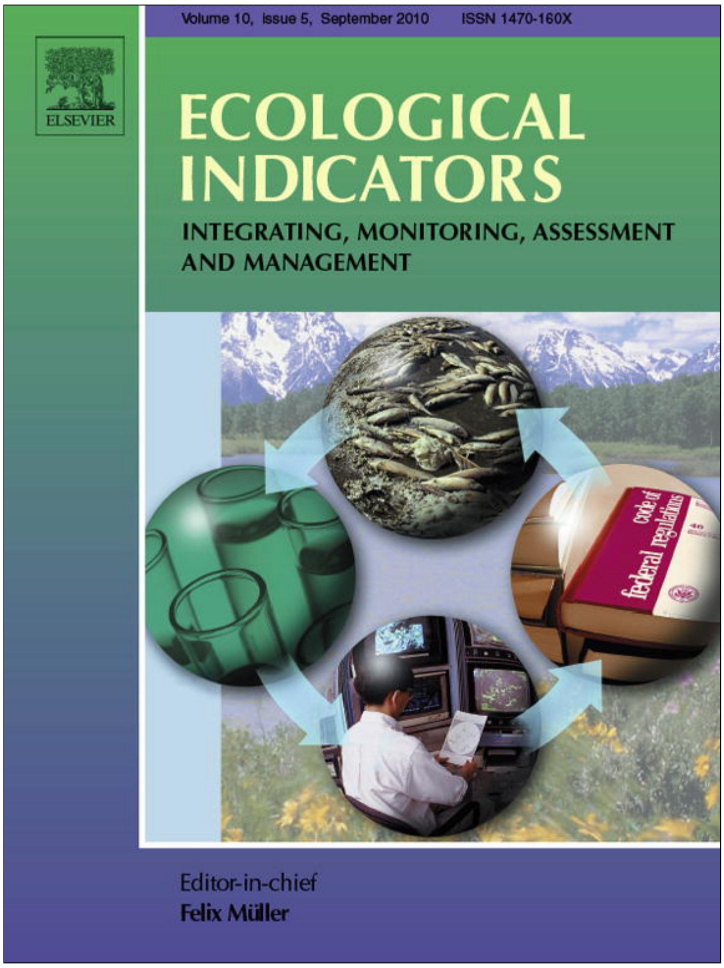
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Soil free-living nematodes as indicators of both industrial pollution and livestock activity in Central Asia

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The effect of industrial pollution on soil free-living nematode communities, trophic groups, and taxon composition was investigated along an 18-km transect that included the Angren power plant, a gold-refinery plant, farm areas, and recreation areas. Soil samples were collected in May 2005 and October 2006 from the upper (0–10 and 10–20 cm) soil layers in downwind directions from the industrial complex emission sources of the Angren industrial sites.

Direct and indirect (through soil property changes), separate and integrated effects of industrial pollution and livestock activity on the soil nematode community were found. The total number of nematodes was found to be negatively correlated with the amounts of chemical elements in soil and positively correlated with the calcium concentration in soil. The nematode communities, trophic diversity, and taxon composition were found to be affected by the variety and concentration of chemical elements.

The widely used ecological indices applied in the present research were sensitive to environmental disturbances caused by industrial pollution as well as livestock activity. The Wasilewska index, nematode channel ratio, and maturity index were mostly affected by trace metal concentration, while the diversity indices and species richness were mostly affected by soil property changes. The nematode channel ratio indicated that the bacterial-based decomposition process was dominant in soils exposed to both strong industrial pollution and livestock activity. The diversity indices indicated the disappearance of rare species in the industrial area and an increase of the contribution of common nematodes with increasing depth and distance from the unfavorable area. The current study confirmed that the grazing in accompaniment to industrial pollution, intensify a negative effect on soil nematode communities.

1. Introduction

Soil free-living nematode communities and their structural changes have been found to be one of the best biological tools for assessing soil disturbances, including heavy-metal pollution (Bongers et al., 2001; Georgieva et al., 2002) and agricultural and grazing activities (Yeates and Bongers, 1999; Kandji et al., 2001; Mills and Adl, 2006) in terrestrial systems (Gupta and Yeates, 1997; Neher, 1999). Due to their sensitivity to changes in the soil ecosystem and their ability to reflect differences between undisturbed and human-impacted environments, the free-living nematodes are considered to be useful and inexpensive indicators for ecological research (Porazinska et al., 1999). Previous investigations showed that density, biomass, trophic structure, species diversity, and sex ratio of soil free-living nematode communities were sensitive to anthropogenic changes in soil ecosystems (Georgieva et al., 2002; Yeates, 2003; Pen-Mouratov et al., 2008).

Various ecological indices such as Wasilewska, nematode channel ratio, Shannon–Weaver diversity, richness, and maturity, were accepted in numerous research studies as useful tools for the assessment of changes occurring in nematode assemblages undergoing environmental disturbances (Bongers, 1990; Yeates and Bird, 1994; Wasilewska, 1997; Pen-Mouratov et al., 2004).

To assess the anthropogenic effects of human activity on the environment, the current ecological research was conducted in the Angren industrial area, which is one of the largest industrial complexes in Uzbekistan, and includes coal mining, a coal-fueled power plant, and resin industries, and is located in the immediate vicinity of agricultural ecosystems and farming areas. Moreover, livestock management is basically by peasant farms that widely and limitlessly use the industrial area for cattle grazing.

Previous studies showed that surface and ground water in this area, as well as soil and vegetation, are highly contaminated with heavy metals (UNECE, 2000). Emissions, mainly sulfur dioxide (44–48%), carbon dioxide (38–40%), nitrogen dioxide (10–15%),

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ammonia, ammonium nitrate, hydrogen fluoride gas (HF), and solid suspended particulates, heavy metals (Pb, Cd, Hg, etc.), average about 100,000 tons/year. Over the last few decades, these industrial pollutions have caused severe damage to the natural ecosystems of the area and have dramatically increased the impact of heavy-metal-rich dust and fly-ash particles in this area (UNECE, 2000).

The objectives of this study were:

- To determine the abundance, trophic structure, and generic diversity of the soil free-living nematode communities under the influence of industrial pollution.
- To determine the abundance, trophic structure, and genus diversity of the soil free-living nematode communities in the grazing area located next to the industrial area.
- To evaluate the combined effect of industrial pollution and grazing activity on the abundance, trophic structure, and generic diversity of the soil free-living nematode communities.

2. Material and methods

2.1. Study site

The study sites were situated 114 km from Tashkent along the Akhangaran River Valley (the right tributary of the Sir-Darya River), in foothills between the Chatkal and Kurama Mountain ranges (western Tien-Shan), extending into the southeast part of the Tashkent region of the Republic of Uzbekistan. The industrial complexes include coal mining, a coal-fueled power plant, and resin industries located on the upper side of the Akhangaran River Valley, near the city of Angren (41°01′N–70°09′E).

Angren is the largest coal mining and power-producing center in Uzbekistan, and was developed during and after World War II. The Angren coal-burning power plant (259 MW capacity) is one of the major sources of air and soil pollution in this area. It works on a basis of brown coal from the nearby Angren coal field (production capacity of 2.5 million tons per year, ash content 11–35%). The coal mining and power-generation industries in Angren use old equipment that has not been upgraded since the 1990s. Air pollution control technology is in poor condition and several units need to be modernized.

The Angren coal mining and combustion industrial center is located on the left bank of the Akhangaran River in the southwest part of the Chatkal range foothills. The Akhangaran Valley represents a large intermountain hollow, where plain, pre-mountain, and middle-mountain types of reliefs are found. The relief changes from hilly to foothilly in Angren. The altitude increases from northwest to southeast (for the Kurama ranges) in Angren (700–2300 m) (UTEMWO, 2005).

The research area represents a mountain-valley area with a large variability of seasonal and daily air temperature and wind direction. Thermal inversions provide cyclic circulation of air masses and cause pendulum distributions of dust and gas-smoke emissions from the industrial enterprises. The prevalent wind at the study area is in a northeastern direction. An additional feature of the study area location is that it is surrounded by a chain of mountains that create poor conditions for air circulation. This further worsens the air pollution and the secondary pollution of soils and vegetation in the valley. Since 1994, the State Committee for Geology and Mineral Resources has carried out environmental monitoring in the Angren area.

The climate is sharply continental for the hull area, with an absolute maximum of 40 °C in summer and −25 °C in winter (average annual temperature ranging from 14° to 15 °C). Average annual precipitation amount is 339–511 mm (96% of this precipitation falls during the autumn, winter, and spring seasons) (Information Agency Jahon of the Ministry of Foreign Affairs of the Republic of Uzbekistan, 2003).

Uzbekistan agriculture specializes in intensive and industrial technologies of meat and milk production. In 2000, the ruminant stock of Uzbekistan amounted to 5,281,800 heads, including 2,310,000 cows and 8,863,600 sheep and goats of all breeds (Makhmudov and Khaitov, 2000). At present, the livestock is managed by two types of farms: public-sector agricultural cooperatives and peasant farms. The peasant farmers widely and limitlessly use the Angren industrial area for cattle grazing that, in turn–through overgrazing, leads to the development of soil erosion.

The vegetation cover throughout the study sites is dominated by annual and perennial plants, the most common being *Astragalus*, *Stipa*, *Medicago*, and *Artemisia*. The soils in the study area are classified as Calcisols and haplic (fluvic) (FAO, 2003), with high levels of $CaCO_3$ contributing to a stable accumulation of heavy metals in the upper soil profile. This soil area is characterized by a low content of organic matter with no special fertilizer application (Makhmudov and Khaitov, 2000). Previous studies indicated that the Calcisol properties in the current study area have the following values: about 200 mg 100 g^{-1} total carbon; 6 mg 100 g^{-1} total nitrogen; 2–3 mg 100 g^{-1} total phosphorus; 7.3–12 mg 100 g^{-1} potassium; and 6 mg 100 g^{-1} magnesium, 7.8–8.5 pH. The percentage of soil-particle size at intervals between 0.2–0.02% and less than 0.02% amounted to 54.5 and 43.3%, respectively, while percentage of soil-particle size at intervals varying from 0.2 to 2.0% amounted to 2.2% only (Egamberdiyeva and Hoflich, 2003; Egamberdiyeva, 2007).

