 μg m^{-2} at Bonarka in 2000. The input of lead was about 10 times higher than cadmium and varied from 406 μg m^{-2} at Węglówka in 1998 to 3717 μg m^{-2} at Bonarka in 2000. Input of Cu, Zn and Fe to the forest floor showed the similar tendency. During 1998–2000, the highest heavy metal concentrations in the litter fall and their impact on the forest floor were always found at sites close to the Cracow conurbation and, in the eastern transect, close to a steel works. Input of metals to the forest floor tended to decrease with increasing distance from the centre of Cracow.

Keywords: Urban pollution; Heavy metals; Litter fall; Input; Forest floor

1. Introduction

Increasing urbanisation results in the production of a wide range of different pollutants that can have an adverse effect on the surrounding environment. This pollution originates from large-scale human activities, including industrial manufacturing and energy production, coal and oil combustion (both industrial and residential), heavy traffic and other small local sources (Cotrufo et al., 1995; Pacyna et al., 1995; Pouyat et al., 1994). Elevated levels of gaseous pollutants, such as SO_2, NO_x and ozone, may result in perturbations in forest ecosystems located within or near the urban areas (Amundson et al., 1990; Gatz, 1991; Pearson and Mansfield, 1994). Heavy metal contamination is one of the most commonly used measures of urbanisation (Cotrufo et al., 1995; Watmough et al., 1998) but still little is known about effect of urbanisation on forest ecosystem (Hutchinson and Sager, 2000). The Cracow conurbation is one of the largest in Poland (inhabited by almost one million people) with over 30 large and small industrial sources. An old steel works, operated since 1952, a heating plant and an electric power plant are the main sources of heavy metal emissions. The Cracow region was among the four most highly polluted areas in Poland (Nowicki, 1993). The situation has improved considerably during the last 11 years, but the district still maintains third place in the rankings of industrial emissions in the country (Turzański and Wertz, 1997; Turzański, 1999b, 2000, 2001; Environment, 2001).

The effect of urban pollution from the Cracow conurbation on surrounding small forest ecosystems has been studied during the past 3 years (1998–2000). As part of this study, we are assessing the effects of urban conurbation on a number of potentially vulnerable and important parameters. Some preliminary results of this investigation, regarding heavy metal accumulation in tree leaves, transplanted lichens and rodents tissues, have been published elsewhere (Gdula-Argasińska et al., 2000; Budka et al., 2001), and the aim of the present study was to estimate the inputs of heavy metals to the forest floor that were due to urban pollution from Cracow.

* Corresponding author.
E-mail address: sawicka@eko.uj.edu.pl (K. Sawicka-Kapusta).

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2. Material and methods

2.1. Forest sites

Seven forest sites that differed in their distance from the centre of Cracow and from busy road were located along either a southern or an eastern transects and along the prevailing wind direction were selected (Fig. 1, Table 1). All of the forests were deciduous but only four contained similar stands of *Tilio-Carpinetum* habitat: Rajsko, Mogilany, Koło and Ispina. Kornatka is degradated remnants of *Tilio-Carpinetum* with present stand of mixed pine forest (*Pino-Quercetum*). Węglówka represents degradation phase of *Tilio-Carpinetum* with *Pinus sylvestris* and *Abies alba*.

2.2. Litter traps

At each of the study sites, three squares (10 × 10 m) were marked out and, each year at beginning of September, five litter traps were distributed between the squares. Traps were constructed as 1 m^2 frames, made of wood and with a nylon net (hole size: 1/1 mm) attached at the bottom to form a catchment base. After 2 months of exposure, the litter was collected and sorted into different tree species groups. The quantity of litter fall and the percentage composition of each species were assessed for each 1-m^2 trap. The resultant input of Cd, Pb, Cu, Zn, Fe (in μg or mg m^{-2}) to the forest floor from the litter was determined by chemically analysing the litter.

2.3. Chemical analyses

Metal concentrations in the leaves of the three dominant forest trees (common oak, hornbeam, sycamore) and in the overall litter fall (calculated on the basis of the measured species percentage of the litter) were determined. Dry samples were wet digested in a 4:1 nitric and perchloric acid. Cd, Pb, Zn, Cu and Fe concentrations were determined

