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SPATIAL AND TEMPORAL DISTRIBUTION OF COLLEMBOLA IN ROADSIDE SOIL IN RELATION TO TRAFFIC DENSITY AND WIND DIRECTION

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Abstract

To investigate the possible adverse effects of car exhaust on soil-living invertebrates in roadside verges, community studies were conducted in agricultural fields adjacent to roads of different traffic densities (1500, 650 and 90 vehicles per hour). Monthly soil samples were taken throughout a year along transects (5, 25, 50, 100 and 200 m) in both directions off the roads. Collembola were collected using modified Berlese funnels. Lead concentrations in soil increased with traffic density and were highest at the leeward side of the road. There was no influence of traffic density on levels of cadmium in roadside soil. Analysis of variance revealed that traffic density had a significant negative effect on collembolan abundance, but there were interactions with distance from the road and with wind direction. Abundance of Collembola was highest in summer and autumn. The distribution of Collembola along the transects was not correlated with the lead distribution. It is concluded that (i) heavy traffic may adversely affect abundance of Collembola in roadside soils, (ii) it remains unsure whether the effects can be attributed to lead accumulation alone or to other influences of heavy traffic, (iii) wind direction plays an important role in the distribution of traffic-related contaminants and their possible effects on soil Collembola.

Keywords: Collembola, community, spatial distribution, soil invertebrates, traffic, heavy metals, lead, cadmium

Introduction

The extensive use of automobiles is one of the most important sources of heavy metal contamination in the roadside environment (Garcia and Milan, 1994). High concentrations of lead derived from motor vehicles that operate with leaded gasoline can affect the diversity, frequency and relative abundance of individual species in the soil community, as well as the dynamic processes that they catalyze (Edwards and Bohlen 1995). It is mentioned that problems are expected to increase especially in tropical environments where the increase of traffic density is not always accompanied by proportional control measures for air pollution for instance, air pollution in Bangkok, Thailand has a demonstrable influence on respiratory disease among the exposed population (Vichit-Vadakan *et al.*, 2001). Similar problems around Egyptian cities are expected. Thus, exhaust contaminants can affect the overall structure and function of ecosystems.

Collembola are by far the most abundant hexapods in soil and attain high densities of up to 100,000 individuals per m^2 (Kampichler *et al.*, 2000). They live in wet as well as in dry ecosystems and contribute functionally to different trophic levels within the terrestrial food web (Rusek, 1998). They can exert a significant influence on mineralization processes and nutrient cycling via trophic interactions with decomposer microorganisms (Verhoef and Brussaard, 1990; Lussenhop, 1992). Soil zoologists have been trying to discern the factors governing the distribution of Collembola at different spatial scales (Usher and Booth, 1986). Various soil factors (i.e. soil type, plant cover and intensity of soil cultivation) directly influence the soil microarthropod community with respect to number and composition (Andren and Lagerlof,1983) and their spatial distribution (Farrar and Crossely, 1983).

Accumulation of lead has been recorded in soils adjacent to major roads; the levels of contamination usually decrease with distance from the road and increase with traffic volume (Zimdahl and Arvik, 1973; Smith 1976). The influence of lead on the abundance of soil organisms will thus depend on the distance from the road (Van Capelleveen *et al.*, 1986; Khalil *et al.*, 2003). Little is however known about the effect of traffic density on spatial and temporal dynamics of soil Collembola.

In this study, seasonal changes in community structure of collembolan communities were studied as a function of time and distance in soil adjacent to roads with different traffic densities. The main goal of this study was to test the hypotheses that (i) wind direction plays an important role in quantitative heavy metal (Pb, Cd) distribution, (ii) there is a relationship between metal distribution and collembolan abundance along transects off the road; and (iii) the distribution patterns of Collembola are affected by exhausts from motor vehicles.

Materials and Methods

Sampling and study sites

Three agro-ecosystems of similar vegetational rotation (mainly annual crops; clover in winter and corn in summer) in Sohag Governorate, Egypt were chosen on the basis of traffic densities. The high density (H) road had 1500 vehicles per hour, the moderate density (M) road 650 vehicles per hour and the low density (L) road 90 vehicles per hour.