2.2. Sampling

Six sampling stations (3 km apart) downwind a deposition gradient of 18 km long from the main source of pollution (Fig. 1), were selected as follow: the southeastern part of the Angren power plant [Station (ST) I]; the southwestern edge of the Angren power plant (ST II), continuing in a downwind direction to the recreation area (ST III); first grazing area (ST IV); gold-refinery plant (ST V); and second grazing area (ST VI). At each of these stations of size 10 × 10 m, four random soil samples from each soil layer (0–10 and 10–20 cm) and from six sampling stations were collected from the open spaces in May 2005 and October 2006 ($4 \times 2 \times 6 \times 2 = 96$ soil samples). Each soil sample was placed in an individual plastic bag and transported to the laboratory in an insulated container. At the laboratory, they were kept in cold storage at 4 °C and sieved through a 2-mm mesh sieve before biological and chemical analyses. Subsamples from each sample were used for determination of chemical element content and were subsequently ground in an agate mortar and homogenized before spectral and chemical analyses.

2.3. Sample analysis

Each of the 96 soil samples was subjected to the following analyses:

a. Soil moisture (SM) of the subsamples was measured gravimetrically as percentage of dry mass by drying the samples to a constant weight (105 °C, 48 h).
b. Organic matter was determined by oxidization with dichromate in the presence of H_2SO_4, without application of external heat (Rowell, 1994).
c. Soil pH was determined in H_2O (soil solution ratio 1:2) with a potentiometric glass electrode.
d. Soluble cations (Ca^{2+}, Na^{+}, and K^{+}) were determined by a flame photometer (Rhoades, 1982).
e. Total soluble nitrogen (TSN) in soil was determined by using the method of Houba et al. (1987). The amounts of TSN in the

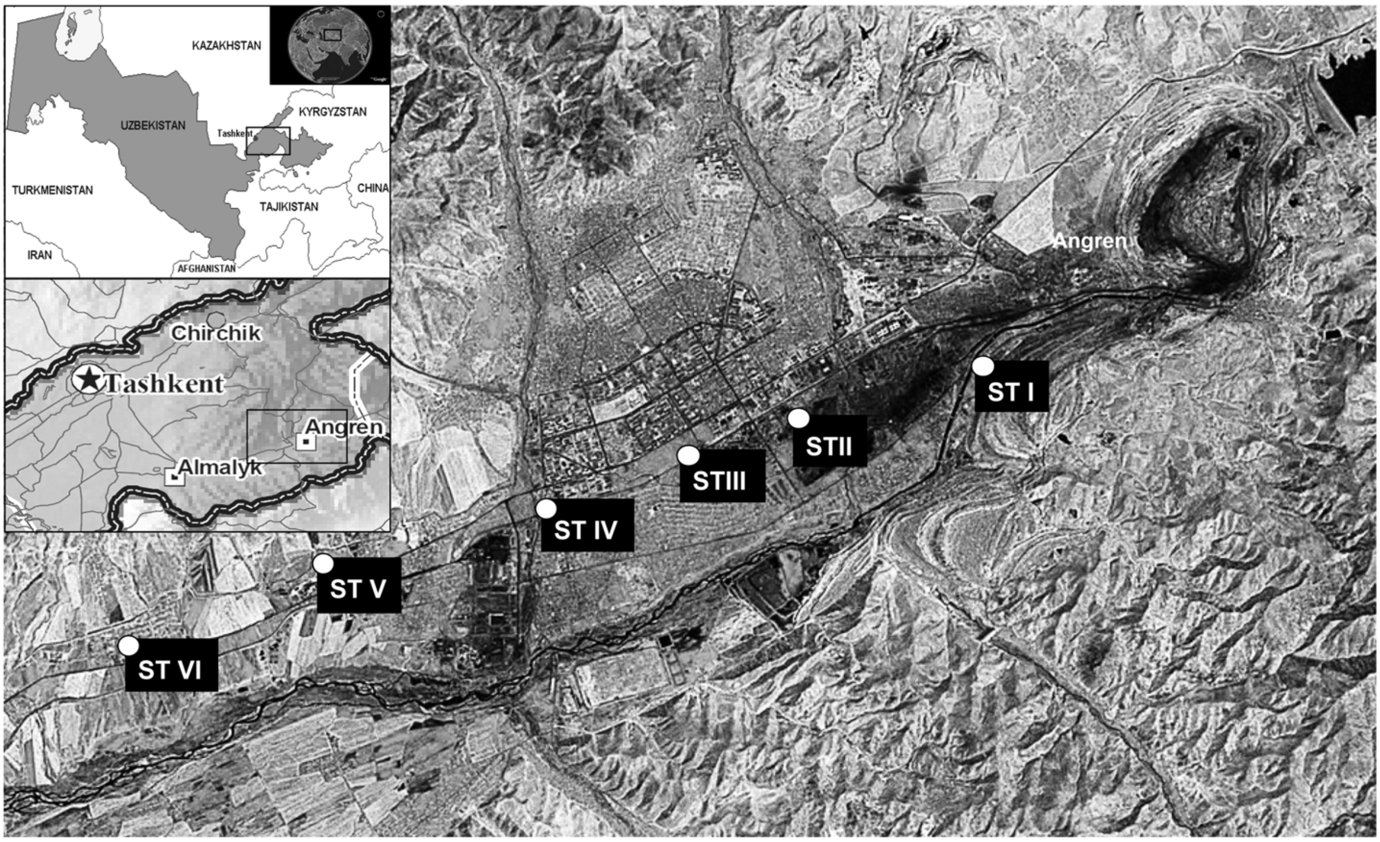

Fig. 1. Location of the study area (Google Earth map of the Angren Valley, with sampling spots).

soil extracts were determined using a Skalar Autoanalyzer unit (S.F.A.S., 1995).

f. Metal concentrations were determined using the atomic absorption spectrometry (AAS) method (Zeien and Brummer, 1989; Zeien, 1995) and XRF spectrometer ED 2000Rh (Oxford Instruments, England) for multi-element analysis. Subsamples from each sample were air-dried, manually ground using an agate mortar, and homogenized before preparation of powder pellets for XRF analyses. The metals were extracted by digestion with three parts of concentrated HNO_3 and one part of concentrated $HClO_3$ for atomic absorption analysis.

g. The nematode population was extracted from 100-g aliquots of the soil samples using the Baermann funnel procedure (Cairns, 1960). The recovered organisms were counted and preserved in formaldehyde (Steinberger and Sarig, 1993). The nematodes from each sample were collected and identified according to order, family, and genus using a compound microscope.

2.4. Ecological indices and statistical analysis

The characteristics of the nematode communities were described by means of the following indices: (1) absolute abundance of individuals per 100 g dry soil; (2) abundance of omnivore-predator (OP), plant-parasitic (PP), fungal-feeding (FF) and bacterial-feeding (BF) nematodes (trophic structure) (Steinberger and Loboda, 1991; Steinberger and Sarig, 1993; Pen-Mouratov et al., 2003, 2004); (3) Wasilewska index (WI), WI = (FF + BF)/PP (Wasilewska, 1994); (4) the nematode channel ratio (NCR), NCR = BF/(BF + FF), where BF and FF are the proportions of the nematode fauna allocated to bacterivorous and fungivorous groups (Yeates et al., 2003); (5) Simpson's dominance index, $\lambda = \Sigma Pi^2$ (Simpson, 1949); (6) Shannon–Weaver index, $H' = -\Sigma Pi$ (ln *Pi*), where *P* is the proportion of individuals in the *i*th taxon (Shannon and Weaver, 1949); (7) richness, SR = (*S* − 1)/ln(*N*), where *S* is the number of taxa and *N* is the number of individuals identified (Yeates and King, 1997); and (8) maturity index, $MI = \sum \upsilon_i fi/n$, where υ_i, is the *c*–*p* value assigned by Bongers (1990) of the *i*th genus in the nematode, *fi* is the frequency of family *i* in sample, and *n* is total number of individuals in a sample (Neher and Darby, 2005). The CP (colonizer–persistor) values describe the nematode life strategies, and range from 1 (*r*-selected or colonizers with short generation times, large population fluctuations, high fecundity, and tolerant to disturbance) to 5 (K-selected or persisters, produce few offspring, appear later in succession, and sensitive to disturbance).

The data presented in this study are reported as oven-dried weights. All data were subjected to statistical analysis of variance using the SAS model [GLM, (SAS, 1988)] and were used to evaluate the spatial dependence between the soil properties and pollution levels. Duncan's multiple range tests were used to evaluate differences between separate means (Sokal and Rohlf, 1969). Differences obtained at levels of $p < 0.05$ were considered significant.

Terminology: In order to avoid discussion about the term "heavy metal" (Duffus, 2002), we applied in the present paper the term "trace metal" as a metal found in low concentration, in mass fractions of ppm or less, in some specified source, e.g., soil, plant, tissue, ground water.

3. Results

3.1. Chemical elements

The mean soil moisture content ranged from 2.63 to 8.57% between sampling sites (Table 1). Soil moisture (SM) was found to be significantly (16%) greater ($p < 0.001$) at the 10–20-cm soil depth

Table 1
Range of concentration of soil properties and heavy metals in soils of Angren industrial area at 0–20 cm soil depth.

