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Soil communities along a gradient of urbanization

BY

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Synopsis: Several soil abiotic factors were measured and their relation with the Shannon-Weaver index of diversity (H') for soil communities at sites along a gradient of urbanization was examined.

Strong negative correlations were detected between H' and soil lead concentration and between H' and percent sand, whereas positive correlations existed between H' and distance from the center of the city, and H' and percent clay.

Keywords: Lead - urbanization - soil texture - soil moisture - soil communities - soil organic matter - diversity index - urban ecology.

INTRODUCTION

Since the beginning of the present century, researchers have focused their attention to the effects of anthropogenic pollution on biota (HAYWOOD, 1907). That early interest in heavy metals has currently culminated in a plethora of reports and papers on the effects of heavy metals upon communities, populations and individuals (ANTONOVICS *et al.*, 1971; HUGHES *et al.*, 1980; COMMITTEE ON BIOLOGIC EFFECTS OF ATMOSPHERIC POLLUTANTS, 1972; LAGERWERFF and SPECHT, 1970).

The metals most commonly associated with man-made pollution of the atmosphere, lithosphere or hydrosphere are cadmium, nickel, lead and zinc. Elevated concentrations of the above metals have been found around point-sources such as mines or smelters (STROJAN, 1975; WRIGHT and STRINGER, 1980; BISESSAR, 1982) or even in urban environments (CHAMBERLAIN *et al.*, 1979; LITTLE and WIFFEN, 1978; DAY *et al.*, 1979; WILLIAMSON and EVANS, 1972).

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The concentration of any of the above four metals can and has been used as a measure of urbanization. Urbanization is defined here as aggregation of human populations with subsequent perturbation of the environment. Lead has been used as a measure of urbanization more frequently than the rest of the metals (LAGERWERFF and SPECHT, 1970; BUCHAUER, 1973; LITTLE and WIFFEN, 1978; GULSON, *et al.*, 1981) because of its severe toxic effects upon humans. Data for soil microorganisms support the hypothesis of severe lead toxicity upon soil communities (DOELMAN and HAANSTRA, 1979), although other studies indicate that some soil animals accumulate considerable amounts of heavy metals in their bodies without any obvious effects on their survival (IRELAND, 1975; 1979).

The hypothesis that lead disturbs the composition of soil communities was tested by comparing communities from sites located along a gradient of urbanization which is assumed to represent also a gradient of lead pollution. Additional objectives of the study were: 1) To detect temporal variations in soil community composition, and 2) To incorporate several physicochemical factors, reportedly affecting soil communities, in a model which would predict the change in soil community composition associated with the above factors.

I. — THE STUDY AREA

In Washington, D. C., Massachussetts Avenue is a main traffic artery running from Northwest to Southeast and then turning to a Northeast direction (Fig. 1). It was selected as a transect because of three reasons: 1) It runs in a constant direction from the center of the city to the suburbs. Along its length, there are many public places, which do not require any special permit for sampling. 2) The traffic volume on Massachussetts Avenue gradually declines as one goes from the center to the outskirts of the city. However, the traffic counts data provided by the Traffic Bureau of the District of Columbia were fragmentary and inconsistent and were not used in the study. 3) Massachussetts Avenue crosses many residential, commercial and recreational areas, and it provides a representative sample of the variety of zones existing within a city.

Using the U.S. Capitol as the center, eight concentric circles of 1.6, 3.2, ..., 12.8 km radii were drawn on a map of the city. Within each ring defined by two adjacent circles and on, or as close as possible to, the transect, one sampling station was selected, for a total of eight sampling stations. Sites 1, 2 and 3 were not located on Massachussetts Avenue but were selected to satisfy the desire to include the Mall, the Ellipse and Washington Circle. A more detailed description of the sampling sites is given by SANTAS (1982). The distance of each site from the center was the straight line distance from the U.S. Capitol determined from maps of the U.S. Geologic Survey.