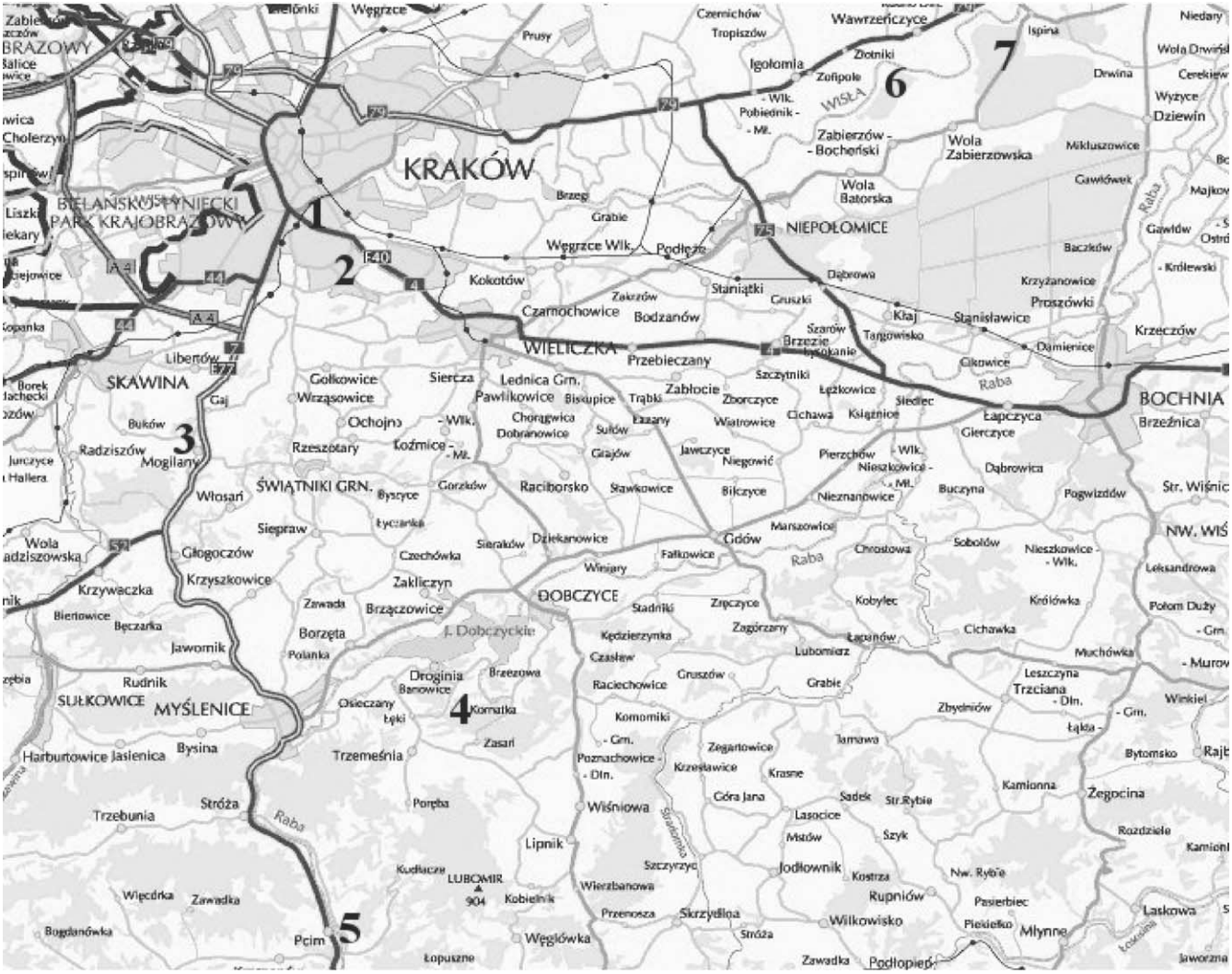

Fig. 1. Forest sites locations. (1) Bonarka; (2) Rajsko; (3) Mogilany; (4) Kornatka; (5) Węglówka; (6) Koło; (7) Ispina.

Table 1
Forest sites situated along southern and eastern transect from Cracow conurbation

Site	Southern transect				
	Distance from		pH of soil	Cd fall (mg/m^2/year)	Pb fall (mg/m^2/year)
	centre of Cracow (km)	Zakopianka highway (km)			
Bonarka	3	0.1	8.17	0.71	26
Rajsko	8	3 (east)	4.23	0.45	21
Mogilany	14	1 (west)	4.40	0.45	18
Kornatka	26	7.5 (east)	4.37	0.40	17
Węglówka	35	1.5 (east)	4.40	0.33	9
Site	Eastern transect				
	Distance from		pH	Cd fall (mg/m^2/year)	Pb fall (mg/m^2/year)
	Centre of Cracow (km)	Sendzimir steel work (km)			
Staniątki	21 (southeast)	13 (south east)	5.88	Studied only in 1998	
Koło	26	15	5.0	0.46	14
Ispina	31	20	4.98	0.68	37

Data regarding Cd and Pb fall (mg/m^2/year) from air quality monitoring stations located nearby investigated forest sites (Turzański, 1999a, 2000).

using an Instrumentation Laboratory IL 251 flame atomic absorption spectrophotometer. Reference materials (SRM 1573A) were also analysed. The recovery ranged from 90% to 105%. Data are presented in μg g^{-1} dry weight.

