Acta Soc. Zool. Bohem. **77**: 121–128, 2013
ISSN 1211-376X

Geostatistical modelling of the abundance of soil Collembola in an air-polluted urbanized area in Warsaw (Poland)

Kamil Rzeszowski[1)] & Maria Sterzyńska[2)]

Museum and Institute of Zoology, Polish Academy of Sciences, Wilcza 64, PL–00-679 Warsaw, Poland;
[1)] corresponding author; e-mail: krzeszowski@miiz.waw.pl
[2)] majka@miiz.waw.pl

Received 3 May 2013; *accepted 16 June 2013*
Published 5 August 2013

Abstract. Airborne pollution (airborne dust particules and gases) may significantly disturb soil habitats and thus influence the spatial variability in collembolan assemblages in urban ecosystems. A geostatistic-based tool – kriging was used to interpolate values of the airborne pollutants PM_{10} and NO_2 and the abundance of Collembola in an urban area in Warsaw. Collembola were sampled at 25 sites distributed randomly within the city. Geostatistical modelling revealed changes in the spatial pattern of the assemblages of Collembola. The recorded directional trend, with the highest abundance in the city center, indicates that air quality could determining the spatial correlation of Collembola with environmental changes due to air pollution.

Key words. Geostatistics, kriging, urban ecology, landscape ecology, Collembola, abundance, Poland.

INTRODUCTION

Airborne dust particles and gases are the main components of environmental pollution. Precipitation of fine particulate matter (airborne dust particles, PM)) may cause many changes in soils. It specifically affects the availability of alkaline cations, influences the cycling of nutrients, especially nitrogen, through its effects on bacteria and fungi (Grantz et al. 2003) and contamination with heavy metals (Soriano et al. 2012). Gases, such as nitrogen oxides and sulphur bearing compounds (sulphur dioxide and hydrogen sulfide), react with water and other chemicals in the air to form acidic pollutants known as acid rain. Acidic pollutants lead to changes in soil pH, which alter basic soil functions (Liang et al. 2012). Disturbances caused by airborne pollutants may affect soil fauna assemblages (Rusek & Marshall 2000) and their patterns of distribution (e.g. Hågvar & Abrahamsen 1990). Changes in the structure of collembolan assemblages are well documented (e.g. Santamaría et al. 2012, Wahl et al. 2012).

Urban ecosystems and urban soils are highly disturbed and stressed by airborne pollutants. Mechanisms of their release and possible associated effects depend mainly on the conditions of exposure and urban land cover. Levels of soil contamination in cities are clearly associated with the distribution of the main sources of air pollutants – streets and point emitters (Manta et al. 2002). Heterogeneity in the precipitation of airborne pollutants causes an increase in the spatial heterogeneity in the properties of soils (McIntyre et al. 2001, Pickett & Cadenasso 2009). As a consequence urban soils are known to have peculiar characteristics such as unpredictable layering, degraded structure and high concentrations of trace elements (e.g Kabata-Pendias & Pendias 1992, Tiller 1992). The uneven distribution of airborne pollutants and its correlation with a heterogeneous spatial configuration of the urban landscape not only affects soil properties but also the soil fauna.

Presented at the 12th Central European Workshop on Soil Zoology, České Budějovice, Czech Republic, 8–11 April 2013.

Effect of airborne pollutants on collembolan assemblages has been rarely investigated in urban areas (Buşmachiu & Poiras 2003, Fiera 2009a, b). In urban landscapes there are many factors that are related to each other that influence collembolan assemblages.

Geostatistical interpolation is one way of connecting the heterogenous spatial configuration of urban landscapes and environmental pollution with the variability in collembolan assemblages. But until now geostatistical tools were used only to study soil fauna at fine spatial scales (e.g. Robertson & Freckman 1995, Ettema et al. 1998, Gutierrez-Lopez et al. 2010, Jimenez et al. 2011). Knowledge of the functioning of urban ecosystems, urban soils and soil faunal communities is of vital importance when planning future urban development if we are to minimize its negative environmental effects, both on city inhabitants, as well as plants and animals (Niemelä 1999).

The principal objective of this study was to assess variation in the abundance of Collembola in urban soils and determine the usefulness of geostatistic-based interpolation by kriging for predicting variation in Collembola assemblages due to environmental pollution in urban landscape.