II. — MATERIALS AND METHODS

A variety of diversity indices exists (LEGENDRE and LEGENDRE, 1983). The Shannon-Weaner index (H'), as defined by the formula: $H' = -\Sigma p_i \log_2 p_i$ where p_i is the proportion of the total sample belonging to the ith species, expressed in numbers or biomass and the logarithm taken to base 2 to provide binary units (bits) of information (PIELOU, 1969), is an index particularly popular among researchers. Its popularity stems from the fact that H' is relatively independent from sample size and more sensitive to the addition or rarer taxa (PEET, 1974; COX, 1985).

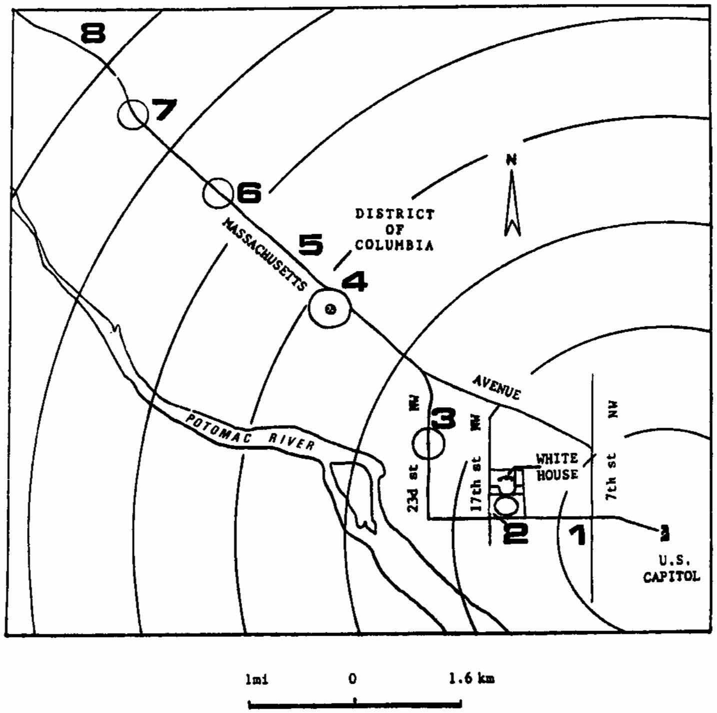

FIG. 1. — Map of Washington, D.C. showing the location of the transect (Massachussetts Avenue) and the eight sampling sites at increasing distances from the center of the city. (See text for details).

Soil samples were collected with a soil corer 7.5 cm in diameter and 15 cm deep. From November 1980 through May 1981, four soil cores per site per month were extracted, with the exception of December 1980 and January 1981 when the ground was frozen. Two soil cores were extracted from a strip 1-3 m away from the paved edge of the road (hereafter designated « close » to the road), whereas another two were extracted from a strip 5-10 m away from the same edge (hereafter designated « away » from the road). A more intensive sampling regime was not adopted because: 1) It would disrupt soil community composition, therefore introducing bias to the results of subsequent months, and 2) In some cases (e.g. sites 1, 2, 4 and 5) urbanization was so severe, that only a few square meters of soil were available for sampling.

Each soil core was inverted in a one-gallon plastic bag which was tied shut and brought to the laboratory, where it was immediately stored at 4-5° C before further examination.

A mercury thermometer was inserted in a hole (2 cm in diameter by 10 cm deep) in the soil and a reading of the soil temperature was obtained after equilibration occurred. Four replicate soil temperature readings per site per collecting period were taken.

In the laboratory, Berlese extractors with a wire screen (2 mm mesh size) and incadescent light (Sylvania, soft white, 150 W bulbs) were used to extract the soil organisms from the cores. The bulbs were placed at a height of 20 cm above the soil core, providing a temperature ranging between 45 and 50° C at the surface of the core. The organisms were collected in 70 % ethanol and were stored in ethanol at room temperature for identification. LEVI and LEVI (1968), BLAND and JACQUES (1978) and BARNES (1980) were used for identifying the organisms collected from the extractors.