2.4. Statistical analyses

Two-way analyses of variance and post hoc Tukey test were used to determine the statistical differences in heavy metal concentrations in the litter fall and metal input to the forest floor between sites and years (Łomnicki, 1995).

3. Results and discussion

Tables 2–4 and Fig. 2 show the amount of litter input of different tree species at each forest site during three consecutive years (1998–2000). Oak (*Quercus robur*) was present at all study sites. It was the dominant species at four sites, and comprised 28.1–80.3% of the total litter input at Węglówka and Kornatka, respectively. Hornbeam (*Carpinus betulus*) was found at all sites, except Bonarka and was the dominant tree species at Rajsko. At Mogilany, Ispina and Koło, hornbeam was the second most important contributor to litter fall (35.7%, 41.3%, 42.6%) in 1999 (Table 3). Norway maple (*Acer platanoides*) was the dominant tree species in Bonarka and composed between 44.6% and 76.0% of a whole litter input depending on the year. Lime (*Tilia cordata*) was the dominant species in Koło, and comprised 51.9% of total litter fall in 1999 and 59.5% in 2000 (Tables 3 and 4).

The average litter fall in 1998 ranged from 123.3 g m^{-2} at Staniątki to 245.4 g m^{-2} at Rajsko. During the subsequent 2 years, litter input was higher and much less variable between sites. In 1999, litter fall varied from 233.4 g m^{-2} (Kornatka) to 325.1 g m^{-2} (Mogilany) and in 2000 the lowest input (225.8 g m^{-2}) was at Koło and the highest (365.5 g m^{-2}) at Węglówka (Tables 2–4).

Heavy metals concentration in the litter fall showed differences between the investigated forest sites. The highest

Table 2
Average composition of litter fall in urban corridor sites in 1998 [g and (%) of different species]

Species	Bonarka (N=6)	Rajsko (N=6)	Mogilany (N=6)	Kornatka (N=6)	Węglówka (N=6)	Staniątki (N=6)	Ispina (N=6)
Quecus robur	48.2 (4.7)	601.4 (40.8)	819.1 (58.0)	574.2 (75.0)	347.7 (43.2)	453.7 (61.2)	801.9 (61.9)
Carpinus betulus	–	722.9 (49.1)	515.1 (36.5)	10.6 (1.4)	17.1 (2.1)	–	366.8 (28.3)
Acer pseudoplatanus	157.4 (15.3)	–	16.4 (1.2)	8.3 (1.1)	70.6 (8.7)	–	–
Acer platanoides	459.9 (44.6)	–	–	–	–	–	1.8 (0.1)
Fagus sylvatica	–	–	–	43.4 (5.7)	176.8 (21.9)	–	–
Pinus sylvestris	128.5 (12.5)	–	–	12.1 (1.6)	78.8 (9.8)	–	–
Betula pendula	6.1 (0.6)	146.8 (10.0)	58.0 (4.1)	85.4 (11.1)	–	–	20.8 (1.6)
Tilia cordata		–	2.8 (0.2)	–	30.9 (3.8)	–	64.2 (5.0)
Alnus incana	–	–	–	15.3 (2.0)	–	92.6 (12.5)	–
Larix decidua	–	–	–	11.9 (1.6)	36.4 (4.5)	–	–
Other species	230.1 (22.3)	1.0 (0.1)	–	3.9 (0.5)	48.9 (6.0)	193.6 (26.3)	39.9 (3.1)
Σ [g]	1030.2	1472.1	1411.4	765.1	807.2	739.9	1295.4
$\bar{X}$ [g m^{-2}]	171.7	245.4	235.2	127.5	134.5	123.3	215.9

Table 3
Average composition of litter fall in urban corridor sites in 1999 [g and (%) of different species]