MATERIAL AND METHODS

Study area

Research was carried out in an urban area of Warsaw (52° 20' N, 21° 00' E, ca. 40 m a. s. l.) that is ca. 500 km^2. It is a typical metropolitan area in Central Europe. The natural vegetation for this area is lime-oak-hornbeam (*Tilio-Carpi-*

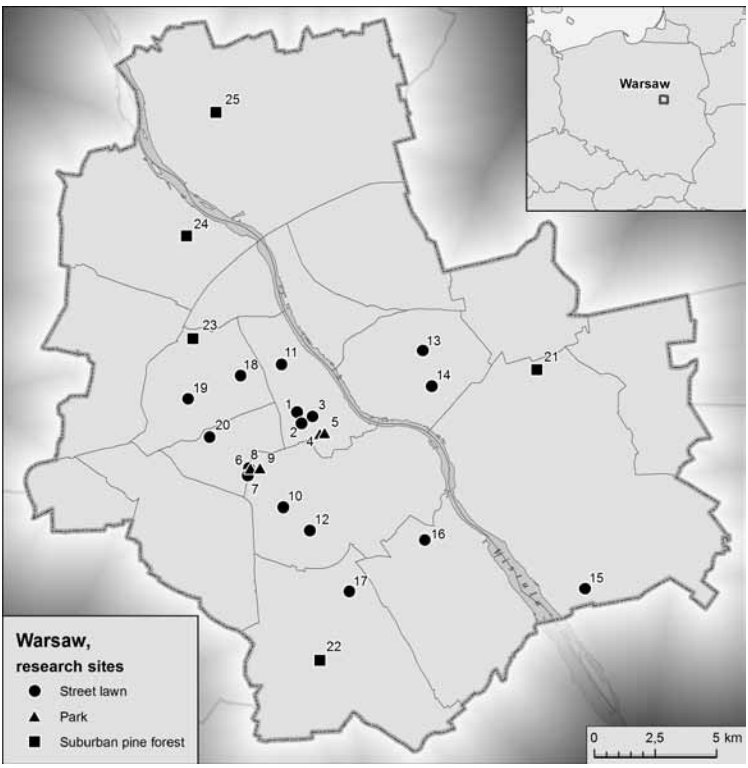

Fig. 1. Location of the study sites in Warsaw.

netum) woodland. Urbanization has almost completely destroyed the primeval woodlands, with only a few parches of forest remaining within the city, mainly in the suburbs, plus a few highly modified patches in built-up areas. Grassland, i.e. more or less open lawns of anthropogenic origin, is the main substitute community. They constitute nearly 70% of Warsaw's green areas. The remaining green areas are various types of thickets, allotments and home gardens, etc. In terms of phytosociology, urban lawns resemble pasture communities (the *Cynosurion* alliance) or moist meadows (the *Arrhenatherion* alliance), both of which belong to the order *Arrhenatheretalia* (Ślipiński et al. 2012).

Twenty five sites were selected at random within the study area (Fig. 1). The sites included street and housing estate lawns (16 sites), parks (4 sites) and suburban pines forests (5 sites).

Sampling

Soil Collembola were sampled in September 2012. Ten soil cores, each of 5.5 cm in diameter and 10 cm long were collected from each site. Collembola were extracted from these soil cores using a MacFadyen apparatus. The individuals were counted in each sample and their abundances per square meter were calculated for each site.

Environmental variables

Research sites were subjected to physico-chemical analyses with respect to soil humidity, soil electric conductivity (EC), soil pH, soil temperature and thickness of grass cover. All these parameters were measured at the same time as the samples of soil for extracting Collembola were collected. Soil humidity, EC and temperature were measured using automated ProCheck sensors. The mean concentration of airborne particles of ~10 micrometers or less per 24 hours and per year (PM_{10}/24h; PM_{10}/year), and NO_2 concentration per year (NO_2/year) were chosen as air quality factors that are most likely to have caused significant disturbances in soil properties within the city area. The PM_{10} in Warsaw originated mainly from exhaust fumes of motor vehicles. They are characterized by high concentrations of trace elements such as S, K, Ca, Na, Al and Fe (Majewski & Łykowski 2008).

