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Article

Diversity and Abundance of Soil Animals as Influenced by Long-Term Fertilization in Grey Desert Soil, China

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Abstract: The relationship between soil fauna and different fertilizer management practices is of growing concern. The aim of this research was to investigate the response of soil fauna to fertilization regimes, to explore the relationships among the community of soil animals, soil moisture and crop yields. The application of organic fertilizers (*i.e.*, sheep manure or crop residues) increased crop yields and promoted the number of individuals and species of soil fauna owing to the exogenous organic matter that fertilizers provided for the survival and development of soil fauna. Furthermore, the treatments that applied sheep manure (*i.e.*, sheep manure only or nitrogen, phosphorus, potassium and sheep manure plus) were significantly beneficial for increasing crop yields and diversity of soil fauna compared to treatments with crop residues returned (*i.e.*, crop residues returned only or nitrogen, phosphorus, potassium and crop residues returned to the field) ($p < 0.05$) due to the response of soil fauna to diverse exogenous nutrients and the effect of soil fertility. Therefore, the finding that soil fauna abundance is significantly positively correlated with soil moisture and crop yield may mean the effects of fertilizer applications on soil animals were partly masked by the soil moisture and crop yield.

Keywords: long-term fertilization; soil fauna; crop yield; grey desert soil

1. Introduction

Soil fauna are important components of agricultural ecosystems, due to their functional roles in these processes and the provision of various ecosystem services—for example, they would accelerate the organic matter decomposition and nutrient transformation [1,2]. It is known that the application of fertilizers can enhance soil fertility and promote soil rehabilitation. However, the most profound impact of fertilizers on soil properties is their ability of changing crop yields [3]. This process will subsequently change the diversity and abundance of soil fauna by affecting the habitation environment of the soil fauna [4,5]. Therefore, the community of soil animals in croplands is closely related to fertilization regimes [6,7].

Previous research has shown the relationship between the biodiversity of soil fauna and ecosystem function in soil systems [8,9]. They also reported that long-term organic and mineral fertilization in a field experiment led to increased abundance of soil micro-arthropods (e.g., Collembola) [10]. The application of green manure herbage management effects on earthworm populations has also been reported [11]. Blanchart [12] reported that a long-term legume cover crop increased macrofauna and predatory nematode density and biomass (especially earthworms and termites). Long-term manure fertilizer increased the abundance of total nematodes, and the relative abundance of bacterivores [6]. However, long-term nutrient fertilization did not affect faunal abundances and had no such effects on community composition of Oribatida and Collembola [13]. In fact, combination of long-term organic and chemical fertilizer treatments reduced the abundance of Oribatida such as *Epilohmannia* sp. and *Xylobates* sp. [14]. These results indicate that the relationship between habit types under different fertilizer regimes and functional soil fauna plays a key role in ecological sustainability in agriculture. Although the relationship between soil fauna and long-term fertilization regimes has received sustained attention, there are few studies on grey desert soils. The fact that the changes in the crop yields makes them sustainable to obtain the response of soil fauna to fertilization regimes. Belonging to weathered soils, they are typically managed with little external input, which contributes to nutrient-poor soils under a typical continental arid climate [15]. However, they are important agricultural soils in northwestern China, because as much as 52,528 square kilometers of grey desert soils are cultivated agricultural land across China and more than a quarter is in Xinjiang [16]. Long-term fertilization can inevitably cause changes in the soil fertility and productivity while maintaining and improving crop yields [17–19]. Soil fauna has been shown to be sensitive for sustainable processes in agriculture [20]. Therefore, this study aims to investigate the following: (1) the effects of long-term fertilization on the structure of the community of soil animals; (2) the relationship among major the community of soil animals, soil moisture, and crop yield caused by fertilization regimes.