Species	Bonarka ($N=4$)	Rajsko ($N=4$)	Mogilany ($N=5$)	Kornatka ($N=5$)	Węglówka ($N=5$)	Koło ($N=5$)	Ispina ($N=5$)
Quercus robur	226.1 (18.1)	412.7 (34.1)	969.9 (59.6)	878.3 (75.2)	343.9 (28.1)	61.4 (4.7)	715.2 (44.8)
Carpinus betulus	–	479.5 (41.2)	580.9 (35.7)	16.5 (1.4)	47.6 (3.9)	561.8 (42.6)	661.2 (41.3)
Acer pseudoplatanus	64.1 (5.1)	–	10.7 (0.7)	2.2 (0.2)	73.0 (6.0)	–	–
Acer platanoides	948.4 (76.0)	0.5	–	–	–	–	–
Fagus sylvatica	–	–	–	38.1 (3.3)	213.4 (17.5)	–	–
Pinus sylvestris	–	–	–	15.9 (1.4)	114.0 (9.3)	–	–
Betula pendula	–	283.3 (23.4)	32.0 (2.0)	133.7 (11.4)	0.3	0.2	14.8 (0.9)
Tilia cordata	–	–	2.6 (0.2)	0.1	97.8 (8.0)	683.8 (51.9)	102.4 (6.4)
Alnus incana	–	4.5 (0.4)	28.8 (1.8)	25.2 (2.2)	1.0 (0.1)	6.0 (0.5)	–
Larix decidua	–	–	–	32.3 (2.8)	177.3 (14.5)	–	–
Other species	9.9 (0.8)	10.7 (0.9)	0.4	24.8 (2.1)	154.6 (12.6)	4.5 (0.3)	107.7 (6.6)
Σ [g]	1248.5	1209.2	1625.3	1167.0	1222.9	1317.7	1601.3
$\bar{X}$ [g m^{-2}]	312.1	302.3	325.1	233.4	244.6	263.5	320.3

cadmium concentration was found at Bonarka (1.20 μg g^{-1}) in 2000 and Rajsko (1.14 μg g^{-1}) in 1998, while the lowest concentration was found at Kornatka (0.49 μg g^{-1}) in 2000. In 1999, the highest cadmium concentration was also registered at Bonarka, but no statistical differences were found between the forest sites. Cadmium concentration in the litter fall was found to be similar in each of the 3 years that were investigated, with the exception of significantly lower values at Kornatka, Węglówka and Ispina in 2000 compared with 1999 and 1998 (Table 5).

Lead concentration in the litter fall over the 3 years ranged from 2.77 μg g^{-1} at Kornatka (in 2000) to 12.32 μg g^{-1} at Bonarka (in 1998). High lead concentrations (11.71 μg g^{-1}) were also found in 1998 at Rajsko and lead levels in litter fall at both Bonarka and Rajsko were significantly higher than at the other sites (Table 5). In 1999 and 2000, the highest litter fall lead concentration was also at Bonarka, which was located 3 km from the centre of Cracow. Similarly, the high lead concentrations were found in mixed leaves at Rajsko and Koło, forest sites situated close to the Cracow conurbation and to the steel work, respectively. High lead concentrations in the litter fall were found consistently at these sites in all the study years (Table 5).

Average copper concentrations in litter fall were similar at all the forest sites in both 1998 and 1999, ranging from 6.0 μg g^{-1} at Węglówka to 10.7 μg g^{-1} at Staniatki. In 2000, the copper concentrations at Węglówka and Koło were significantly lower than those at the same sites in 1999 (Table 6).

During all years, the highest zinc concentration in the litter fall was found at Rajsko while the lowest at Węglówka. The zinc concentrations in litter fall in 2000 were significantly lower at Rajsko than in 1999 and 1998, indicating that there was an decrease in zinc level in the polluted air (Table 6).

Iron concentrations in the litter fall were higher at forest sites close to the city (Bonarka, Rajsko and Mogilany) then at sites far from Cracow conurbation (Węglówka and Kornatka). Generally, iron concentration was significantly lower in 1999 than in 1998 and 2000 (Table 6).

Input of heavy metals to the forest floor depends on metal concentration in the litter fall, and the yearly dynamics of litter (Grodzińska and Laskowski, 1996). Species composition also influences metal input to the litter because different trees accumulate the different amount of heavy metals. From the other part of this study, heavy metal

Table 4
Average composition of litter fall in urban corridor sites in 2000 [g and (%) of different species]

Species	Bonarka ($N=5$)	Rajsko ($N=5$)	Mogilany ($N=5$)	Kornatka ($N=5$)	Węglówka ($N=5$)	Koło ($N=5$)	Ispina ($N=5$)
Quercus robur	289.4 (18.2)	802.8 (61.8)	783.9 (56.9)	1142 (80.3)	572.2 (31.3)	125.0 (11.1)	1056.6 (60.3)
Carpinus betulus	–	316.3 (24.3)	530.6 (38.5)	13.2 (0.9)	44.4 (2.4)	331.1 (29.3)	352.8 (20.1)
Acer pseudoplatanus	158.5 (10.0)	–	8.0 (0.6)	1.5 (0.1)	119.6 (6.5)	–	–
Acer platanoides	1136.5 (71.4)	–	–	–	–	–	–
Fagus sylvatica	–	–	–	36.0 (2.5)	407.4 (22.3)	–	–
Pinus sylvestris	–	–	–	16.6 (1.2)	227.0 (12.4)	–	–
Betula pendula	–	179.0 (13.8)	50.4 (3.7)	162.3 (11.4)	–	–	97.2 (5.6)
Tilia cordata	–	–	0.7 (0.1)	–	168.4 (9.3)	671.6 (59.5)	82.5 (4.7)
Alnus incana	–	–	–	8.1 (0.7)	–	–	–
Larix decidua	–	–	–	21.6 (1.5)	90.8 (5.0)	–	–
Other species	6.6 (0.4)	1.0 (0.1)	3.0 (0.2)	19.9 (1.4)	197.7 (10.8)	1.3 (0.1)	163.0 (9.3)
Σ [g]	1591	1299.1	1376.6	1421.2	1827.5	1129	1752.1
$\bar{X}$ [g m^{-2}]	318.2	259.8	275.3	284.2	365.5	225.8	350.4