	Sampling sites												GLM	
	Upper soil layer						Deeper soil layer						$^x p$ values	$^y p$ values
	ST I	ST II	ST III	ST IV	ST V	ST VI	ST I	ST II	ST III	ST IV	ST V	ST VI		
SM (%)	3.48^{cd}	2.63^{d}	5.07^{b}	6.47^{a}	3.82^{c}	4.28^{cb}	5.75^{c}	4.43^{d}	7.03^{b}	8.57^{a}	4.43^{d}	5.08^{dc}	0.0001	0.0001
OM (%)	1.93^{a}	1.85^{a}	2.12^{a}	1.87^{a}	0.52^{c}	1.50^{b}	1.38^{a}	1.58^{a}	1.70^{a}	1.48^{a}	0.37^{c}	0.72^{b}	0.0001	0.0001
TSN	4.31c	6.60b	14.50a	5.23b	1.96d	4.26c	1.42c	4.2b	6.82a	1.55c	1.83c	2.41c	0.0001	0.01
pH	7.92^{a}	8.03^{a}	7.95^{a}	7.93^{a}	8.05^{a}	8.10^{a}	8.00^{a}	7.93^{a}	8.02^{a}	8.05^{a}	8.10^{a}	8.06^{a}	NS	NS
EC	0.40^{c}	0.50^{a}	0.48^{ba}	0.40^{c}	0.42^{bc}	0.42^{bc}	0.40^{a}	0.43^{a}	0.40^{a}	0.38^{a}	0.40^{a}	0.38^{a}	0.03	NS
Ca^{z}	46.7^{a}	47.7^{a}	48.5^{a}	44.5^{a}	50.2^{a}	49.2^{a}	47.3^{ba}	43.7^{b}	45.8^{b}	44.5^{b}	52.5^{a}	47.5^{ba}	NS	0.02
Na^{z}	65.0^{b}	78.7^{a}	68.8^{b}	69.0^{b}	73.0^{ba}	69.7^{b}	66.5^{a}	75.8^{a}	69.2^{a}	67.7^{a}	68.8^{a}	68.7^{a}	0.02	NS
K^{z}	9.7^{b}	7.2^{b}	15.5^{a}	18.7^{a}	4.8^{b}	8.8^{b}	5.2^{c}	5.0^{c}	9.5^{b}	14.0^{a}	2.5^{d}	4.2^{dc}	0.0001	0.0001
Sc^{z}	20.2^{a}	16.7^{bc}	14.7^{c}	15.8^{c}	20.0^{a}	18.8^{ba}	17.7^{b}	13.0^{c}	14.0^{c}	15.0^{c}	19.0^{b}	21.3^{a}	0.0004	0.0001
V^{z}	93.7^{cd}	92.2^{d}	97.0^{b}	95.5^{cb}	111.5^{a}	114.3^{a}	95.3^{b}	82.5^{c}	96.7^{b}	92.3^{b}	114.3^{a}	110.3^{a}	0.0001	0.0001
Cr^{z}	54.2^{c}	46.5^{d}	74.2^{b}	60.2^{c}	89.7^{a}	85.3^{a}	65.3^{c}	45.0^{d}	80.3^{b}	67.7^{c}	88.7^{a}	89.0^{a}	0.0001	0.0001
Co^{z}	9.7^{d}	10.2^{d}	13.3^{bc}	13.2^{c}	15.3^{a}	15.2^{ba}	11.8^{b}	9.7^{c}	13.2^{b}	11.3^{cb}	13.0^{b}	16.7^{a}	0.0001	0.0001
Ni^{z}	22.0^{d}	20.7^{d}	35.8^{b}	28.2^{c}	40.8^{a}	39.2^{a}	25.5^{c}	22.0^{d}	40.7^{a}	34.2^{b}	40.5^{a}	36.5^{b}	0.0001	0.0001
Cu^{z}	60.7^{a}	60.2^{a}	43.2^{c}	50.8^{b}	30.0^{e}	39.3^{d}	57.8^{a}	58.7^{a}	36.0^{c}	47.7^{b}	29.8^{c}	31.2^{c}	0.0001	0.0001
Zn^{z}	1153^{a}	907^{b}	342^{d}	656^{c}	87^{f}	128^{e}	963^{a}	708^{b}	254^{d}	476^{c}	82^{e}	94^{e}	0.0001	0.0001
Ga^{z}	22.7^{a}	21.8^{ba}	18.2^{c}	20.7^{b}	15.0^{d}	15.0^{d}	19.7^{a}	19.5^{a}	16.7^{b}	17.2^{b}	14.8^{c}	14.5^{c}	0.0001	0.0001
Rb^{z}	108^{c}	113^{bc}	124^{a}	119^{ba}	100^{d}	95^{d}	115^{b}	132^{a}	131^{a}	136^{a}	101^{c}	95^{c}	0.0001	0.0001
Sr^{z}	605^{a}	625^{a}	246^{c}	428^{b}	206^{c}	231^{c}	564^{a}	499^{b}	201^{d}	337^{c}	214^{d}	247^{d}	0.0001	0.0001
Zr^{z}	245^{b}	270^{a}	226^{c}	263^{a}	192^{d}	175^{d}	219^{c}	265^{a}	223^{c}	237^{b}	189^{d}	180^{e}	0.0001	0.0001
Nb^{z}	22.0^{ba}	23.2^{a}	19.2^{c}	20.7^{bc}	13.3^{d}	13.2^{d}	18.2^{c}	23.3^{a}	20.5^{b}	20.2^{b}	14.2^{d}	11.8^{e}	0.0001	0.0001
Pb^{z}	392^{a}	302^{b}	138^{d}	243^{c}	34^{e}	49^{e}	253^{a}	237^{a}	81^{cb}	124^{b}	26^{c}	29^{c}	0.0001	0.0001
Th^{z}	23.7^{b}	26.5^{a}	18.3^{c}	24.7^{ba}	11.8^{d}	11.7^{d}	21.0^{b}	26.0^{a}	16.5^{c}	20.3^{b}	12.8^{d}	10.0^{e}	0.0001	0.0001
U^{z}	11.2^{a}	10.7^{a}	5.5^{c}	8.8^{b}	2.7^{d}	3.5^{d}	7.8^{b}	9.8^{a}	5.3^{c}	7.0^{b}	3.5^{d}	2.2^{d}	0.0001	0.0001

Sampling sites: ST I, power plant southeastern part; ST II, power plant southwestern part; ST III, recreation area; ST IV, first farming area; ST V, gold-refinery plant; ST VI, second farming area.
Different letters indicate significant differences between sampling location, $n = 72$.
NS, not significantly different.
[x] p values, upper soil layer.
[y] p values, deeper soil layer.
[z] mg kg^{-1} dry soil.

than at the 0–10-cm depth (Fig. 2), with no significant differences between sampling stations I, II, V, and VI (Table 1). Soil moisture at sampling station IV was significantly higher ($p < 0.0001$) than at the other sampling sites. The SM was negatively correlated with Na ($p < 0.05$, where correlation coefficient 'r' equaled 0.37).

Unlike soil moisture content, organic matter content (OM) was found to be significantly ($p < 0.001$) higher (14%) in the upper (0–10 cm) soil layer than in the deeper (10–20 cm) soil layer along the sampling sites (Fig. 2). Organic matter content was significantly different between sampling sites, reaching maximal values at sampling station III ($p < 0.01$) (Table 1), and being negatively correlated with Ca, Sc, V, Co, Cr, Ni, and positively correlated with SM, K, Cu, Zn, Ga, Rb, Sr, Zr, Nb, Pb, Th, and U (Table 2).

Total soluble nitrogen (TSN) was found to be significantly different ($p < 0.0001$) between sampling stations. The TSN values were found to be low in the power-plant area (STs I and II), increasing along a downwind direction, reaching maximal values at the recreation area (ST III) and followed by decreasing at the first farming area (ST IV). There was a sharp decrease at the upper soil layer at the gold-refinery-plant area (ST V), with some increase at the second farming area (ST VI) (Table 1). TSN was found to be correlated with SM, OM, and K (where correlation coefficient equaled 0.34, 0.44, and 0.64 respectively by $p < 0.0001$), and Ni ($r = 0.22$, by $p < 0.05$).

No significant differences in pH levels were found between the sampling stations. The soils were weakly alkaline, with pH values ranging from 7.92 to 8.10 (Table 1).

The soluble cations Ca^{2+}, Na^{+}, and K^{+} were significantly different between sampling sites (Table 1). Moreover, Ca^{2+} reached maximal values at the gold-refinery-plant area (ST V), Na was maximal at the southwestern part of the Angren power plant (ST II), and K was maximal in the first farming area (ST IV). Calcium and potassium were found to be negatively and positively correlated with the observed soil properties and trace metals ($p < 0.05$), where Ca was positively correlated with V ($r = 0.34$, in the deeper soil layer); negatively correlated with OM ($r = -0.39$ in the deeper soil layer), Rb ($r = -0.34$ in the deeper soil layer) and K ($r = -0.39$ and -0.42 in the upper and deeper soil layers, respectively). While K was found to be positively correlated with SM ($r = 0.33$ and 0.66 in the upper and deeper soil layers, respectively), OM ($r = 0.40$ and 0.50 in the upper and deeper soil layers, respectively), Zr ($r = 0.34$ and 0.44 in the upper and deeper soil layers, respectively), Th ($r = 0.39$ and 0.37 in the upper and deeper soil layers, respectively), Rb ($r = 0.57$ in the deeper soil layer), and Nb ($r = 0.52$ in the deeper soil layer), and negatively correlated with V ($r = -0.35$ and -0.47 in the upper and deeper soil layers, respectively) and K ($r = -0.39$ in the upper soil layer). Unlike the two above-mentioned chemical elements, Na was not sensitive to any observed soil properties (except EC) or trace metals.

The total trace metal content (Fig. 2) was highest near the Angren power-plant area (STs I and II), decreasing along the downwind direction and then again increased after the gold-refinery-plant area (ST V).

Contents of most of the observed metals (Cu, Zn, Ga, Sr, Zr, Nb, Th, and U) were found to be maximal near the Angren power-plant area (STs I and II), decreasing significantly along the downwind direction, while high concentrations of Rb enveloped the recreation and grazing areas (Table 1). Ni content reached a maximum at the gold-refinery-plant area (ST V), Co content was maximal in the second farming area (ST VI), while V content was highest at the gold-refinery-plant area and next to at the grazing areas (STs V and VI) (Table 1).