A square metal sampling device (10 x 10 cm) was used to take soil samples to a depth of 5 cm. The sampling period covered a full annual cycle. In each month, four samples were taken at each of five distances (5, 25, 50, 100 and 200 m), in a transect perpendicular to the road. Thus, a total of twenty sample units were taken from each distance. Wind direction was also taken into consideration; sampling was carried out at each side of the road in all three areas. In total, 4 (replicates) x 5 (distances) x 2 (wind directions) x 3 (traffic densities) x 12 (months) = 720 samples were taken and extracted for Collembola.

Vehicle densities were measured by means of a rubber rope and a counting device placed at the roadside. The average traffic density was based on four seasonal records. The sampling sites were denoted H_W, H_L, M_W, M_L, L_W, and L_L for high (H), moderate (M) and low (L) density, each of which could be either windward (W) or leeward (L).

Samples were transported to the laboratory and extracted using modified Berlese funnels. All animals were prepared and identified to species as explained in detail by Al-Assiuty *et al.* (1993).

Data processing and data analysis

To determine the effect of traffic density, distance and wind direction, a three-way analysis of variance (ANOVA) was applied (Sokal and Rohlf, 1995) using wind (two levels), traffic density (three levels) and distance (five levels) as factors. Kruskal-Wallis test (Steel and Torrie, 1976) was applied to compare between the data of heavy metals. Fluctuations of population density were evaluated using the coefficient of variation (Al-Assiuty and Khalil, 1996). Spatial aggregation was evaluated from the dispersion index s^2/m where s = standard deviation, and m = arithmetic mean. The spatial distribution of Collembola and heavy metals (lead and cadmium) along the transect was quantified by the average distance or centre of gravity of the distribution (*M*) and the distance variation, (*S*)

$$M = \frac{\sum_{i=1}^{k} d_i n_i}{N} \qquad \text{and} \qquad S = \sqrt{\frac{\sum_{i=1}^{k} n_i (d_i - M)^2}{N}}$$

where *M* is the distance index, d_i is the distance from the road at sampling location *i* (i = 1, 2,…5) in the gradient), n_i is the abundance of Collembola or the metal concentration at sampling location *i*, *N* is the total abundance of individuals or the sum of the metal concentrations, and *S* is the distance variation. The formulae for the distance index (*M*) and distance deviation (*S*) were used by Usher, (1970) and Faber and Joosse, (1993) to determine the vertical distribution of collembolan species, and by Hasegawa, (1997) for the temporal succession of Collembola and Cryptostigmata (Acari).

Metal analysis

On four seasons of the twelve sampling occasions, samples were taken for metal analysis, one at each distance. Analysis of lead and cadmium were carried out using acid digestion and flame atomic absorption spectophotometry (Perkin Elmer 2380) as explained in detail elsewhere (Khalil *et al.*, 2004).

Results

Metal concentrations

Analysis of variance-Kruskal Wallis test applied to the measurements of lead and cadmium in roadside soil (Table 1) demonstrated a significant effect of traffic density, lead being highest at the site with the highest traffic density. In addition, at all sites the lead concentration was higher at the leeward side of the road, compared to the windward side, however, this effect was not significant for cadmium where no obvious trends could be observed.

Abundance of Collembola

All collembolan species extracted from the six transects were counted and identified. Table 2 lists the species composition per site. The community was dominated by *Xenylla inermi*s, *Friesea claviseta*, *Folsomides parvulus* and *Cryptopygus thermophilus*. Most of the species occurred at all sites. However, *Isotomurus palustris* was restricted for M_W, *Prodrepanura musatica* and *Lepidocyrtus cyaneus* were restricted for L_L and M_W, respectively, *Parisotoma notabilis* was restricted for M_W and L_W, *Seira traegaardhi* was restricted as shared species for H_W and L_W and *Cyphoderus bidenticulatus* was recorded as shared species for H_L and L_W and there was no difference in species richness among traffic densities.