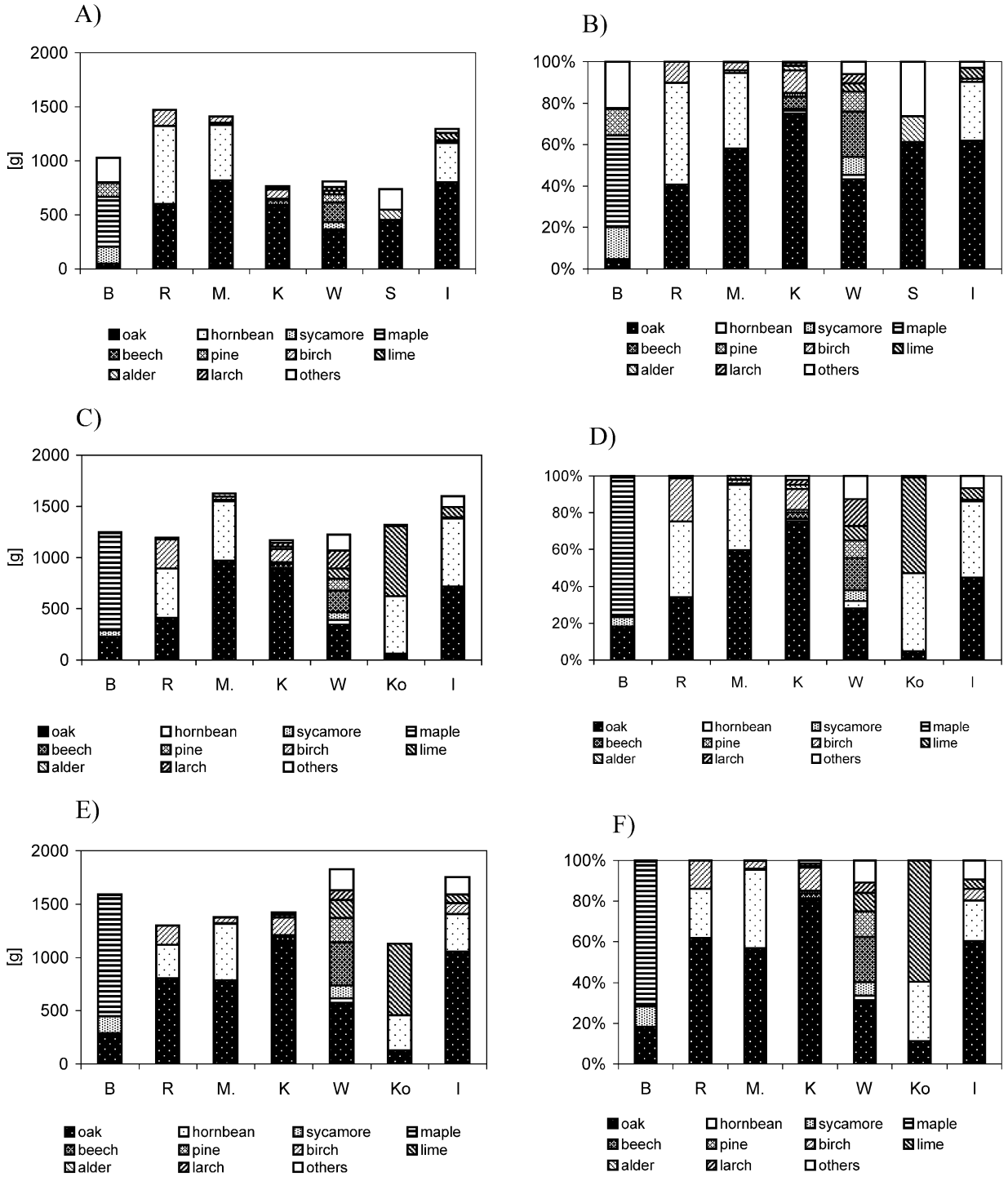

Fig. 2. Composition of litter fall in urban corridor sites in 1998: (A) grams, (B) percent of different species; in 1999: (C) grams, (D) percent of different species; in 2000: (E) grams, (F) percent of different species. B—Bonarka, R—Rajsko, M.—Mogilany, K—Kornatka, W—Węglówka, Ko—Koło, S—Staniatki, I—Ispina.