Geostatistical analyses

For each site the values of the pollutant concentrations were estimated by interpolation from 1366 data points that originated from an integrated Gaussian puff modelling of air quality dispersion for Warsaw (CALPUFF) using a CALMET processor (a diagnostic 3-dimensional meteorological model). This model was designed to simulate the dispersion of buoyant pollution plumes, puff or continuous point and area pollution sources as well as the dispersion of pollution form continuous line sources. The model also includes algorithms for handling the effect of meteorological variables and topography of the modelled area. The CALPUFF model was obtained from Voivodeship Inspectorate for Environmental Protection in Warsaw. We used the latest available CALPUFF model for Warsaw, with data from the year 2011. Interpolation of pollutant concentrations was done using ordinary kriging. Ordinary kriging was also used to predict the spatial variation in the mean abundance of Collembola at the sites studied. In order to reduce the standard errors of estimation, five sites were excluded from modelling – points with extremely high and low abundances. All geostatistical analyses were done using software ArcGIS for Desktop 10.1 with Geostatistical Analyst extension (ESRI 2011).

Statistical analyses

Kruskal-Wallis one-way ANOVA was used to test significance of the differences in collembolan abundance and environmental variables recorded at the sites studied in street lawns, parks and suburban pine forests. Spearman's rank correlation was used to identify whether the abundance of Collembola was monotonically associated with the environmental variables measured (mean PM_{10}/year, mean PM_{10}/24h, mean NO_2/year, soil pH, soil humidity, soil temperature, soil EC and thickness of grass cover). Thickness of grass cover was correlated with mean abundance of Collembola after exclusion of forested sites. To correlate collembolan abundance with level of urban landscape fragmentation we used an index of urban compactness (I_{UC}), which was calculated as the percentage of the surface covered with vegetation within a set of rectangles within the study area. We used 9 rectangles of 5750×5980 m. The average abundance of Collembola, based on all the sites sampled within a given rectangle, was correlated with the I_{UC} index.

Before geostatistical and statistical analyses, the values of collembolan abundance were log $x_{(10+1)}$ transformed to fulfill requirements for normality. All calculations were done using Statistica 7.0.

RESULTS

The urban habitats studied (street lawns, parks and suburban forests) differed in their physico-chemical soil properties, levels of air pollution and abundance of Collembola (Table 1). The soil pH, humidity, EC, temperature and thickness of grass cover differed significantly when soils of urban biotopes were compared (ANOVA, Kruskal-Wallis test, $p<0.05$). There were no significant differences among urban habitats in levels of air pollution (mean PM_{10}/year, mean PM_{10}/24h and mean NO_2/year), soil temperature and mean abundance of Collembola (ANOVA Kruskal-Wallis,

Table 1. Abundance of Collembola, soil characteristics and concentration of air pollutants (mean values ± SD) in different urban habitats in Warsaw

urban habitat	street lawns n=16	parks n=4	suburban pine forests n=5
abundance (thousand inds./m^2)	4.01± 4.67	6.50± 6.20	2.23± 2.10
soil humidity (%)	6.72± 0.76	6.27± 0.47	4.51± 0.78
soil temperature (°C)	17.43± 10.13	29.68± 2.91	5.17± 3.23
soil electric conductivity (mS/cm)	19.49± 2.57	16.02± 2.30	19.32± 3.09
thickness of grass cover (cm)	0.07± 0.08	0.08± 0.01	0.01± 0.01
mean PM_{10}/year (µg/m^3)	33.95± 4.37	34.20± 1.39	29.79± 2.61
mean PM_{10}/24 h (µg/m^3)	58.31± 7.65	59.77± 2.26	51.85± 4.85
mean NO_2/year (µg/m^3)	29.00± 7.97	29.92± 2.38	20.49± 5.45

Table 2. Differences in the abundance of Collembola and environmental variables recorded in urban habitats (street lawns, parks and suburban pines forests). H – Kruskal-Wallis one-way ANOVA, p – significance level ($p<0.05$), values of collembolan abundances were log $x_{(10+1)}$ transformed, significant p-values are in bold

tested variable	H	p
mean abundance of Collembola (ind/m^2)	1.333	0.513
soil pH	**11.493**	**0.003**
soil humidity (%)	**11.088**	**0.003**
soil temperature (°C)	5.005	0.081
soil EC (mS/cm)	**9.421**	**0.009**
thickness of grass cover (cm)	**9.420**	**0.010**
PM_{10}/year (µg/m^3)	4.454	0.107
PM_{10}/24h (µg/m^3)	4.246	0.120
NO_2/year (µg/m^3)	4.801	0.091

$p>0.05$), (Table 2). The Spearman's rank correlation coefficient (r_s) detected monotonic trends in the abundance of Collembola and fairly positive correlations with soil humidity, soil EC, PM_{10}/24h and NO_2/year (Table 3).