Three-way analysis of variance was applied to the data pooled over all seasons. This showed a small but significant overall effect of traffic density (Table 3), implying that the abundance of Collembola was highest at the low traffic density site, and lowest at the high traffic density site. The overall effect of distance was not significant, neither was the overall effect of wind direction, however, there was a significant three-way interaction, implying that at some sites the effects of distance and traffic density were opposite to the effects at other sites. This pattern in the data becomes more obvious when the observations are presented with respect to distance and compared idividually (Fig. 1 a,b,c). At the H_L site, it could be observed that the population density of Collembola was the highest at 5 m distance, while at 200 m-distance the lowest value was recorded. In site H_W, there was no obvious pattern of collembolan abundance with distance. In site M, no differences between the two sides of the road could be recorded at all distances except at 50 m, where the abundance was higher at the windward side than at the leeward side. At site L, the annual population density of Collembola was high at the leeward side, at 25 m and 100 m from the road when compared with the densities at the same distances at the other side.

Obviously, the distribution of Collembola with respect to distance from the road was complicated and a clear gradient was observed only at some of the sites as shown in Figure 1.

Seasonal changes

Another perspective is obtained by pooling the abundance over all distances per site, for each sampling time. Monthly changes in population density are displayed graphically in Figs. 2 a, b, and c. At site H_L, the annual cycle of the population density indicates that there were two peaks per year; one in July and the other in November, while in site H_W, three peaks per year in March, May and November were observed. At site M_L, the population density of Collembola dropped during February and three peaks were observed in April, August and November while in M_W, no obvious fluctuation could be seen during late-winter till mid-summer however, a marked decrease was observed in October. At site L no clear differences in annual fluctuation pattern of the collembolan community could be observed between the two sides of the road. The population density of Collembola increased in May and stayed high during summer until autumn. At site L_L, the main peak of abundance fell in July but in site L_W, two peaks in March and May were recorded.

In general, it can be concluded that the warm seasons (summer and autumn) showed the highest abundance of Collembola (Fig. 2). The difference between winter/spring (lower density) and summer/autumn (higher density) was greatest at the low traffic density sites.

Spatial distribution

The distribution of Collembola and metals were analysed by calculating the distance index and the distance variation for both Collembola and metal concentrations in each season (Table 4). The center of gravity of the Collembola distribution was located at a distance varying between 41.9 m (site M_W in spring) and 93.5 m (site H_W in summer). The centre of the Pb distribution was further away from the road (varying between 52.0 m and 132 m). Consequently, there was no correlation between Collembola abundance and metal concentration. As concerns the distance deviations (S), the data revealed a relationship between spatial distribution of Collembola and wind direction at all sampling sites: the spatial variation in the leeward transect was always smaller than that in the windward transect (Table 4).

Spatial distribution was also analysed in terms of the aggregation index (variance of abundance relative to mean). For every season the index was calculated at each site. Fig. 3 shows that the area exposed to low traffic density had the lowest aggregation index; the seasonal changes of spatial distribution are very large at the high traffic density site.

Discussion

The data of this study showed that Collembola abundance was influenced by traffic density. Overall, the largest numbers were found at sites with low traffic density and the smallest numbers occurred at the high traffic density site. There was no influence of traffic density on levels of cadmium in roadside soil where metal analysis revealed that the total cadmium contents of the studied soils ranged between 1.8-3.8 µg g^{1}. These ranges lie in generally accepted values among uncontaminated soils where, in normal agricultural soil, the total cadmium contents ranges between <0.1 µg g^{1} to 10 µg g^{1} (Yaron *et al.*, 1996). The lead concentrations however, were highest at the high traffic density site, and were always higher on the leeward side of the road than on the windward side. The question may be asked whether the lead concentration can be the cause for the observed differences in Collembola abundance.

The concentration of lead in soil was not clearly related to distance in our study. Lead emitted from car exhausts is often distribution in a decreasing gradient with distance from the road. Wood (2000) concluded that the impact of a rural highway on soil contamination was restricted to within 15 m from the hard shoulder on both sides while any significant contamination was restricted to within 5 m. However, other studies have shown that lead contamination may proceed further away. For example, Van Capelleveen *et al.* (1986) measured elevated Pb concentrations up to a distance of 35 m from the road.