The hydrometer method (BOUYOUCOS, 1927 and 1936 as described in COX, 1985) was used to determine soil texture by particle size analysis. The results were expressed as percent sand, silt and clay in the soil.

Each core dried in the Berlese extractors was placed in a sieve with 2 mm mesh size and a portion of the fraction passing the sieve was selected at random and analyzed for lead. Preparation of the sample included extraction of the soil lead in an aqueous solution of nitric acid (1:1 v/v). An extractant to soil ratio of 5:1 (v/w) as recommended by GEDROITS (1963), was prepared by adding 125 ml of the above nitric acid solution to 25 g of dry 2 mm fraction, swirled to mix for 1 min and left to slake overnight. The supernatant was filtered *in vacuo* through a 0.45 μm glass membrane filter (Millipore HA) and the filtrate was made to a final volume of 250 ml with deionized water. Lead was determined colorimetrically with the dithizone method in a Hach DR/2 spectrophotometer following the protocol described in the Hach Company Instructions Manual (1977). The results are expressed as mg Pb/kg soil or, equivalently, ppm.

Organic matter was determined as percent loss on ignition by placing a weighed portion of Berlese funnel dried soil in a muffle furnace at 800° C for 4 hr.

On 7 May 1981, five days after a severe rainstorm, a complete set of 32 soil cores (4 cores/site) was taken in order to assess the moisture holding capacity of the soil. A subsample from the 2 mm fraction of each soil core was selected at random, weighed and placed in an oven at 105° C for 24 hr. Soil moisture holding capacity is expressed as percent weight loss on a dry soil weight basis.

Two-way ANOVAS with collecting period and site as the main sources of variation were performed on the data. In order to keep the paper as concise as possible, only data on soil lead concentration and species diversity (H') are presented here, although in the multiple regression equation, data for the other factors are included as well. Whenever data had to be transformed (e. g. soil lead, soil moisture, etc.) ANOVAS and means analyses were performed on the transformed data, 95 % Just Significant Confidence Intervals (SNEDECOR and COCHRAN, 1980) calculated and placed about the transformed means, and the results converted back to their original scale. Throughout the present study a significance level of 0.05 is used.

III. — RESULTS

A total of 39 taxa were observed throughout the study, and the per site species richness ranged from eleven to twenty-three (see Appendix).

Since the data for lead did not show homogeneity of variance, they were log transformed before the ANOVA was performed (SNEDECOR and COCHRAN, 1980). Collection period and site had significant contributions ($F = 8.64$, $df = 3, 117$, $P < 0.05$ and $F = 11.14$, $df = 7, 117$, $P < 0.05$, respectively). Lead levels for April and May (Fig 2) were twice as high as those for February and March. Site 2 was the most severely contaminated one, with lead levels higher than those of sites 5, 6, 7 and 8 (Fig. 3). Site 8, the most distant from the center of the city, was the least contaminated one, with soil lead concentrations significantly lower than any other site.

Shannon-Weaver diversity indices (H') were calculated for each soil core extracted during the study. « Information » in the cores ranged from undetermined, for samples with no organisms in them, to a maximum of 2.69 bits/

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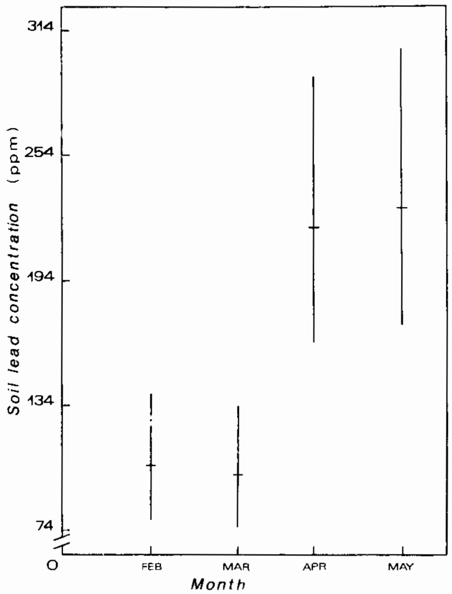