Geostatistical modelling of the parameters of the airborne pollutants fitted a Gaussian model. The high value of the C/(C0+C) ratio and negligible nugget effect (very low nugget variances) indicated that in an urban area of Warsaw the highest spatial variation was in mean NO_2/year and

Table 3. Correlations of Collembolan abundance (log $x_{(10+1)}$ transformed) with environmental variables recorded in an urban area of Warsaw. r_s – Spearman's rank correlation coefficient, df – degree of freedom (n-2), p – significance level ($p<0.05$), significant p-values are in bold

tested variable	r_s	df	p
soil pH	0.066	18	0.754
soil humidity (%)	**0.567**	18	**0.003**
soil temperature (°C)	–0.341	18	0.095
soil EC (mS/cm)	**0.525**	18	**0.007**
PM_{10}/year (µg/m^3)	0.374	18	0.065
PM_{10}/24h (µg/m^3)	**0.425**	18	**0.003**
NO_2/year (µg/m^3)	**0.415**	18	**0.039**
thickness of grass cover (cm)	–0.221	18	0.348
index of urban compactness, I_{uc} (%)	–0.166	7	0.668

then in descending order mean PM_{10}/year and mean PM_{10}/24h (Table 4). The interpolation of mean concentration of air pollutants derived from the geostatistical model using ordinary kriging revealed a progressive gradient from the periphery to the center of the city (Fig 2). Analysis of the spatial variation in collembolan abundance in the urban area studied using a Gaussian model revealed directional changes. However, the negative value of the C/(C0+C) ratio that has a large nugget effect suggested a low and discontinuous spatial autocorrelation (Table 5). Interpolation of mean abundance of Collembola using ordinary kriging predicted that collembolan abundance was highest in the city center and decreases toward its periphery (Fig. 3).