Sjögren (1997) assessed the impact of heavy metals on dispersal rate of five collembolan species. She found that the tested Collembola had a higher rate of dispersal in polluted soil than in unpolluted soil. The effect of metal in soil on dispersal of Collembola may be due to (i) direct avoidance behaviour, (ii) the distribution of fungi (as a food source), and (iii) a change of resource quality of decomposing organic matter due to contamination. Hasegawa (1997) indicated that the difference of colonization pattern between soil arthropod species was probably due to species-specific responses to the change of resource quality of decomposing litter. Chauvat and Ponge (2002) and Gillet and Ponge (2003) showed that the spatial distribution of Collembola in soil may be affected by heavy metal pollution. These results could explain the seasonal changes of aggregation as observed in our study and the fact that the seasonal dynamics of aggregation were greatest in the high traffic density site.

Comparing our data to laboratory-based toxicity thresholds of lead does not provide indications that the concentrations in the roadside verges in our study were directly toxic to Collembola. Effects of lead on Collembola are usually observed at concentrations above 500 mg/kg (Sandifer and Hopken, 1996; Bongers *et al.*, 2004). Van Straalen, (1993) used a statistical extrapolation model fed by laboratory data to calculate a critical concentration for sensitive soil invertebrates (HC5) for Pb of 76.6 mg/kg. The average concentration in the soil at the most polluted site in our study (63 mg/kg) is still below this value.

Bengtsson and Tranvik (1989), in a review of field studies, suggested that the critical level of lead for forest soil invertebrates was 100-200 mg/kg. This range was based on effects on abundance, diversity and life history parameters. Lock *et al.* (2003), in a field study of an abandoned mining site in Belgium found negative correlations between Collembola and lead in soil, but the strongest effects were not due to lead, but to zinc. Hågvar and Abrahamsen (1990) studied collembolan communities in a natural lead gradient and found the lowest species diversity at the highest lead concentrations. Posthuma (1997) re-analysed these data and estimated a critical threshold of 219 mg/kg. So also, the available field data indicate that effects of lead in soil on Collembola communities occur above the levels found in our study.
Vichit-Vadakan *et al.* (2001) reported that in tropical environments the increase of traffic density is not always accompanied by proportional control measures for air pollution and has a demonstrable influence on respiratory disease among the exposed population. The present study however, has not addressed human health problems but on the other hand, the effects on invertebrates indicate that the problems are not far away.

It is concluded that (1) traffic density may affect Collembola populations in roadside soils, up to 100 m from the road, (2) the wind direction plays an important role in the distribution of exhausts and also in the effects on Collembola, (3) lead concentrations cannot be identified as the sole cause for the effects; other contaminants or physical road-associated influences may also play a role.

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Table 1. Pb and Cd concentrations (mg/kg) in the different study sites. Means are given with standard deviations based on twenty replicates (data pooled over five samples in the distance gradient, taken at four sampling occasions in a year).

	H_L	H_W	M_L	M_W	L_L	L_W
Lead	63 ± 17.7	30.8 ± 12.2	45.8 ± 14.7	30.8 ± 2.4	14.9 ± 28.2	22.3 ± 10.3
Cadmium	0.27 ± 2	0.51 ± 2.2	0.51 ± 2.7	0.73 ± 3.8	1.57 ± 3.2	0.93 ± 1.8

H_L = High traffic density–leeward, H_W = High traffic density–-windward,
M_L = Moderate traffic density–leeward, M_W = Moderate traffic density–windward,
L_L = Low traffic density–-leeward, L_W = Low traffic density–windward
Analysis of variance-Kruskal Wallis test showed a significant effect of traffic density for lead $P< 0.05$ df =2 however, the effect was not significant for cadmium.

Table 2. Abundance of Collembola species (no. per m^2) in the study areas as a function of traffic density and wind direction. The data were pooled over all 12 sampling occasions and five distances at each site.

Species	H_L	H_W	M_L	M_W	L_L	L_W
Hypogastruridae						
Ceratophysella denticulata	105	76	124	155	33	-
Xenylla inermis	466	49	831	541	1014	1015
Neanuridae						
Friesea claviseta	1723	1782	1400	3180	2157	3297
Onychiuridae						
Microphorura absoloni	16	68	82	16	114	-
Tullbergiidae						
Paratullbergia callipygos	42	24	57	66	25	16
Isotomidae						
Folsomides parvulus	2032	1389	3440	1697	2999	2056
Parisotoma notabilis				141		49
Isotoma viridis	197	291	50	446	298	139
Hemisotoma orientalis	94	32		107	207	74
Cryptopygus thermophilus	6124	4649	3257	3599	4941	4014
Isotomurus palustris	-	-	-	16	-	-
Entomobryidae						
Prodrepanura musatica	-	-	-	-	8	-
Lepidocyrtus cyaneus	-	-	-	41	-	-
Seira traegaardhi	-	24	-	-	-	158
Pseudosinella octopunctata	133	140	91	-	41	18
Cyphoderidae						
Cyphoderus bidenticulatus	16	-	-	-	-	66
Sminthuridae						
Sphaeridia pumilis	-	41	25	58	-	32
Total number of individuals	10948	8565	9357	10063	11837	10934
Total number of species	11	12	10	13	11	12