3.2. Nematode-community structure

Forty-eight nematode taxa were identified in the present investigation: ten taxa belonged to the bacterivore trophic group, eight

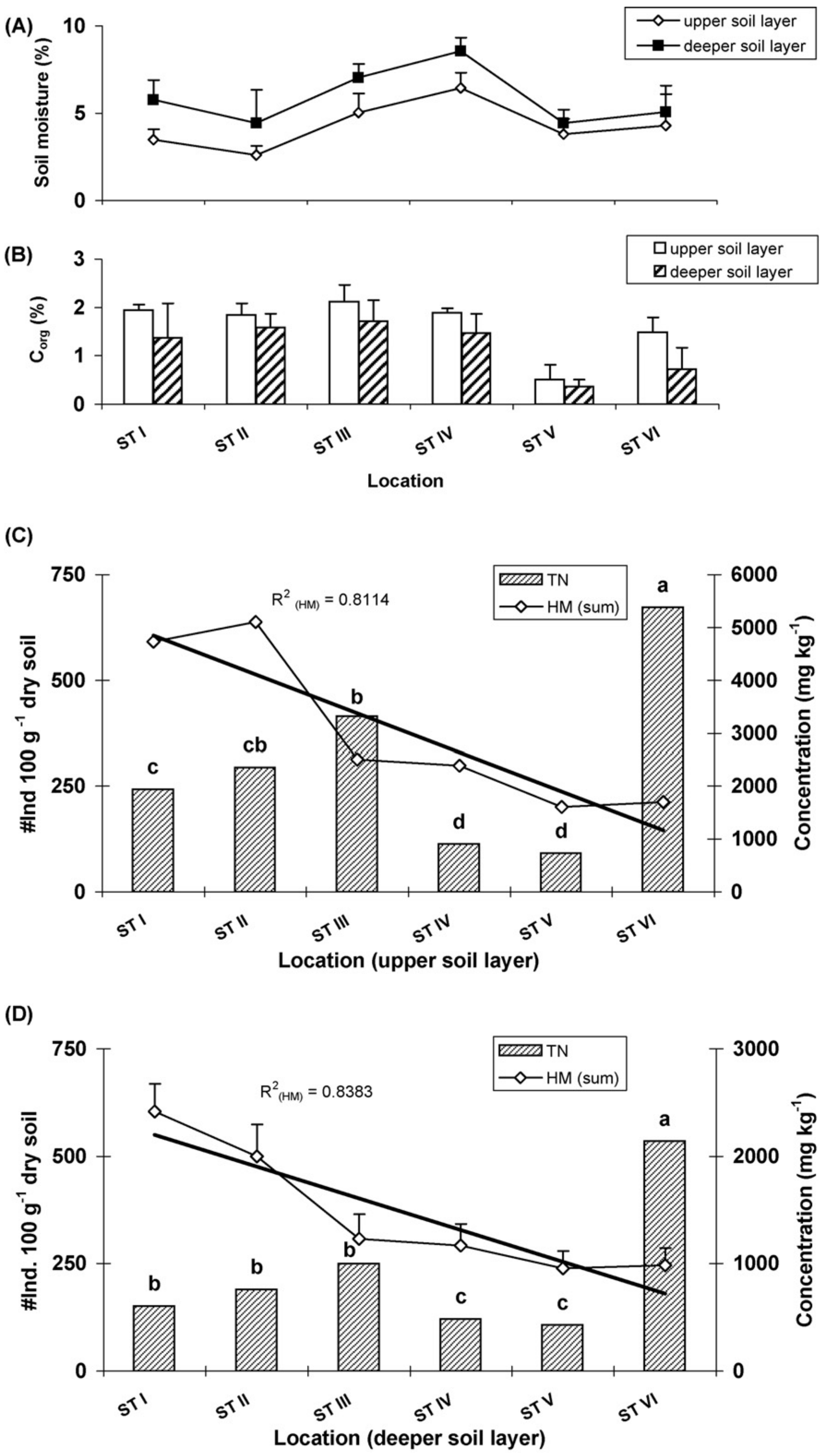

Fig. 2. Changes in soil moisture (A), organic matter (B), total trace metal concentration (HM sum), and total number (TN) of free-living nematodes (C and D) at different stations along the deposition gradient in two soil layers (0–10 cm and 10–20 cm) in the Angren study area. The various measures are on a basis of percentage of dry weight/100 g soil basis; matched so that C and D are each adjacent to the appropriate depth intervals. Different letters indicate significant differences ($p < 0.05$, $n = 72$) using Duncan's multiple range test. R^2, regression values between the pollution source stations.

were fungivores, nineteen were plant-parasites, and eleven were omnivores-predators (Table 3).

Mean density of the soil free-living nematodes decreased in areas with soil pollution and neighboring areas, increasing with distance from the pollution source toward the recreation area (ST III), with a sharp decrease in the first grazing (ST IV) and gold-plant areas (ST V), and increasing again in the second grazing area (ST VI) (Fig. 2). Nematode density was 1.26–1.60 times higher in the upper soil layer at STs I, II, III, and VI than in the deeper soil layer ($p < 0.01$), while it was 1.07–1.17 times lower in the upper soil layer at STs IV and V than in the deeper soil layer (Fig. 2).

Table 2
Correlation coefficient between total number of nematodes, trophic groups, soil properties and heavy metals in the Angren industrial area.

	TNEM		BF		FF		PP		OP		SM		OM	
	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De
SM					0.36*						1	1		0.37*
OM									0.36*				1	1
TSN			0.28**											
pH														
EC						0.45**			0.33*					
Ca	0.47**						0.40*		0.40*					−0.39*
Na										−0.34*				
K			0.55***		0.33*					0.33*	0.66***	0.40**	0.50***	
Sc													−0.36*	−0.53***
V						−0.37*	0.35*						−0.64***	−0.69***
Cr								0.33*					−0.50***	−0.58***
Co								0.39*					−0.41**	−0.39*
Ni													−0.47***	−0.44**
Cu								−0.35*					0.61***	0.57***
Zn								−0.34*					0.52***	0.52***
Ga								−0.33*					0.49***	0.49***
Rb		−0.32*	0.44**				−0.41*	−0.41*					0.59***	0.60***
Sr				0.45**									0.39*	0.42**
Zr	−0.33*			0.56***	0.42*	−0.38*						0.45**	0.65***	
Nb				0.42*			−0.32*	−0.40*		0.38*			0.56***	0.62***
Pb				0.59***	0.33*		−0.33*					0.53***	0.53***	
Th				0.48**		0.40*		−0.40*					0.50***	0.61***
U				0.55***	0.38*		−0.45**					0.48***	0.60***	

TNEM, total nematode abundance; BF, bacterivores; FF, fungivores; PP, plant-parasites; OP, omnivores-predators.
Up, upper; De, deeper soil layers
* Values with $p < 0.05$.
** Values with $p < 0.01$.
*** Values with $p < 0.001$.

3.3. *Trophic groups and nematode species*

Trophic group density was found to be affected by sampling location (Table 4), with no significant difference between soil layers.

Density of the bacterivores (BF) and the omnivores-predators (OP) increased with distance from the southeastern part of the Angren power plant (ST I), reaching maximal values in the recreation area, and then, again decreasing in other sampling stations such as the industrial and grazing areas (Table 4). The plant-parasite (PP) nematodes were maximal in the farthest grazing area, with lower values in the other sampling stations (Table 4). No significant difference in fungivore nematode abundance was found between the different sampling stations (Table 4).

The BF nematodes were positively affected by TSN, K, Rb, Sr, Zr, Nb, Pb, Th, and U (Table 2). The FF nematodes were negatively correlated with V and positively correlated with SM, EC, K, Zr, Pb, Th, and U (Table 2). Beside bacterivores and fungivores, the PPs were, for the most part, negatively affected by the observed metals (Cu, Zn, Ga, Rb, Zr, Nb, Pb, Th, and U) and they were positively correlated with Ca, V, Cr, and Co (Table 2). The OP exhibited a negative correlation with Na and a positive correlation with OM, EC, Ca, and Nb (Table 2).

The *Cephalobus* and *Chiloplacus* were the most dominant bacterivore nematodes, reaching maximal values either at the edge of the industrial pollution area (ST II) or in the recreation area (ST III) (Table 3). The *Aphelenchus*, being the most common among the fungivores, and the *Helicotylenchus* along with *Filenchus*, being the most common among the plant-parasite nematodes, reached maximal values at the farthest grazing area (ST VI) (Table 3). The *Dorylaimus* and *Mesodorylaimus* were the most widespread among the omnivores-predators, with maximal values in the recreation area (ST III) (Table 3).

It was found that eight in twelve BF genera, six in eight FF genera, thirteen in twenty PP genera, and ten in thirteen omnivore-predator genera, were correlated with the observed soil properties and metal concentrations (Table 5). *Acrobeles*, *Acrobeloides*, *Cephalobus*, *Chiloplacus*, *Eucephalobus*, *Metateratocephalus*, *Aphelenchoides*, *Aphelenchus*, *Ditylenchus*, *Nothotylenchus*, *Paraphelenchus*, *Tylencholaimellus*, *Criconema*, *Heterodera*, *Paralongidorus*, *Trophurus*, *Paratylenchus*, *Psilenchus*, *Tetylenchus*, *Tylenchorhynchus*, and *Xiphinema* showed correlation with soil properties (Table 5). *Acrobeles*, *Acrobeloides*, *Cephalobus*, *Cervidellus*, *Chiloplacus*, *Metateratocephalus*, *Mesorhabditis*, *Aphelenchus*, *Paraphelenchus*, *Tylencholaimellus*, *Tylencholaimus*, *Filenchus*, *Helicotylenchus*, *Heterodera*, *Hoplolaimus*, *Meloidogyne*, *Trophurus*, *Telotylenchus*, *Tetylenchus*, *Discolaimoides*, *Dorylaimus*, *Dorylaimoides*, *Eudorylaimus*, *Mesodorylaimus*, and *Mononchus* showed correlation with heavy metals.

The following nematodes did not show correlation with the observed soil properties or metals: *Monhystera*, *Panagrolaimus*, *Aphelenchoides*, *Ditylenchus*, *Anguina*, *Criconema*, *Merlinius*, *Longidorus*, *Psilenchus*, *Xiphinema*, and *Nygolaimus*.