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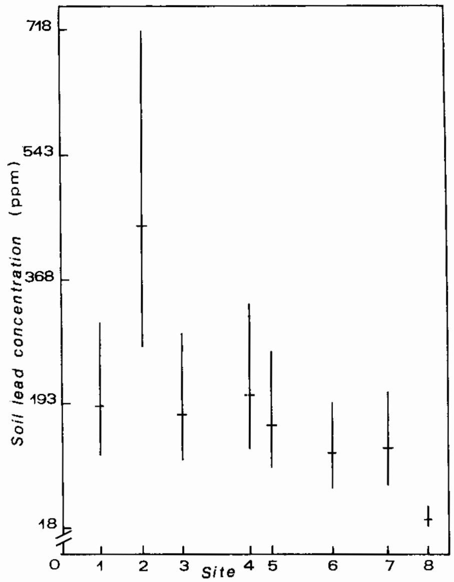

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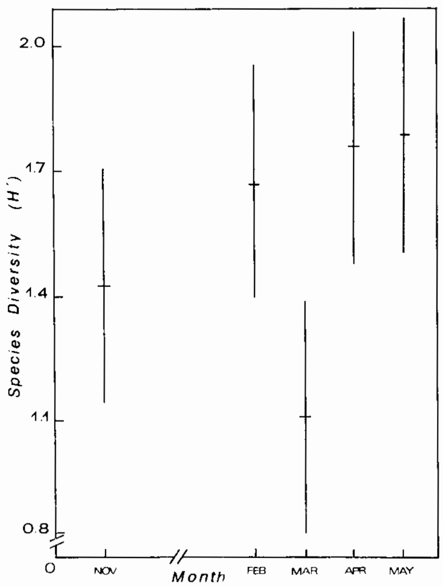

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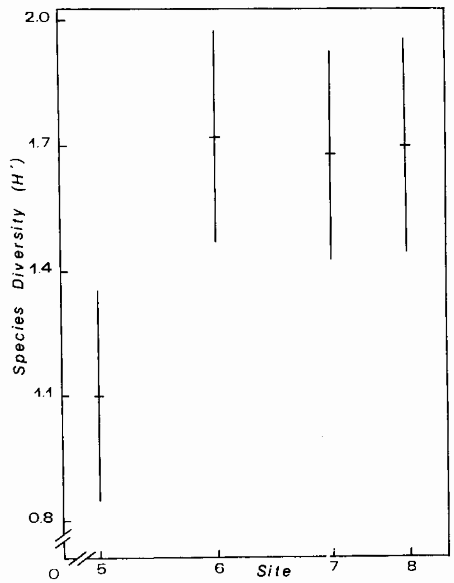

FIG. 2. — Means analysis for lead concentration in soil cores extracted in various sampling periods. Means ± 95 % Just Significant Confidence Intervals.

FIG. 3. — Means analysis for lead concentration in soil cores extracted from various sampling sites. Sites are plotted as distances from the center of the city (U.S. Capitol). Means ± 95 % Just Significant Confidence Intervals.

FIG. 4. — Means analysis for species diversity (H') in soil cores extracted in various sampling periods. Means ± 95 % Just Significant Confidence Intervals.

FIG. 5. — Means analysis for species diversity (H') in soil cores extracted from various sampling sites. Sites are plotted as distances from the center of the city (U.S. Capitol). Means ± 95 % Just Significant Confidence Intervals.

individual. Since all of the missing values were due to the method used and not due to accidental loss of data, estimates of the missing values from existing data are not permissible (SNEDECOR and COCHRAN, 1980). All of the soil cores with no organisms in them were taken from the first four sites, closer to the center of the city. The data from the first four sites were discarded and a three-way ANOVA was performed on the remaining data, using collecting site, collecting period and distance from the paved edge of the road (« close » vs « away ») as the main sources of variation. Only the variation due to collecting period ($F = 3.49$, $df = 4, 40$, $P < 0.05$) and site ($F = 4.89$, $df = 3, 40$, $P < 0.05$) were significant. Means analysis for the species diversity in each month is shown in Fig. 4 and for diversity at each site in Fig. 5.