concentration was analysed in leaves of sycamore, hornbeam and oak growing on the same forest sites. It was found that sycamore accumulate the highest concentration of metals in comparison with hornbeam and oak. The lowest amount of investigated metals was found in oak leaves (Gdula-Argasińska et al., 2000; Bajorek, 2000; Jaworska, 2001). It is important that leaves of species among those three are dominant in the litter fall.

Cadmium input to the forest floor ranged from 84 μg m^{-2} at Kornatka in 1998 to 382 μg m^{-2} at Bonarka in 2000 (Table 5). Input of this metal tended to be higher in Bonarka and Rajsko, close to the city centre, although concentrations

Table 5
Average biomass of litter (g m^{-2}), cadmium and lead concentrations (μg g^{-1} d.w.) in mixed leaves, and input of these metals to the forest floor in different sites of Cracow conurbation in 1998–2000 (in each site $N=5$)

Year	Site	Average biomass of litter	Cadmium		Lead	
			Concentration in mixed leaves $X \pm$ S.E.	Input to the forest floor [μg m^{-2}]	Concentration in mixed leaves $X \pm$ S.E.	Input to the forest floor [μg m^{-2}]
1998	Bonarka	171.7	0.90 ± 0.00^{ab1}	154 ± 1^{d1}	12.32 ± 0.70^{a1}	2115 ± 119^{a1}
	Rajsko	245.4	1.14 ± 0.03^{a1}	280 ± 8^{a1}	11.71 ± 0.34^{a1}	2874 ± 83^{b1}
	Mogilany	235.2	0.91 ± 0.10^{ab1}	214 ± 14^{c1}	3.70 ± 0.34^{b1}	870 ± 80^{d1}
	Kornatka	127.5	0.66 ± 0.03^{b1}	84 ± 4^{b1}	$4.05 \pm 0.59^{b1,2}$	516 ± 75^{c1}
	Węglówka	134.5	0.80 ± 0.10^{b1}	108 ± 14^{b1}	3.02 ± 0.01^{b1}	406 ± 1^{c1}
	Staniątki	123.3	0.86 ± 0.03^{b1}	106 ± 4^{b1}	3.32 ± 0.33^{b1}	409 ± 41^{c1}
	Ispina	215.9	0.80 ± 0.06^{b1}	173 ± 12^{cd1}	2.98 ± 0.01^{b1}	643 ± 2^{cd1}
1999	Bonarka	312.1	1.00 ± 0.06^{a1}	312 ± 19^{a2}	10.50 ± 0.04^{a1}	$3277 \pm 13^{a1,2}$
	Rajsko	302.3	0.76 ± 0.06^{a2}	$230 \pm 19^{ab1,2}$	$7.16 \pm 0.31^{b1,2}$	$2164 \pm 93^{b1,2}$
	Mogilany	325.1	0.70 ± 0.06^{a1}	228 ± 19^{ab1}	3.82 ± 0.67^{c1}	1242 ± 217^{c1}
	Kornatka	233.4	0.77 ± 0.04^{a1}	180 ± 8^{b2}	5.19 ± 0.33^{bc1}	1211 ± 77^{c2}
	Węglówka	244.6	0.79 ± 0.00^{a1}	193 ± 0^{b2}	4.79 ± 0.33^{bc1}	1172 ± 82^{c2}
	Koło	263.5	0.87 ± 0.09^{a1}	229 ± 23^{ab2}	6.48 ± 1.15^{b2}	1707 ± 303^{bc2}
	Ispina	320.3	0.80 ± 0.10^{a1}	256 ± 33^{ab2}	4.16 ± 0.89^{bc2}	1332 ± 284^{bc2}
2000	Bonarka	318.2	1.20 ± 0.09^{c1}	382 ± 31^{a2}	11.68 ± 0.3^{c1}	3717 ± 96^{a2}
	Rajsko	259.8	0.72 ± 0.01^{ad2}	187 ± 3^{bc2}	5.97 ± 0.23^{a2}	1551 ± 61^{b2}
	Mogilany	275.3	0.75 ± 0.04^{a1}	206 ± 11^{b1}	4.45 ± 0.18^{ab1}	1225 ± 51^{bc1}
	Kornatka	284.2	0.49 ± 0.01^{b2}	139 ± 4^{c2}	2.77 ± 0.09^{b2}	$787 \pm 26^{c1,2}$
	Węglówka	365.5	0.51 ± 0.02^{bd2}	186 ± 9^{bc2}	4.31 ± 0.02^{ab1}	1575 ± 84^{b2}
	Koło	225.8	0.75 ± 0.00^{a1}	169 ± 1^{bc2}	$5.56 \pm 0.24^{a1,2}$	1255 ± 55^{bc2}
	Ispina	350.4	0.55 ± 0.02^{ab2}	$193 \pm 8^{bc1,2}$	3.01 ± 0.25^{b1}	$1055 \pm 90^{bc1,2}$