3.4. *Ecological indices*

The WI values ranged from 0.2 to 6.12 and were highest (0.0001) in the upper soil layer in the recreation area (ST III) and in the deeper soil layer at the southwestern part of the Angren power plant (ST II) (Fig. 3).

The NCR values ranged between 0.16 and 0.85, with no difference between sampling locations in the deeper soil layer (Fig. 3). However, the NCR values were significantly lower in the upper soil layer ($p < 0.003$) at STs I and VI, with no differences between other stations (Fig. 3).

The mean of Simpson's dominance index (λ) ranged from 0.18 to 0.52, with maximal values ($p < 0.0004$) in the deeper soil layer at the southwestern part of the Angren power plant (ST 2) (Fig. 3).

The H' index showed no differences between sampling stations in the upper soil layer (Fig. 3). However, the H' was minimal ($p < 0.01$) in the deeper soil layer at ST I, with no differences between other sampling stations (Fig. 3).

Table 3
Mean abundance (ind. 100 g^{-1} dry soil) of nematode genera in different sampling stations of the Angren industrial area.

	Sampling stations						p value**	
	ST I	ST II	ST III	ST IV	ST V	ST VI	Depth	Location
Bacterivores*								
Acrobeles	5.08^{a}	nf	nf	1.33^{a}	nf	4.33^{a}	NS	NS
Acrobeloides	0.67^{c}	13.0^{a}	11.25^{ba}	1.83^{c}	4.92^{bc}	nf	NS	0.002
Cephalobus	9.42^{b}	4.75^{b}	48.75^{a}	10.75^{b}	4.83^{b}	2.25^{b}	NS	0.004
Cervidellus	3.42^{a}	3.08^{a}	nf	0.67^{a}	nf	nf	NS	NS
Chiloplacus	14.92^{bc}	46.50^{a}	32.50^{ba}	8.42^{bc}	13.00^{bc}	0.33^{c}	NS	0.01
Eucephalobus	nf	2.58^{a}	2.50^{a}	3.92^{a}	2.33^{a}	0.75^{a}	NS	NS
Metateratocephalus	nf	nf	nf	nf	1.67^{a}	0.33^{a}	NS	NS
Mesorhabditis	0.92^{a}	1.42^{a}	nf	4.50^{a}	nf	nf	NS	NS
Monhystera	nf	nf	0.75	nf	nf	nf	NS	NS
Panagrolaimus	nf	3.33^{a}	3.67^{a}	nf	1.75^{a}	nf	0.02	NS
Fungivores								
Aphelenchoides	2.92^{a}	3.75^{a}	11.58^{a}	2.08^{a}	5.83^{a}	3.58^{a}	NS	NS
Aphelenchus	16.42^{a}	7.50^{ba}	10.08^{ba}	2.75^{b}	3.00^{b}	22.33^{a}	0.008	0.001
Diphtherophora	nf	nf	nf	nf	nf	0.33	NS	NS
Ditylenchus	nf	nf	nf	1.17^{a}	nf	13.42^{a}	NS	NS
Nothotylenchus	2.92^{a}	2.33^{a}	8.00^{a}	8.08^{a}	2.58^{a}	13.42^{a}	NS	NS
Paraphelenchus	2.25^{a}	1.08^{a}	1.75^{a}	nf	nf	nf	NS	NS
Tylencholaimellus	3.17^{ba}	7.25^{a}	1.5^{b}	1.33^{b}	nf	nf	NS	0.02
Tylencholaimus	14.92^{a}	11.50^{ba}	6.92^{bac}	1.00^{c}	4.17^{bc}	0.75^{c}	NS	0.02
Plant-parasites								
Anguina	nf	nf	nf	1.17^{b}	nf	7.83^{a}	NS	0.05
Criconema	nf	nf	nf	nf	nf	4.33	NS	NS
Filenchus	1.58^{b}	5.92^{b}	24.17^{b}	14.58^{b}	15.58^{b}	56.08^{a}	NS	0.002
Helicotylenchus	nf	nf	5.50^{b}	7.17^{b}	3.67^{b}	340.50^{a}	NS	0.0001
Heterodera	nf	1.58^{ba}	1.67^{ba}	nf	nf	6.75^{a}	NS	NS
Hoplolaimus	nf	nf	nf	0.92^{a}	4.42^{a}	2.27^{a}	NS	NS
Meloidogyne	nf	nf	nf	1.00^{b}	nf	6.83^{a}	NS	NS
Merlinius	nf	nf	nf	nf	0.92	nf	NS	NS
Longidorus	1.08^{a}	6.17^{a}	nf	nf	0.92^{a}	nf	NS	NS
Paralongidorus	nf	nf	1.83	nf	nf	nf	NS	NS
Trophurus	nf	nf	nf	nf	0.58^{b}	3.42^{a}	NS	0.05
Paratylenchus	nf	nf	2.75^{a}	nf	2.34^{a}	2.83^{a}	NS	NS
Pratylenchus	1.25^{ba}	0.08^{b}	1.67^{ba}	0.33^{b}	0.42^{b}	2.50^{a}	NS	0.01
Psilenchus	nf	nf	nf	nf	0.58	nf	NS	NS
Telotylenchus	nf	1.08	nf	nf	nf	nf	NS	NS
Tetylenchus	3.33^{b}	1.58^{b}	1.25^{b}	nf	1.62^{b}	15.75^{a}	NS	0.02
Tylenchorhynchus	34.42^{a}	6.08^{a}	15.75^{a}	5.83^{a}	1.00^{a}	8.83^{a}	NS	NS
Tylenchus	9.33^{b}	22.92^{ba}	11.58^{b}	17.58^{ba}	9.83^{b}	31.17^{a}	0.04	0.004
Xiphinema	nf	1.75^{a}	nf	nf	nf	0.50^{a}	NS	NS
Omnivores-predators								
Aporcelaimus	14.42^{a}	5.00^{ba}	12.67^{a}	2.25^{b}	nf	0.33^{b}	NS	0.01
Aporcelaimellus	nf	1.00^{a}	5.50^{a}	nf	0.67^{a}	nf	NS	NS
Discolaimus	nf	nf	0.92	nf	nf	nf	NS	NS
Discolaimoides	nf	nf	nf	nf	nf	0.33	NS	NS
Dorylaimus	5.58^{c}	11.50^{ba}	19.67^{a}	4.33^{c}	2.50^{c}	3.83^{c}	NS	NS
Dorylaimoides	nf	3.25^{b}	12.58^{a}	nf	1.25^{b}	0.33^{b}	0.05	0.006
Eudorylaimus	9.33^{b}	21.42^{ba}	30.58^{a}	4.42^{b}	1.25^{b}	13.58^{ba}	NS	0.03
Mesodorylaimus	13.58^{ba}	18.50^{ba}	22.00^{a}	1.17^{b}	0.67^{b}	12.33^{ba}	0.01	0.002
Mononchus	nf	nf	0.75^{a}	1.92^{a}	nf	0.50^{a}	NS	NS
Nygolaimus	3.00^{ba}	5.17^{a}	nf	nf	nf	nf	NS	NS
Thonus	10.92^{ba}	6.67^{ba}	17.42^{a}	1.33^{b}	1.92^{b}	19.33^{a}	NS	0.04

Different letters indicate significant differences between sampling location, $n = 72$.
nf, not found; NS, not significantly different.
* By classification Yeates and King (1997).
** By 'GLM' statistical analysis, where values of $p < 0.05$ were considered significant.

Table 4
Comparative change (%) in abundance of each nematode trophic group at the sampling stations of the Angren industrial area.

	Sampling stations					
	ST I	ST II	ST III	ST IV	ST V	ST VI
Bacterivores (BF)	12^{b}	27^{a}	36^{a}	12^{b}	10^{b}	3^{b}
Fungivores (FF)	21^{a}	16^{a}	20^{a}	8^{a}	8^{a}	27^{a}
Plant-parasites (PP)	7^{b}	6^{b}	9^{b}	7^{b}	6^{b}	65^{a}
Omnivores-predators (OP)	17^{b}	22^{b}	37^{a}	5^{c}	3^{c}	16^{bc}

Sampling sites: ST I, power plant southeastern part; ST II, power plant southwestern part; ST III, recreation area; ST IV, first farming area; ST V, gold-refinery plant; ST VI, second farming area.
Different letters indicate significant differences between sampling stations.

Table 5
Correlation coefficient between soil free-living nematode genera and soil properties and heavy metals in the Angren industrial area.

	SM		OM		EC		Ca		Na		K		Sc	
	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De
Bacterivores														
Acrobeles						0.52**					0.34*			−0.35*
Acrobeloides											0.38*			
Cephalobus										−0.36*				
Cervidellus														
Chiloplacus											0.39*			
Eucephalobus			0.36*		−0.34*			−0.35*					0.40*	
Metateratocephalus												0.37*		
Mesorhabditis														
Monhystera														
Panagrolaimus														
Fungivores														
Aphelenchoides						0.34*	0.37*							
Aphelenchus								0.33*						
Diphtherophora														
Ditylenchus	0.44**										0.48**			
Nothotylenchus						0.36*								−0.39*
Paraphelenchus						0.46**								−0.33*
Tylencholaimellus						0.52**								
Tylencholaimus														
Plant-parasites														
Anguina														
Criconema							0.37*	0.39*						
Filenchus							0.38*	0.39*						
Helicotylenchus														
Heterodera			−0.39*	−0.33*	−0.34*	−0.35*								
Hoplolaimus														
Meloidogyne														
Merlinius														
Longidorus						0.36*								
Paralongidorus							0.37*	−0.38*						
Trophurus							0.33*	−0.38						
Paratylenchus							0.33*							
Pratylenchus														
Psilenchus						0.36*								−0.39*
Telotylenchus														
Tetylenchus								−0.40*				0.50**		
Tylenchorhynchus												0.43**		
Tylenchus														
Xiphinema			0.40*											
Omnivores-predators														
Aporcelaimus							0.33*			0.46*				
Aporcelaimellus						0.36*		−0.33*						
Discolaimus														0.33*
Discolaimoides												−0.35*		
Dorylaimus	0.33*						0.39*							
Dorylaimoides	−0.38*											0.37*		
Eudorylaimus	−0.34*									−0.36*				
Mesodorylaimus		0.33*										0.49**		
Mononchus														
Nygolaimus			0.33*							−0.33*				
Thonus														