The following variables, transformed as shown to stabilize their variances, were used in a multiple linear regression model:

1. Species diversity (H′) as the dependent variable,
2. Distance of the site from the U.S. Capitol,
3. Log transformed mean soil lead concentration,
4. Mean soil temperature,
5. Arcsin transformed percent sand content,
6. Arcsin transformed percent clay content,
7. Arcsin transformed percent organic matter,
8. Arcsin transformed percent moisture holding capacity.

The data were averaged over all months and they were run on a multiple regression program (BMDP1R). Since average estimates of diversity could be obtained for sites 1, 2, 3 and 4, data from these sites were included in the analysis as well. Percent silt content of the soil was not included in the multiple regression because it is not a truly independent variable. In any soil, the sum of percent sand, percent silt and percent clay is constant (equal to 100). Therefore, only two out of the three variables (percent sand, silt and clay) are really independent, the third being calculated by subtracting the sum of the other two from 100.

Table I shows the correlation matrix for all possible pairs of variables. Species diversity is most positively correlated with distance and most negatively with lead. Lead, in turn, is most negatively correlated with distance, whereas distance is negatively correlated with percent sand. Sites closer to the inner city have been extensively amended with sand and, therefore, contain relatively lower proportions of clay than sites farther away from the center of the city. Equally high intercorrelations exist between sand and lead, and sand, clay and moisture holding capacity. Water molecules are adsorbed on negatively charged clay particles and become immobilized for various lengths of time.

The ANOVA for the regression analysis showed that the regression of species diversity on the rest of the variables was significant ($F = 557.35$, $df = 6$, $P < 0.05$). Soil temperature was not included in the regression because: 1) It did not vary significantly ($cv = 0.05$), and 2) It was poorly correlated with the rest of the variables (Tab. I). The regression coefficients for distance and sand were not significantly different from zero ($t = 6.65$,

TAB. I

CORRELATION MATRIX

Pairwise correlation coefficients for the eight variables studied. The observations for each variable were averaged over the entire period of the study and introduced to a multiple linear regression program. (H′ = Shannon-Weaner index of diversity, DIST = linear distance of each site from the center of the city, LEAD = log transformed soil lead concentration, TEMP = soil temperature, SAND = arcsin transformed percent sand content, CLAY = arcsin transformed percent clay content, OMAT = arcsin transformed percent organic matter in the soil, MOIST = arcsin transformed percent moisture holding capacity of soil).

	H′	DIST	LEAD	TEMP	SAND	CLAY	OMAT	MOIST
H′	1.00							
DIST	0.85	1.00						
LEAD	− 0.73	− 0.78	1.00					
TEMP	− 0.04	− 0,10	− 0.23	1.00				
SAND	− 0.59	− 0.70	0.44	− 0.88	1.00			
CLAY	0.42	0.49	− 0.05	− 0.12	− 0.80	1.00		
OMAT	0.17	− 0.01	0.16	− 0.17	− 0.52	0.34	1.00	
MOIST	0.33	0.44	0.21	− 0.10	− 0.89	0.80	0.64	1.00

$P > 0.05$ and $t = 9.10$, $P > 0.05$, respectively) and thus, it seems that these two variables did not contribute significantly to the variation of H′. From all of the above, it is concluded that the equation predicting H′ is:

$$H' = -4.554 - 1.379X_1 + 0.240X_2 + 0.247X_3 - 0.202X_4$$

where:

X_1 is the log lead concentration in the soil (in ppm),
X_2 is the arcsin percent clay content,
X_3 is the arcsin percent organic matter,
X_4 is the arcsin percent moisture holding capacity.

IV. — DISCUSSION

To test the hypothesis that urbanization causes stressful conditions for soil communities, soil samples extracted from various sites located along a gradient of urbanization and in different months were analyzed for a number of factors. Among the factors studied were both physical (soil texture, soil temperature, soil moisture) and chemical (soil lead content, soil organic matter) ones. The Shannon-Weaner index of diverstiy (H′) was used to monitor diversity of the soil communities and the relation between H′ and the above abiotic factors examined.