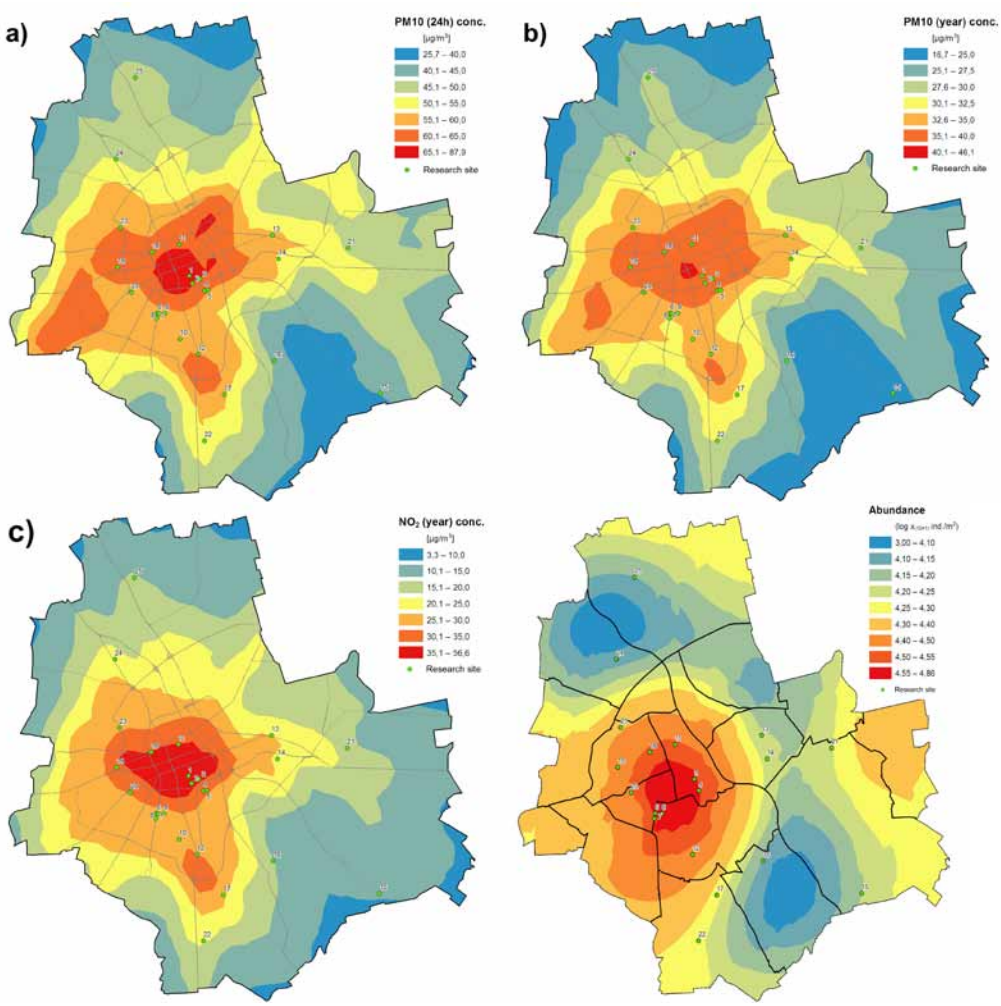

Fig. 2. Maps of the concentrations of air pollutants: a) mean PM_{10}/year ($\mu g/m^3$); b) mean PM_{10}/24h ($\mu g/m^3$); c) mean NO_2/year ($\mu g/m^3$) in an urban area of Warsaw, which were interpolated using ordinary kriging. The 25 research sites are indicated. 3 – map of the mean abundance of Collembola (log $x_{(10+1)}$ ind./m^2) in an urban area of Warsaw, which were interpolated using ordinary kriging.

Table 4. Semivariogram parameters of the geostatistical model of air pollutants recorded in an urban area of Warsaw (n=1366). C0 – nugget variance, C0+C – sill, C/(C0+C) – ratio of spatial variance (C) to sill (C0+C)

variable	model	C0+C	C0	range (m)	C/(C0+C)
PM_{10}/year	Gaussian	1.15	0.124	25559	0.89
PM_{10}/24h	Gaussian	1.12	0.167	25946	0.85
NO_2/year	Gaussian	1.32	0.090	31282	0.93

Table 5. Semivariogram parameters of the geostatistical model of collembolan abundance recorded in an urban area of Warsaw (n=1366). C0 – nugget variance, C0+C – sill, C/(C0+C) – ratio of spatial variance (C) to sill (C0+C)

model	C0+C	C0	range (m)	C/(C0+C)
Gaussian	0.56	0.836	10800	–0.47

DISCUSSION

Geostatistical techniques (interpolation using ordinary kriging) documented a spatial variation in airborne pollutants and soil Collembolan abundance in an urban area of Warsaw. The geostatistical models of the levels of airborne pollutants (PM_{10}/year, PM_{10}/24h; and NO_2/year) indicate a high spatial variation and presence of a progressive gradient from the periphery to the center of the city. Airborne pollutants affect soil habitats and soil faunal assemblages (Rusek & Marshall 2000). Precipitation of airborne dust particles results in, among other things, in the contamination of soil with heavy metals (Soriano et al. 2012) and degradation of soil microbial communities (Grantz et al. 2003). Nitrogen oxides is one of the main source of acid rain, which causes changes in soil pH thus altering basic soil functions (Liang et al. 2012). Our results based on geostatistical modelling reveal that the highest collembolan abundances occur in areas with the highest concentration of airborne pollutants, which clearly increase towards the center of the city. The monotonic trends in the abundance of Collembola and significant positive correlation with PM_{10}/24h and NO_2/year detected by Spearman's rank correlation allow us to assume that the recorded spatial trend in collembolan abundance might be the result of the effect of air pollutants on urban soils. However, our measure of Spearman's rank correlation of Collembolan abundance with the environmental factors studied indicates an inconsistent response of collembolan abundance to these factors. In urban landscape the spatial heterogenity in urban soils is caused by urban climate, biotic composition, buildings and infrastructure, and demographic-social patterns (Pickett & Cadenasso 2009). Fragmented urban landscapes and the interaction with different levels and frequencies of disturbance create many gradients in environmental factors, which can directly and indirectly shape soil faunal assemblages and the nature of their response to disturbance.