	V		Cr		Co		Ni		Cu		Zn		Ga	
	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De
Bacterivores														
Acrobeles													0.41*	
Acrobeloides		−0.34*		−0.39*										
Cephalobus				−0.33*										
Cervidellus								−0.38*	0.35*	−0.33*	0.38**	0.42*		0.46*
Chiloplacus				−0.50**			−0.45**	0.37*		0.40*		0.54**		
Eucephalobus														
Metateratocephalus		0.34*												
Mesorhabditis		−0.35*		−0.46**			−0.48**	0.44**		0.42**		0.38*		
Monhystera														
Panagrolaimus														
Fungivores														
Aphelenchoides														
Aphelenchus				−0.35*				−0.36*		0.35*		0.40*		0.38*
Diphtherophora														

Table 5 (*Continued*)

	V		Cr		Co		Ni		Cu		Zn		Ga	
	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De
Ditylenchus														
Nothotylenchus														
Paraphelenchus		−0.34*												
Tylencholaimellus		−0.40*		−0.50**			−0.45**	−0.36*				0.43**		
Tylencholaimus		−0.33*		−0.39*				−0.36*						
Plant-parasites														
Anguina														
Criconema														
Filenchus	0.34*		0.41*		0.42*	0.50**	0.40*		−0.35*		−0.43*	−0.35*	−0.50**	
Helicotylenchus	0.36*													
Heterodera														
Hoplolaimus		0.38*		0.34*										
Meloidogyne						0.37*								
Merlinius														
Longidorus														
Paralongidorus														
Trophurus	0.33*					0.34*								
Paratylenchus														
Pratylenchus														
Psilenchus														
Telotylenchus		−0.34*												
Tetylenchus						0.49**								
Tylenchorhynchus														
Tylenchus														
Xiphinema														
Omnivores-predators														
Aporcelaimus														
Aporcelaimellus														
Discolaimus														
Discolaimoides						0.35*								
Dorylaimus					−0.35*									
Dorylaimoides														
Eudorylaimus														
Mesodorylaimus														
Mononchus														
Nygolaimus														
Thonus														

	Rb		Sr		Zr		Nb		Pb		Th		U	
	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De
Bacterivores														
Acrobeles			0.33*								0.36*		0.37*	
Acrobeloides					0.40*		0.36*				0.36*			
Cephalobus														
Cervidellus			0.33*	0.36*	0.33*					0.47**				0.33*
Chiloplacus	0.33*			0.38*	0.55***		0.38*			0.51**	0.46**			0.49**
Eucephalobus														
Metateratocephalus														
Mesorhabditis				0.47**	0.47**		0.38*			0.51**	0.47**			0.44**
Monhystera														
Panagrolaimus														
Fungivores														
Aphelenchoides														
Aphelenchus	−0.36*			0.36*	0.37*					0.45**	0.41*			0.39*
Diphtherophora														
Ditylenchus														
Nothotylenchus														
Paraphelenchus		0.35*												
Tylencholaimellus					0.56***		0.43**			0.39*	0.48**			0.39*
Tylencholaimus					0.38*						0.34*			
Plant-parasites														
Anguina														
Criconema														
Filenchus			−0.40*		−0.43**	−0.35*	−0.42*	−0.38*	−0.43**	−0.35*	−0.40*	−0.42*	−0.40*	−0.39*
Helicotylenchus		0.40*				−0.39*		−0.37*				−0.39*		−0.35*
Heterodera												−0.34*		
Hoplolaimus														−0.34*
Meloidogyne														
Merlinius														
Longidorus														
Paralongidorus														

Table 5 (*Continued*)

	Rb		Sr		Zr		Nb		Pb		Th		U	
	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De
Trophurus														
Paratylenchus														
Pratylenchus														
Psilenchus														
Telotylenchus		0.34*												
Tetylenchus		−0.36*				−0.37*		−0.39*				−0.38*		−0.35*
Tylenchorhynchus														
Tylenchus														
Xiphinema														
Omnivores-predators														
Aporcelaimus														
Aporcelaimellus														
Discolaimus														
Discolaimoides														
Dorylaimus			0.37*					0.40*						
Dorylaimoides	0.35*													
Eudorylaimus								0.38*						
Mesodorylaimus								0.51**						
Mononchus		−0.33*												
Nygolaimus														
Thonus														

n/m, upper/deeper soil layers.
Up, upper; De, deeper soil layers.
* Values with $p < 0.05$.
** Values with $p < 0.01$.
*** Values with $p < 0.001$.

The SR values ranged between 0.76 and 1.55, with no differences between sampling stations in the deeper soil layer (Fig. 3). However, in the upper soil layer, the SR was highest in the recreation area (ST III) and was minimal at the southeastern part of the Angren power plant (ST I).

The MI values ranged between 2.4 and 3.38, with no differences between sampling stations in the upper soil layers (Fig. 3). However, in the deeper soil layer, the MI values increased at ST III and reached maximal values at ST VI, with no differences between other sampling stations (Fig. 3).

All the applied ecological indices were sensitive to environmental changes. However, WI, NCR, and MI indices were mostly sensitive to metal concentration, while λ, *H′*, and SR were mostly sensitive to soil property changes (Table 6).

4. Discussion and conclusions

The intensive and extensive ecological investigations of the last decades came to the conclusion that industrial pollution in different parts of the world has direct and indirect (through soil property changes), strong and negative effects on soil nematode communities and trophic composition (Yeates et al., 1994; Georgieva et al., 2002; Sánchez-Moreno et al., 2006). The results obtained in this study are in agreement with both the above-mentioned and our own previous investigations carried out in different Uzbekistan areas, thus confirming a strong effect of industrial pollution on soil nematode communities and their habitats, with nematode density decreasing at the source of pollution (Pen-Mouratov et al., 2008).

The main soil properties were found to be tightly interdependent on metal concentration, including relative stable elements. In this aspect, our study is consistent with the investigation of Christiansen et al. (2002), who discovered a positive correlation between relatively stable elements such as Zr, Rb, Nb, and OM. Moreover, in the present study, the organic matter was found to be higher near the main source of pollution in comparison to the most remote station. By means of lab experiments, Kawakami et al. (2008) learned that the Zr negatively influences gram-positive. Hence, it can be assumed that along with active trace elements whose negative effect has been well studied, some trace elements, traditionally referred to as inactive elements, can decrease soil microbial abundance that, in turn, leads to accumulation of non-decaying OM in soil. Soil microbial abundance decreasing naturally enough reflects on an abundance of soil free-living nematodes.

Exposure to industrial pollution is known to affect both the nematode density and the trophic group composition of nematode communities (Bongers and Bongers, 1998; Korthals et al., 1998; Pen-Mouratov et al., 2008). At the same time, nematodes belonging to different trophic associations can peculiarly respond to differences in kinds of soil pollution. In the present study, both the nematode density and trophic diversity were found to be strongly dependent on environmental disturbance. The fungivorous nematodes (*Aphelenchus*, *Aphelenchoides*, and *Ditylenchus*) were regarded as insensitive to most pollutants in contrast to bacterivores (Acrobeles), which appear to be the most sensitive taxa (Korthals et al., 1996a, 1996b; Nagy et al., 2004), including a sensitivity to food-resource decrease (Kawakami et al., 2008). The plant-parasite nematode density was the lowest at the source of pollution; this is the exact opposite of data obtained for other industrial regions of this country (Pen-Mouratov et al., 2008). In contrast to other nematode trophic groups, the plant-parasite nematode community was predominantly negatively correlated with the observed chemical elements such as Cu, Zn, Ga, Rb, Zr, Nb, Pb, Th, and U. Therefore, in the present case, both the direct impact of pollution on the plant-parasite nematode community and the indirect negative influence through a vegetation-density decrease, must be considered. The omnivore-predator nematodes belonging to K-strategists, in agreement with numerous publications (e.g., Georgieva et al., 2002; Wasilewska, 1997; Zullini and Peretti, 1986), were more numerous in unindustrialized areas, i.e., they preferred eco-friendly surroundings to metal-contaminated areas.

Our data indicate that 82% of the observed nematode species were affected by either the soil properties or metal concentration. Among them, *Eucephalobus*, *Nothotylenchus*, *Paralongidurus*, *Aporcelaimus*, and *Discolaimus* were correlated only with the observed soil properties; *Meloidoginae*, *Tetylenchus*, and *Discolaimoides* were correlated only with the observed metals; and