The association of diversity indices with stability has been questioned (HURLBERT, 1971) and to date the dispute over the diversity/stability hypothesis remains unresolved (PIMM, 1984; MAY, 1974; WHITTAKER, 1975; ALATALO, 1981). Indices of species diversity provide a convenient way of combining species abundance (number of individuals belonging to a given taxon) and species richness (number of different taxa in the community) in a single value. In addition, the obstacle of identification is removed by assigning arbitrary working taxonomic units to the specimens collected. For all of the above reasons, indices of species diversity are applied to assess changes in communities caused by stressfull environmental conditions (RUGGIERO and MERCHANT, 1979), and to compare distantly located communities (WOODWELL and SMITH, 1969; TURNER, 1985; LEGENDRE and LEGENDRE, 1983). Distance from the center of the city and soil lead content were highly correlated ($r = -0.78$), as it can be seen in Table I. This agrees with the suggestion that lead can be used as a measure of urbanization (KLOKE and RIEBARTSCH, 1964). Sites located at greater distances from the center of the city had lower soil lead concentrations and higher indices of species diversity than sites located closer to the center. It is tempting to attribute the decreased diversity of inner city sites to stressful conditions of lead, soil texture, moisture, organic matter or an interaction involving one or more of the above factors. The evidence presented here supports this assumption, but it does not prove any causative relationship between the above factors and diversity.

The regression fitted among the different variables accounted for a great deal of the observed variation (multiple $R^2 = 0.9997$) when all eight independent variables were included. No significant changes in the predicted species diversity occurred when soil temperature and percent sand content were ommited from the regression equation. This might be due to either the small variation in soil temperature or to the insignificant regression coefficients of temperature and/or sand.

A multitude of factors is often associated with certain observations of soil communities and/or soil processes. Multivariate methods, such as multiple regression, principal component analysis and reciprocal analysis have been employed in many cases to interpret the observed patterns of soil community distribution (CANCELA DA FONSECA, 1980; SGARDELIS *et al.*, 1981; STAMOU *et al.*, 1984; USHER, 1976; USHER *et al.*, 1982). The strengths and weaknesses of multivariate methods have been extensively reviewed and evaluated by PIELOU (1984) and GAUCH (1982). Most of the times, and for complicated situations such as those occurring in the soil, evidence provided by the above methods of community ordination and/or classification is the only way to account for the results. Laboratory studies provide better control of conditions and, therefore, have been suggested as a possible remedy to the problem of extreme variation in soil communities. The present work reports results from mensurative rather than manipulative experiments (*sensu* HURLBERT, 1984) and uses a multiple linear regression model to reduce the number of independent variables associated with species diversity (H′); such treatment of the results not only does it have predictive value, but it also generates some questions necessitating an in depth investigation.

Unlike the case where « Clean Acts » have been established for various media, such as air and water, no criteria have been proposed for assessing and/or preventing contamination of soil ecosystems. BABICH and STOTZKY (1983) have emphasized the need for measures regulating the input of toxicants in the soil and suggest that bioassays on microorganisms under abiotic conditions resembling the real world seem appropriate.

In conclusion, the present study has detected a negative association between distance from the center of the city and soil lead concentration and a strong negative correlation between lead and species diversity. Overall species diversity (H′) varied significantly with month of the year, whereas H′ correlated rather poorly with soil temperature. On the other hand, there is a positive relationship of distance with species diversity (H′) of soil communities. Unfortunately, the close correlations between distance and most of the other parameters studied here prevent any conclusive inference and demonstrate the need for more research on this topic.

APPENDIX

List of species and species abundance. Entries in the table represent total numbers of specimens per taxon per site summed over the entire period of the study. Cumulative totals for each taxon over sites appear in the last column of the table.