[a,b,c,d] The same letters indicate no statistical differences between sites.
[1,2] The same number indicate no statistical differences between years.

did vary between years. Input of lead to the forest floor was also significantly highest at Bonarka and Rajsko, the nearest sites from to the town. Two sites located east from Sendzimir steel works received also high load of lead. The lowest values for lead input were estimated for Kornatka and Węglówka, which are distant from the Cracow conurbation.

Table 6
Copper, zinc and iron concentrations (μg g^{-1} d.w.) in mixed leaves, and input of these metals to the forest floor in different sites of Cracow conurbation in 1998–2000 (in each site $N=5$)

Year	Site	Copper		Zinc		Iron	
		Concentration in mixed leaves $X \pm$ S.E.	Input to the forest floor (μg m^{-2})	Concentration in mixed leaves $X \pm$ S.E.	Input to the forest floor (mg m^{-2})	Concentration in mixed leaves $X \pm$ S.E.	Input to the forest floor (mg m^{-2})
1998	Bonarka	6.1 ± 0.1^{c1}	1047 ± 9^{a1}	57 ± 1^{b1}	10 ± 0^{d1}	964 ± 13^{c1}	166 ± 2^{a1}
	Rajsko	8.9 ± 0.2^{b1}	2184 ± 46^{b1}	116 ± 1^{e1}	28 ± 0^{a1}	671 ± 4^{d1}	165 ± 1^{a1}
	Mogilany	8.3 ± 0.1^{b1}	1952 ± 27^{c1}	87 ± 0^{a1}	$20 \pm 0^{c1,2}$	329 ± 6^{a1}	77 ± 1^{b1}
	Kornatka	6.1 ± 0.1^{c1}	778 ± 9^{d1}	76 ± 3^{d1}	10 ± 0^{d1}	292 ± 42^{a1}	37 ± 5^{c1}
	Węglówka	6.0 ± 0.1^{c1}	807 ± 13^{d1}	43 ± 1^{f1}	6 ± 0^{b1}	167 ± 4^{e1}	22 ± 0^{d1}
	Staniątki	10.7 ± 0.2^{d1}	1319 ± 23^{e1}	65 ± 0^{a1}	8 ± 0^{e1}	448 ± 10^{b1}	55 ± 1^{e1}
	Ispina	8.3 ± 0.1^{b1}	1792 ± 30^{f1}	91 ± 1^{a1}	20 ± 0^{c1}	513 ± 20^{b1}	111 ± 4^{f1}
1999	Bonarka	6.8 ± 0.3^{ab1}	2122 ± 86^{cd2}	58 ± 4^{d2}	18 ± 1^{b2}	484 ± 4^{c2}	151 ± 1^{a1}
	Rajsko	7.5 ± 0.4^{bcd1}	2267 ± 109^{cd1}	127 ± 3^{b1}	38 ± 1^{a2}	338 ± 20^{a2}	102 ± 6^{d2}
	Mogilany	7.9 ± 0.0^{c1}	2568 ± 10^{b2}	56 ± 2^{d2}	18 ± 1^{b1}	220 ± 4^{b2}	72 ± 1^{b1}
	Kornatka	6.6 ± 0.0^{ad1}	1540 ± 11^{a2}	84 ± 2^{a1}	20 ± 0^{b2}	205 ± 6^{b2}	48 ± 1^{e2}
	Węglówka	6.0 ± 0.2^{a1}	1468 ± 45^{a2}	43 ± 1^{c1}	11 ± 0^{c2}	210 ± 3^{b2}	51 ± 1^{e2}
	Koło	7.6 ± 0.1^{bc2}	2003 ± 18^{c2}	55 ± 0^{d2}	14 ± 0^{c2}	471 ± 7^{c1}	124 ± 2^{c2}
	Ispina	7.2 ± 0.1^{bcd2}	2306 ± 37^{bd2}	60 ± 3^{d2}	19 ± 1^{b2}	326 ± 11^{a2}	104 ± 4^{d1}
2000	Bonarka	8.7 ± 0.3^{a2}	2768 ± 96^{a3}	63 ± 1^{a1}	20 ± 0^{bc2}	826 ± 24^{b1}	263 ± 8^{a2}
	Rajsko	6.9 ± 0.3^{b1}	1793 ± 78^{c2}	89 ± 2^{b2}	23 ± 1^{a3}	408 ± 5^{a2}	106 ± 2^{d2}
	Mogilany	8.6 ± 0.1^{a1}	2367 ± 43^{b2}	76 ± 1^{c1}	21 ± 0^{abc2}	490 ± 30^{a3}	135 ± 8^{bc2}
	Kornatka	5.0 ± 0.1^{c1}	1421 ± 51^{d2}	63 ± 2^{a2}	18 ± 1^{c2}	215 ± 6^{c2}	61 ± 2^{e3}
	Węglówka	4.7 ± 0.0^{c2}	1718 ± 36^{c3}	35 ± 1^{d2}	13 ± 0^{d3}	$175 \pm 7^{c1,2}$	64 ± 3^{e2}
	Koło	5.8 ± 0.0^{c3}	1310 ± 17^{d1}	49 ± 0^{e2}	11 ± 1^{d3}	549 ± 14^{d1}	124 ± 3^{cd2}
	Ispina	7.0 ± 0.2^{b2}	2453 ± 90^{ab2}	63 ± 0^{a2}	22 ± 0^{a3}	448 ± 16^{ad1}	157 ± 6^{b2}