A number of studies report an increase in total abundance of Collembola along increasing gradients of metal pollution (Czarnecki & Łosinski 1985, Bengtsson & Rundgren 1988, Pedersen et al. 1999, Gillet & Ponge 2003, Migliorini et al. 2004, Holmstrup et al. 2007, Fiera 2009a). Such effects may be induced by: (1) a low predator pressure at highly polluted sites (Edwards et al. 1967, Filser et al. 2000); (2) lack of competitive exclusion between sensitive but competitive-strong and competitive weak but more pollution-tolerant species of Collembola at these sites (Hågvar 1990); (3) exclusion of parasites sensitive to pollutants (Bengtsson & Rundgren 1988); and/or (4) changes in growth of fungal species preferred as a source of food in highly disturbed habitats (Hågvar 1990, Caruso et al. 2009). It is generally accepted that the level of response of

Collembola to stress caused by environmental pollution is species specific (e.g. Tranvik & Eijsackers 1989, Tranvik et al. 1993, Haimi & Siira-Pietikäinen 1996, Fountain & Hopkin 2004). However, our results indicate that the abundance of Collembola might also be used as a surrogate of the total effect of disturbance due to air pollution in urban soils and experimental studies (MacCabe & Gotelli 2000).

Acknowledgements

We thank Marcin Gąsior of the GIS department of the Museum and Institute of Zoology, Polish Academy of Sciences (Warsaw, Poland) for his help with geostatistical modelling and to Voivodeship Inspectorate of Environmental Protection in Warsaw for provide results of air pollution modelling.. This study was funded by the Museum and Institute of Zoology, PAS project "Star 2012". The language of the manuscript was kindly checked by Professor Anthony F. G. Dixon (Norwich, UK).

REFERENCES

Bengtsson G. & Rundgren S. 1988: The Gusum case: a brass mill and the distribution of soil Collembola. *Canadian Journal of Zoology* **66**: 1518–1526.

Buşmachiu G. & Poiras L. 2003. Effect of some heavy metals on soil invertebrate communities in parks. *Ecologia, Evoluţa şi Ocrotirea Diversităţii Regnului Animal şi Vegetal* **1**: 211–221.

Caruso T., Migliorini M., Bucci C. & Bargagli R. 2009: Spatial patterns and autocorrelation in the response of microarthropods to soil pollutants: The example of oribatid mites in an abandoned mining and smelting area. *Environmental Pollution* **157**: 2939–2948.

Czarnecki A. & Łosiński J. 1985: The effect of GT seed dressing on the community of Collembola in the soil under sugar beet. *Pedobiologia* **28**: 427–431.

Edwards C. A, Dennis E. B. & Empson P. W. 1967: Pesticides and the soil fauna: effects of aldrin and DDT in an arable filed. *Annals of Appield Biology* **60**: 11–22.

ESRI 2011: *ArcGIS Desktop*. Redlands, CA: Environmental Systems Research Institute.

Ettema C. H., Coleman D. C., Vellidis G., Lowrance R. & Rathbun S. L. 1998: Spatiotemporal distributions of bacterivorous nematodes and soil resources in a restored riparian wetland. *Ecology* **79**: 2721–2734.

Fiera C. 2009a: Biodiversity of Collembola in urban soils and their use as bioindicators for pollution. *Pesquisa Agropecuaria Brasileira* **44**: 868–873.

Fiera C. 2009b: Role of Collembola in soil health and their use as indicators. Pp.: 86–91. In: Crăciun I. (eds.): *Species Monitoring in the Central Parks of Bucharest*. Bucureşti: Universitatea din Bucureşti, 121 pp.

Filser J., Wittmann R. & Lang A. 2000: Response types in Collembola towards copper in the microenvironment. *Environmental Pollution* **107**: 71–78.

Fountain M. T. & Hopkin S. P. 2004: A comparative study of the effects of metal contamination on Collembola in the field and in the laboratory. *Ecotoxicology* **13**: 573–587.

Gillet S. & Ponge J-F. 2003: Changes in species assemblages and diets of Collembola along a gradient of metal pollution. *Applied Soil Ecology* **22**: 127–138.

Grantz D. A., Garner J. H. B. & Johnson D. W. 2003: Ecological effects of particulate matter. *Environment International* **29**: 213–239.

Gutierrez-Lopez M., Jesus J. B., Trigo D., Fernandez R., Novo M. & Diaz-Cosin D. J. 2010: Relationships among spatial distribution of soil microarthropods, earthworm species and soil properties. *Pedobiologia* **53**: 381–389.

Hågvar S. 1990: Reactions to soil acidification in microarthropods: is competition a key factor? *Biology and Fertility of Soils* **9**: 178–181.

Hågvar S. & Abrahamsen G. 1990: Microarthropoda and Enchytraeidae (Oligochaeta) in naturally lead-contaminated soil: a gradient study. *Environmental Entomology* **19**: 1263–1277.