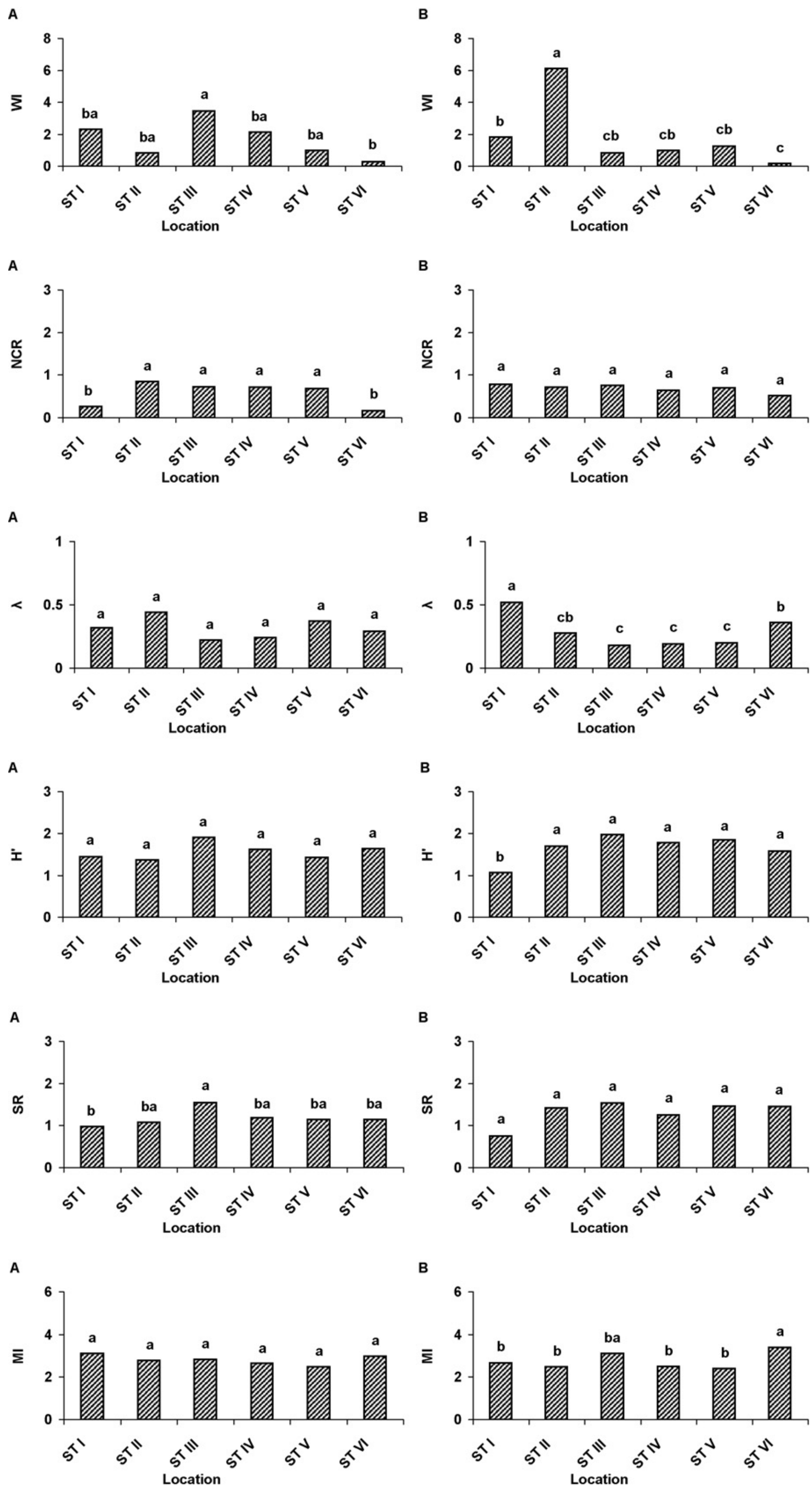

Fig. 3. Variations in soil free-living nematode ecological indices [WI, Wasilewska index; NCR, nematode channel ratio; Simpson's dominance index (λ); Shannon–Weaver index (H'); SR, richness; MI, maturity index] along the deposition transect in the upper (A) and deeper (B) soil layers. Different letters indicate significant differences ($p < 0.05$) using Duncan's multiple range test.

Table 6
Correlation coefficient between ecological indices and soil properties and heavy metals in the Angren industrial area.

	WI		NCR		λ		H'		SR		MI	
	Up	De	Up	De	Up	De	Up	De	Up	De	Up	De
SM												
OM												
pH				−0.59***		−0.36*		0.40*		0.34*		
EC												
Ca										−0.36*	0.33*	
Na												
K	0.57**				−0.33*	−0.36*		0.34*				
Sc		−0.44*										
V	−0.43*	−0.55**	0.34*									
Cr		−0.73***										0.36*
Co		−0.52**										0.48**
Ni		−0.63***										
Cu		0.56**										−0.35*
Zn		0.60***										
Ga	0.41*	0.46**										
Rb			0.44**									
Sr		0.60***										
Zr	0.38*	0.62***	0.40*									
Nb		0.48**										
Pb		0.60***										
Th		0.63***	0.33*									
U		0.68***									−0.43*	

WI, Wasilewska index; NCR, nematode channel ratio; Simpson's dominance index (λ); Shannon–Weaver index (H'); SR, richness; MI, maturity index.
Upper/deeper soil layers.
* Values with $p < 0.05$.
** Values with $p < 0.01$.
*** Values with $p < 0.001$.

Monhystera, *Panagrolaimus*, *Aphelenchoides*, *Ditylenchus*, *Anguina*, *Criconema*, *Merlinius*, *Longidorus*, *Psilenchus*, *Xiphinema*, and *Nygolaimus* were not affected by changes in soil properties and metal concentrations. The *Aphelenchus*, *Tylencholaimellus*, and *Tylencholaimus* belonging to fungivore nematodes were numerous near the industrial source of pollution (coal-burning power plants), while *Cephalobus* belonging to bacterivore nematodes preferred unindustrialized areas.

Previous studies that initiated research on the influence of grazing on nematode communities, gave no clear-cut picture of this effect. Some of those studies affirmed that grazing has a negative effect on soil nematode communities (Li et al., 2005) while others did not reach a clear-cut conclusion (Zolda, 2006) or found that it has a positive effect on soil nematode communities (Freckman et al., 1979; Bardgett et al., 1997). One reason for the difference in the conclusions compared to previous research studies is, possibly, uneven grazing by cattle within large plots (McSorley et al., 2005). The current study confirmed that the grazing, accompanied by industrial pollution, intensifies a negative effect on soil nematode communities. Moreover, while the industrial pollution was slackening, the grazing favored the increase of soil nematode abundance. The trophic structure of nematode communities was found to be sensitive to grazing activity under conditions of industrial pollution, with differences in sensitivity of the separate trophic group. The bacterivores and omnivore-predators were found to be the most sensitive nematodes to both grazing and industrial pollution. Basing on numerous investigations, we're inclined to believe that change in bacterivore density is caused by food source (Kawakami et al., 2008), while a change in omnivore-predators was induced by their (omnivore-predators) indicator-sensitive ability (Korthals et al., 1998; Porazinska et al., 1999; Neher, 2001).

The widely used ecological indices applied in the present research were sensitive to environmental disturbances caused by industrial pollution as well as grazing. The Wasilewska index, describing the relative balance of positive-to-negative impacts of nematodes on primary productivity or stage of decomposition, where a ratio greater than 1 suggests that the positive impact of nematodes outweighs the negative impact on plant productivity (Wasilewska, 1989; Neher and Darby, 2005), was consistent with data obtained by other researchers (0.70–21.63) (Wasilewska, 1994; Zolda, 2006). Our data showed the negative impact of nematodes on primary production in the industrial area (ST II, upper soil layer), in the farthest grazing area (ST VI, both layers), and in the recreation area (ST III, deeper soil layer), and the positive impact of nematodes at the other sampling sites. The nematode channel ratio (NCR) [with variation between 1 (bacterial-feeding nematode dominance) and 0 (fungi-feeding nematode dominance) (Moore and Hunt, 1988; Yeates et al., 2003; Zhang et al., 2007)], indicated that the bacterial-based decomposition process was dominant in soils exposed to both strong industrial pollution and grazing (STs I and VI). These data, supported by other studies (Bardgett et al., 2001; Yeates, 2003), indicated that soil microbial communities in heavily grazed sites are dominated by bacterial-based energy channels of decomposition, whereas in systems that are less intensively grazed or completely unmanaged, fungi play a proportionally greater role. The diversity indices, where the Shannon (H') index is sensitive to rare taxa and the Simpson's index (λ) is used to measure common taxa (Neher, 2001), indicated an increase of the contribution of common nematodes in the deeper soil layer at the industrial (ST I) and the farthest-farm (ST VI) areas, and the disappearance of rare species in the industrial area (ST I). The SR index indicated sensitivity to industrial pollution from the Angren power plant (ST I), with the lowest values near the source of pollution. The maturity index has been used successfully to distinguish between well-functioning ecosystems and heavily disturbed or stressed systems (Yeates et al., 1999; Neher, 1999), where a higher maturity index value indicates that the more mature and stable the ecosystem, the more stable was the condition of soil biota at the deeper soil layers of the recreation area (ST III) and the farthest-farm (ST VI) areas. It was found that the Wasilewska index, nematode channel ratio, and maturity index were mostly affected by metal concentration, while the diversity indices and species richness were mostly affected by soil property changes.

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References

Bardgett, R.D., Leemans, D.K., Cook, R., Hobbs, P.J., 1997. Seasonality of soil biota of grazed and ungrazed hill grasslands. Soil Biol. Biochem. 29, 1285–1294.

Bardgett, R.D., Jones, A.C., Jones, D.L., Kemmitt, S.J., Cook, R., Hobbs, P.J., 2001. Soil microbial community patterns related to the history and intensity of grazing in sub-montane ecosystems. Soil Biol. Biochem. 33, 1653–1664.

Bongers, T., 1990. The maturity index: an ecological measure of environmental disturbance based on nematode species composition. Oecologia 83, 14–19.

Bongers, T., Bongers, M., 1998. Functional diversity of nematodes. Appl. Soil Ecol. 10, 239–251.

Bongers, T., Ilieva-Makulec, K., Ekschmitt, K., 2001. Acute sensitivity of nematode taxa to $CuSO_4$ and relationships with feeding-type and life history classification. Environ. Toxicol. Chem. 20, 1511–1516.

Cairns, E.J., 1960. Methods in nematology. In: Sasser, J.N., Jenkins, W.R. (Eds.), Nematology, Fundamentals and Recent Advances with Emphasis on Plant Parasitic and Soil Forms. University of North Carolina Press, Chapel Hill, NC, pp. 33–84.

Christiansen, C., Bartholdy, J., Kunzendorf, H., 2002. Effects of morphological changes on metal accumulation in a salt marsh sediment of the Skallingen peninsula, Denmark. Wetlands Ecol. Manage. 10, 11–23.

Duffus, J.H., 2002. "Heavy metals" a meaningless term? (IUPAC Technical Report). Pure Appl. Chem. 74, 793–807.

Egamberdiyeva, D., 2007. The effect of plant growth promoting bacteria on growth and nutrient uptake of maize in two different soils. Appl. Soil Ecol. 36, 184–189.