[a,b,c,d,e,f] The same letters indicate no statistical differences between sites.
[1,2,3] The same number indicate no statistical differences between years.

The levels of lead input to the forest floor were higher and similar in 1999 and 2000, and generally lower in 1998 (Table 5).

The higher copper input to the forest floor was in Rajsko, Mogilany and Bonarka. The lowest input was in Kornatka and Węglówka. Zinc input to forest floor ranged from 6 mg m^{-2} in Węglówka in 1998 to 38 mg m^{-2} at Rajsko in 1999. Input of this metal to the forest floor was similar during 3 years, with the highest value in Rajsko. Iron input to the forest floor during 1998–2000, showed the same pattern with statistically lowest values in 1998 (Table 6).

Our findings suggest that input of heavy metals to the forest floor was determined by the concentration of these metals in the mixed leaves, yearly dynamics of litter fall and also the species composition in the litter fall. During all 3 years of investigation, the highest concentration of heavy metals and their impact to the forest floor were always found in the sites closest to the Cracow conurbation and at the sites near the Sendzimir steel works. Input of investigated metals to the forest floor tended to decrease with increasing distance from Cracow. Although air pollution has generally declined in the Małopolska district over the last few years (Environment, 2001; Turzański, 2000, 2001), the metal input to the forest floor in 2000 remains at the same levels, or in the case of some elements, was even higher than in previous years.

The litter fall is of crucial importance in determining the total input of chemical to the forest floor especially on the forest ecosystems (Freedman and Hutchinson, 1980; Tyler, 1981; Grodziński et al., 1984; Laskowski et al., 1993). The annual dynamics of input of nutrients, like N, P and Ca, which are incorporated into the plant tissues, is totally determined by the yearly dynamics of litter fall. The similar dynamics was observed also for K, Mg, and microelements as Mn and Zn. Input of S, Na, is to a large extent determined by anthropogenic sources and their dynamics is not coupled by the litter fall (Grodzińska and Laskowski, 1996). At the beginning of 1990s, environmental assessment and biogeochemistry of a moderately polluted Ratanica catchment located about 40 km south from Cracow were investigated. Input of chemical elements to the forest floor was part of this project. It has been observed that litter fall is the most important factor that influences the total input to the forest floor of heavy metals like Zn and Pb, and, to some extent, Cu and Cd (Grodzińska and Laskowski, 1996).

The input of heavy metals to the forest floor at sites impacted by the Cracow conurbation was similar or even higher than those in the Ratanica catchment. The use of unleaded gasoline in the last few years in Poland has not apparently resulted in decreasing concentrations of lead in litter fall. Similarly, the concentration of other heavy metals did not show dramatic decreases as expected. It is likely that the observed high input of heavy metals to the forest floor from litter fall may have several negative effects on the forest ecosystem by detrimentally affecting soil microorganisms, organic matter decomposition, and soil biological processes (Tyler, 1981; Watmough et al., 1998). These effects are likely to be more severe on the sites that have remained under significant industrial and urban stress for a long period of time. Such areas still exist in Poland (Nowicki, 1993; Environment, 2001). The literature on the input of heavy metals to the forest floor as a result of urban pollution is very scarce. However, it is important to collect data that indicate the negative impact of increasing number of conurbations on the environment.

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