SPECIES	SITES								TOTAL
	1	2	3	4	5	6	7	8	
Aeolothrips fasciatus	2								2
Acanthomyops interjectus			85						85
Aphid sp.			2	1	3		3	2	11
Campala sp.				1					1
Campodea sp.		1		1				1	3
Camponotus pennsylvanicus					1				1
Conoderus vespertinus				1	1	6	2	6	16
Dermapteran larva					1	1	4	1	7
Dermestid beetle			3	2					5
Dysdera crocata						1		1	2
Endria inimica								1	1
Entomobrya multifasciata	1			5	7	8	1		22
Folsomia elongata	39	48	5	38	24	61	114	6	335
Harpalus caliginosus							1	3	4
Iridomyrmex humilis				143	26	1	60	36	266
Isopteran larva							1		1
Isotoma viridis							1		1
Lepidopteran larva	1	1						1	3
Lumbricus terrestris		1	1	5		2	3	14	26
Merothrips morgani			1			6		4	11
Musca domestica (larva)							1		1
Nematode sp.	14	27	8	21	27	20	15	14	146
Oribatid mite unid. sp. # 1	25	5	4	1	12	238	8	2	295
Oribatid mite unid. sp. # 2		2		4	1	3			10
Oribatula sp.			3	16	2	13	2	2	38
Oxidus gracilis							1		1
Pauropod unid. sp.	1	3	4	3	1		1	3	16
Pheidole bicarinata			1				1	1	3
Proturan unid. sp.		1		1		2		1	5
Reticulotermes flavipes				1			1		2
Scutigerella imaculata				2					2
Sminthurinus elegans	6			21	4	10	24	43	108
Solenopsis xyloni			14						14
Tenebroides corticalis					1				1
Tetramorium caespitum		253	634	132	69	20	61	7	1176
Tetranychus sp.	17	1	13	12	26	29	40	32	170
Trombicula sp.	3			2	1	8	6		20
Trombidium sp.				1					1
Zygoribatula sp.	2	14	5	156	79	230	87	73	646
									3458

SUMMARY

Soil samples extracted from various sites along a major traffic artery within the limits of Washington D. C. and in different months of the year were analyzed for both physical (soil texture, soil temperature and soil moisture) and chemical (soil lead concentration, soil organic matter) factors. Relative abundances for the species present in the soil cores were recorded and Shannon-Weaver indices of diversity (H') calculated for each sample.

Habitat availability, as reflected by soil texture, varied significantly with both collecting period and collecting site and it seemed to strongly affect diversity of soil communities. H' was negatively correlated with soil lead, while, there was a positive correlation between H' and distance from the center of the city. The strong positive correlation between lead and distance from the center of the city, as well as the high intercorrelations between most of the other factors studied, did not permit any conclusions about cause and effect to be drawn.

RÉSUMÉ

Communautés terricoles soumises à un gradient d'urbanisation

Afin de vérifier l'hypothèse selon laquelle l'urbanisation a de graves effets sur les communautés terricoles, des échantillons prélevés à des endroits soumis à un gradient d'urbanisation et à différents moments ont été étudiés selon divers facteurs.

Les facteurs étudiés sont de deux sortes : physiques (texture du sol, température, humidité) et chimiques (présence de plomb, matière organique). Nous avons utilisé l'index de diversité Shannon-Weaver (H') pour mesurer la diversité des communautés terricoles et leurs relations avec les facteurs abiotiques ci-dessus.

L'étude a montré une corrélation négative entre la distance par rapport au centre ville et la concentration du plomb dans le sol. Même remarque en ce qui concerne la concentration du plomb et la diversité des communautés terricoles ; l'indice de diversité (H') a varié en général de façon significative avec le mois tandis que l'indice de corrélation entre H' et la température du sol est faible.

D'un autre côté, on constate une corrélation positive entre la distance et la diversité des communautés terricoles. Malheureusement, les fortes corrélations entre la distance et la plupart des autres paramètres étudiés ne permettent pas de faire de déduction définitive et montrent la nécessité d'une recherche détaillée à ce sujet.

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