Egamberdiyeva, D., Hoflich, G., 2003. Influence of growth-promoting bacteria on the growth of wheat in different soils and temperatures. Soil Biol. Biochem. 35, 973–978.

FAO, 2003. Fertilizer Use by Crop in Uzbekistan. Land and Plant Nutrition Management Service Land and Water Development Division, Food and Agriculture Organization (FAO) of the United Nations, Rome, http://www.fao.org/DOCREP/006/Y4711E/y4711e00.htm#Contents.

Freckman, D.W., Duncan, D.A., Larson, J.R., 1979. Nematode density and biomass in an annual grassland ecosystem. J. Range Manage. 32, 418–422.

Georgieva, S.S., McGrath, S.P., Hooper, D.J., Chambers, B.S., 2002. Nematode communities under stress: the long-term effects of heavy metals in soil treated with sewage sludge. Appl. Soil Ecol. 20, 27–42.

Gupta, V.V.S.R., Yeates, G.W., 1997. Soil microfauna as bioindicators of soil health. In: Pankhurst, C.E., Doube, B.M., Gupta, V.V.S.R., Grace, P.R. (Eds.), Soil Biota Management in Sustainable Farming Systems. CAB International, Oxon, UK, pp. 201–233.

Houba, V.J.G., Novozamsky, I., Vittenbogaard, J., Van Der Lee, J.J., 1987. Automatic determination of total soluble nitrogen in soil extracts. Landwirtsch. Forsch. 40, 295–302.

Information Agency Jahon of the Ministry of Foreign Affairs of the Republic of Uzbekistan, 2003.

Kandji, S.T., Ogol, C.K.P.O., Albrecht, A., 2001. Diversity of plant-parasitic nematodes and their relationships with some soil physico-chemical characteristics in improved fallows in western Kenya. Appl. Soil Ecol. 18, 143–157.

Kawakami, H., Yoshida, K., Nishida, Y., Kikuchi, Y., Sato, Y., 2008. Antibacterial properties of metallic elements for alloying evaluated with application of JIS Z 2801:2000. ISIJ Int. 48 (9), 1299–1304.

Korthals, G.W., Alexiev, A.D., Lexmond, T.M., Kammenga, J.E., Bongers, T., 1996a. Long-term effects of copper and pH on the nematode community in an agroecosystem. Environ. Toxicol. Chem. 15, 979–985.

Korthals, G.W., van de Ende, A., van Megen, H., Lexmond, T.M., Kammenga, J.E., Bongers, T., 1996b. Short-term effects of cadmium, copper, nickel and zinc on soil nematodes from different feeding and life-history strategy groups. Appl. Soil Ecol. 4, 107–117.

Korthals, G.W., Popovici, I., Iliev, I., Lexmond, T.M., 1998. Influence of perennial ryegrass on a copper and zinc affected terrestrial nematode community. Appl. Soil Ecol. 10, 73–85.

Li, Q., Mayzlish, E., Shamir, I., Pen-Mouratov, S., Sternberg, M., Steinberger, Y., 2005. Impact of grazing on soil biota in a Mediterranean grassland. Land Degrad. Dev. 16, 581–592.

Makhmudov, M.M., Khaitov, R., 2000. Effective use of steppe pastures and recommendations for raising productivity. ICARDA 26, Tashkent.

McSorley, R., Wang, K.H., Bohlen, P.J., Gathumbi, S.M., 2005. Grazing and nematode communities in pastures: a question of scale. In: Archbold Research Symposium, 11–12 January 2005, MacArthur Agro-ecology Research Center, Lake Placid, FL, USA.

Mills, A., Adl, M.S., 2006. The effects of land use intensification on soil biodiversity in the pasture. Can. J. Plant Sci. 86, 1339–1343 (special issue).

Moore, J.C., Hunt, H.W., 1988. Resource compartmentation and the stability of real ecosystems. Nature 333, 261–263.

Nagy, P., Bakonyi, G., Bongers, T., Kadar, I., Fabian, M., Kiss, I., 2004. Effects of microelements on soil nematode assemblages seven years after contaminating an agricultural field. Sci. Total Environ. 320, 131–143.

Neher, D.A., 1999. Soil community composition and ecosystem processes—comparing agricultural ecosystems with natural ecosystems. Agroforest. Syst. 45, 159–185.

Neher, D.A., 2001. Role of nematodes in soil health and their use as indicators. J. Nematol. 33, 161–168.

Neher, D.A., Darby, B.J., 2005. Computation and application of nematode community indices: general guidelines. In: Abebe, E. (Ed.), Freshwater Nematodes: Ecology and Taxonomy. CABI, pp. 211–222.

Pen-Mouratov, S., Rakhimbaev, M., Steinberger, Y., 2003. Seasonal and spatial variation in nematode communities in the Negev Desert ecosystem. J. Nematol. 35, 157–166.

Pen-Mouratov, S., He, X.L., Steinberger, Y., 2004. Spatial distribution and trophic diversity of nematode populations under *Acacia raddiana* along a temperature gradient in the Negev Desert ecosystem. J. Arid Environ. 56, 339–355.

Pen-Mouratov, S., Shukurov, N., Steinberger, Y., 2008. Influence of industrial heavy metal pollution on soil free-living nematode population. Environ. Pollut. 152, 172–183.

Porazinska, D.L., Duncan, L.W., McSorley, R., Graham, J.H., 1999. Nematode communities as indicators of status and processes of a soil ecosystem influenced by agricultural management practices. Appl. Soil Ecol. 13, 69–86.

Rhoades, J.D., 1982. Soluble salts. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2, Chemical and Microbiological Properties. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 167–179.

Rowell, D.L., 1994. Soil Science: Methods and Applications. Longman Group UK Ltd., London.

Sánchez-Moreno, S., Camargo, J.A., Navas, A., 2006. Ecotoxicological assessment of the impact of residual heavy metals on soil nematodes in the Guadiamar river basin (Southern Spain). Environ. Monit. Assess. 116, 245–262.

SAS Inst, 1988. SAS/ATAT User's Guide, Release 6.03. SAS Institute Inc., Cary, NC.

S.F.A.S., 1995. Manual-San Plus Analyzer. SKALAR Analytical, The Netherlands.

Shannon, C.E., Weaver, W., 1949. The Mathematical Theory of Communication. University of Illinois Press, Urbana, IL.

Simpson, E.H., 1949. Measurement of diversity. Nature 163, 668.

Sokal, R., Rohlf, F.J., 1969. Biometry: Principles, Practices and Statistics in Biological Research. W.H. Freeman and Co., San Francisco, CA.

Steinberger, Y., Loboda, I., 1991. Nematode population dynamics and trophic structure in a soil profile under the canopy of the desert shrub *Zygophyllum dumosum*. Pedobiologia 35, 191–197.

Steinberger, Y., Sarig, S., 1993. Response by soil nematode populations in the soil microbial biomass to a rain episode in the hot, dry Negev Desert. Biol. Fertil. Soils 16, 188–192.

United Nations Economic Commission for Europe (UNECE), 2000. Environmental Performance Review of Uzbekistan. UN Economic Commission for Europe Information Service Palais des Nations, Geneva, Switzerland.

UTEMWO, 2005. First Uzbekistan International Exhibition Mining World, www.mining.ite-uzbekistan.uz; www.angren.info, Uzbekistan.

Wasilewska, L., 1989. The role of nematodes in agroecosystems. Zesz. Probl. Postepow Nauk Rolniczych 358, 7–16.

Wasilewska, L., 1994. The effect of age of meadows on succession and diversity in soil nematode communities. Pedobiologia 38, 1–11.

Wasilewska, L., 1997. Soil invertebrates as bioindicators, with special reference to soil-inhabiting nematodes. Russ. J. Nematol. 5, 113–126.

Yeates, G.W., 2003. Nematodes as soil indicators: functional and biodiversity aspects. Biol. Fertil. Soils 37, 199–210.

Yeates, G.W., Bird, A.F., 1994. Some observations on the influence of agricultural practices on the nematode faunae of some South Australian soils. Fundam. Appl. Nematol. 17, 133–145.

Yeates, G.W., Orchard, V.A., Speir, T.W., Hunt, J.L., Hermans, M.C.C., 1994. Impact of pasture contamination by copper, chromium, arsenic timber preservative on soil biological activity. Biol. Fertil. Soils 18, 200–208.

Yeates, G.W., Bongers, T., 1999. Nematode diversity in agroecosystems. Agric. Ecosyst. Environ. 74, 113–135.

Yeates, G.W., King, K.L., 1997. Soil nematodes as indicators of the effect of management on grasslands in the New England Tablelands (NSW): comparison of native and improved grasslands. Pedobiologia 41, 526–536.

Yeates, G.W., Wardle, D.A., Watson, R.N., 1999. Responses of soil nematode populations, community structure, diversity and temporal variability to agricultural intensification over a seven-year period. Soil Biol. Biochem. 31, 1721–1733.

Yeates, G.W., Percival, H.J., Parshotam, A., 2003. Soil nematode responses to year-to-year variation of low levels of heavy metals. Aust. J. Soil Res. 41, 613–625.

Zeien, H., 1995. Chemische Extraktionen zur Bestimmung der Bindungsformen von Schwermetallen in Boden, 284 pp. Bonner Bodenkundliche Abhandlungen 17.

Zeien, H., Brummer, G.W., 1989. Chemische extraktionen zur bestimmung von schwerbetallbindungsformen in Boden. Mitt. Dtsch. Bodenkundl. Ges. 59, 505–510.

Zhang, W.D., Wang, X.F., Li, Q., Jiang, Y., Liang, W.J., 2007. Soil nematode responses to heavy metal stress. Helminthologia 44, 87–91.

Zolda, P., 2006. Nematode communities of grazed and ungrazed semi-natural steppe grasslands in Eastern Austria. Pedobiologia 50, 11–22.

Zullini, A., Peretti, E., 1986. Lead pollution and moss-inhabiting nematodes of an industrial area. Water Air Soil Pollut. 27, 403–410.