H_L = High traffic density-leeward, H_W = High traffic density–windward,
M_L = Moderate traffic density–leeward, M_W = Moderate traffic density–windward,
L_L = Low traffic density–leeward, L_W = Low traffic density–windward

Table 3. Three-way analysis of variance for total Collembola abundance (pooled over all sampling occasions).

Source of variation	df	MS	F	P	
Wind direction	1	1515.208	3.505	0.064	n.s.
Traffic density	2	1879.433	4.376	0.015	*
Distance from road	4	410.638	0.956	0.436	n.s.
Wind x Traffic	2	418.633	0.975	0.381	n.s.
Wind x Distance	4	442.646	1.031	0.396	n.s.
Traffic x Distance	8	713.663	1.662	0.119	n.s.
Wind x Traffic x Distance	8	1435.696	3.343	0.002	*
Error	90	429.481			

MS = mean squares, df = degree of freedom, F = F statistic, n.s. = not significant,
* = significant.

Table 4. The distance index: mean distance (M, in m) and distance deviation (S, m) for Collembola abundance and lead and cadmium in the six studied sites

Season	Parameter	H_L	H_W	M_L	M_W	L_L	L_W
Winter	M Coll.	52.5	70.9	73.4	63.3	67.3	88.3
	S Coll.	42.1	77.0	62.0	70.3	59.9	81.3
	M Pb	110	95.1	101	89.7	65.0	74.4
	M Cd	116	64.1	125	73.7	77.8	62.2
Spring	M Coll.	78.7	73.1	50.7	41.9	84.0	62.7
	S Coll.	67.2	85.2	30.6	36.9	71.7	86.2
	M Pb	132.	98.5	110	52.0	89.3	75.3
	M Cd	142	63.0	127	76.1	79.1	72.3
Summer	M Coll.	80.4	93.5	112	85.8	83.7	83.9
	S Coll.	63.2	86.3	78.4	89.1	70.1	79.0
	M Pb	115	76.0	117	69.2	89.1	86.7
	M Cd	112	81.1	123	71.5	85.1	93.0
Autumn	M Coll.	43.1	87.6	66.5	84.5	83.46	52.1
	S Coll.	36.1	73.6	62.3	83.5	61.2	45.1
	M Pb	115	76.3	118	72.8	91.6	63.3
	M Cd	116	63.1	106	75.2	71.3	69.2

M Coll. = distance index of collembolan abundance, S Coll. = distance deviation of collembolan distribution, M Pb = distance index of lead concentrations in soil, M Cd = distance index of cadmium concentrations in soil, H_L = High traffic density–leeward, H_W = High traffic density–windward, M_L = Moderate traffic density–leeward, M_W = Moderate traffic density–windward, L_L = Low traffic density–leeward, L_W = Low traffic density–windward.

Legends to Figures

Fig. 1. Annual population density of Collembola in roadside soils at different distances, at the high traffic density site (a), at intermediate traffic density (b), and at low traffic density (c). The densities are given at the leeward side of the road and the windward side. Columns having the same symbol don't significantly differ from each other (Kruskal-Wallis test).

Fig. 2. Changes in population density of Collembola over the sampling year at the high traffic density site (a), at intermediate traffic density (b), and at low traffic density (c). The densities are given at the leeward side of the road and the windward side.

Fig. 3. Seasonal fluctuation of spatial aggregation (standard deviation relative to mean) of Collembola on the four different sampling sites. H_L = High traffic density–leeward, H_W = High traffic density–windward, M_L = Moderate traffic density–leeward, M_W = Moderate traffic density–windward, L_L = Low traffic density–leeward, L_W = Low traffic density–windward.