Haimi J. & Siira-Pietikäinen A. 1996: Decomposer animal communities in forest soil along heavy metal pollution gradient. *Fresenius Journal of Analytical Chemistry* **354**: 672–675.

Holmstrup M., Maraldo K. & Krogh P. H. 2007: Combined effect of copper and prolonged summer drought on soil microarthropods in the field. *Environmental Pollution* **146**: 525–533.

Jimenez J. J., Decaens T., Amezquita E., Rao I., Thomas R. J. & Lavelle P. 2011: Short-range spatial variability of soil physico-chemical variables related to earthworm clustering in a neotropical gallery forest. *Soil Biology & Biochemistry* **3**: 1071–1080.

Kabata-Pendias A. & Pendias H. 1992: *Trace Elements in Soils and Plants. Second Edition*. Boca Raton: CRC Press, 150 pp.

Liang X. Q., Wang R. Q., Ding W. J., Luo Y. J. & Liu J. 2012: Effects of simulated acid rain on soil chemical properties of potting yellow cinnamon soil under Quercus variabilis. *Applied Mechanics and Materials* **260–261**: 776–780.
MacCabe D. J., Gotelli N. J. 2000: Effects of disturbance frequency, intensity, and area on assemblages of stream macroinvertebrates. *Oecologia* **124**: 270–279.
Majewski G. & Łykowski B. 2008: Skład chemiczny pyłu zawieszonego PM_{10} w aglomeracji warszawskiej. *Acta Scientiarum Polonorum, Formatio Circumiectus* **7**: 81−96.
Manta D. S., Angelone M., Bellanca A., Neri R. & Sprovieria M. 2002: Heavy metals in urban soils: a case study from the city of Palermo (Sicily), Italy. *Science of the Total Environment* **300**: 229–243.
McIntyre N. E., Rango J., Fagan W. F. & Faeth S. H. 2001: Ground arthropod community structure in a heterogeneous urban environment. *Landscape and Urban Planning* **52**: 257–274.
Migliorini M., Pigino G., Bianchi N., Berninia F. & Leonzio C. 2004: The effects of heavy metal contamination on the soil arthropod community of a shooting range. *Environmental Pollution* **129**: 331–340.
Niemelä, J. 1999: Ecology and urban planning. *Biodiversity and Conservation* 8: 119–131.
Pickett S. T. A. & Cadenasso M. L. 2009: Altered resources, disturbance, and heterogeneity: A framework for comparing urban and non-urban soils. *Urban Ecosystems* **12**: 23–44.
Robertson G. P. & Freckman D. W. 1995: The spatial-distribution of nematode trophic groups across a cultivated ecosystem. *Ecology* **76**: 1425–1432.
Rusek J. & Marshall V. G. 2000: Impacts of airborne pollutants on soil fauna. *Annual Review of Ecology and Systematics* **31**: 395–423.
Santamaría J. M., Moraza M. L., Elustondo D. Baquero E., Jordana R., Lasheras E., Bermejo R. & Ariño A. H. 2012: Diversity of Acari and Collembola along a pollution gradient in soils of a pre-pyrenean forest ecosystem. *Environmental Engineering and Management Journal* **11**: 1159–1169.
Soriano A., Pallarés S., Pardo F., Vicente A. B., Sanfeliu T. & Bech J. 2012: Deposition of heavy metals from particulate settleable matter in soils of an industrialised area. *Journal of Geochemical Exploration* **113**: 36–44.
Ślipiński P. Żmichorski M., Czechowski W. 2012: Species diversity and nestedness of ant assemblages in an urban environment. *European Journal of Entomology* **109**: 197–206.
Tiller K. G. 1992: Urban soil contamination in Australia. *Australian Journal of Soil Research* **30**: 937–957.
Tranvik L. & Eijsackers H. 1989: On the advantage of Folsomia fimetarioides over Isotomiella minor (Collembola) in a metal polluted soil. *Oecologia* **80**: 195–200.
Tranvik L., Bengtsson G. & Rundgren S. 1993: Relative abundance and resistance traits of two Collembola species under metal stress. *Journal of Applied Ecology* **30**: 43–52.
Wahl J. J., Theron P. D. & Maboeta M. S. 2012: Soil mesofauna as bioindicators to assess environmental disturbance at a platinum mine in South Africa. *Ecotoxicology and Environmental Safety* **86**: 250–260.