2. Materials and Methods

2.1. Site Description, Climate Characteristics and Soil Properties

The experimental location in the grey desert soil of Xinjiang was one site of the National Long-term Monitoring Network of Soil Fertility and Fertilizer Effects, established in 1990 to investigate the effects of climate, crop rotation and application of inorganic and organic fertilizers on crop yield and soil fertility in the main agricultural areas of China. The experimental site (43°58′ N, 87°25′ E, 600 m *a.s.l.*) was located in the suburbs of Urumqi, Xinjiang, China, and has a typical continental arid climate [15]. The study site is typical oasis farmland with a maize-wheat-cotton crop rotation in order to keep the soil quality not affected by the crops. The mean annual precipitation is 242 mm, 70% of which falls in winter and summer. During the study period, the mean annual temperature was 7.6 °C and the lowest and highest mean monthly air temperatures were −15 °C in January and 27.2 °C in July, respectively. Sunshine time is 2454 h per year. The annual frost-free period is about 156 days. Annual evaporation is about 2570 mm [16]. The soil was classified as a grey desert soil in the Chinese classification and as a Calcaric Cambisol in the FAO soil classification [21]. The soil is a grey desert soil with percentage clay, silt and sand fractions in the top 20 cm of the soil profile of 30.3%, 52.5% and 17.2%, respectively. The main soil properties in the plough layer (0–20 cm) of the fertilizer experiment were as follows: soil pH (water:soil = 2.5:1) 8.1, organic matter 8.8 g C kg^{-1}, total nitrogen (N) 0.87 g N kg^{-1}, total phosphorus (P) 0.67 g P kg^{-1}, total potassium (K) 23.0 g K kg^{-1}, alkaline hydrolysable N 55.2 mg N kg^{-1}, Olsen-P 3.4 mg P kg^{-1} and ammonium acetate (NH_4OAc) extractable K 288.0 mg K kg^{-1}. The field was wasteland before the start of the long-term experiment in April 1990.

2.2. Experimental Design

The long-term fertilization experiment was commenced in April 1990 on cropland of grey desert soil. The plots were hydrologically isolated by partition walls of depth 70 cm filled with cement to avoid unexpected species movement between the individual plots [22]. The study included 11 fertilizer treatments: (1) CK (unfertilized control); (2) N (nitrogen only); (3) NP (nitrogen and phosphorus); (4) NK (nitrogen and potassium); (5) PK (phosphorus and potassium); (6) NPK (nitrogen, phosphorus and potassium); (7) M (sheep manure only); (8) SNPK (nitrogen, phosphorus, potassium and crop residues returned to the field); (9) MNPK (nitrogen, phosphorus, potassium and sheep manure plus); (10) 1.5MNPK (nitrogen, phosphorus, potassium and 1.5 times sheep manure plus); (11) S (crop residues returned only) and; (12) CK_0 (abandonment). Detailed information on the treatments is given in Table 1. Nitrogen fertilizer (as urea) was applied in two split applications, 60% N as basal fertilizer and 40% N as topdressing in the treatments. All phosphorus (P) and potassium (K) fertilizers (as calcium superphosphate and potassium sulfate, respectively), and organic fertilizers (including straw and manure) were applied as basal fertilizers. The sheep dung applied in the study area was collected from the same sheep farm. The fertilizers and manures were evenly broadcast onto the soil surface and immediately incorporated into the plowed soil (0–20 cm depth) by tillage before sowing. Drip irrigation was adopted during the experimental period. Crops were harvested close to the ground with farm machinery, and all harvested biomass was removed from the plots, with little or no crop residues returned to the land except in the SNPK treatment. Each fertilizer treatment had three field replications and the sampling was in a randomized complete block design. The experimental plot covered an area of 468 m^2 and crop yields were determined from the whole plot area. The long-term experiment was conducted during 1990–2014 [15].

Table 1. Treatments and application rates of mineral fertilizers, organic manure and straw in a long-term fertilization experiment in grey desert area.

Treatment	Sheep manure (kg ha^{-1})	Straw (kg ha^{-1})	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
CK	0	0	0	0	0
CK_0	0	0	0	0	0
N	0	0	241.5	0	0
NP	0	0	241.5	138.0	0
NK	0	0	241.5	0	58.5
PK	0	0	0	138.0	58.5
NPK	0	0	241.5	138.0	58.5
M	60,000	0	0	0	0
S	0	4500–9000	0	0	0
SNPK	0	4500–9000	216.7	116.6	52.0
MNPK	30,000	0	84.9	51.4	12.4
1.5 MNPK	60,000	0	151.8	90.4	19.0

Treatments represent habit types labeled as: unfertilized control (CK), nitrogen only (N), nitrogen and phosphorus (NP), nitrogen and potassium (NK), phosphorus and potassium (PK), nitrogen, phosphorus and potassium (NPK), sheep manure only (M), nitrogen, phosphorus, potassium and crop residues returned to the field (SNPK), nitrogen, phosphorus, potassium and sheep manure plus (MNPK), nitrogen, phosphorus, potassium and 1.5 times sheep manure plus (1.5MNPK), crop residues returned only (S), abandonment (CK_0).

2.3. Sampling Methods

Soil samples were taken from the plough layer (0–20 cm) at 10 places in each treatment plot and mixed thoroughly, then air-dried, sieved through a 2.0 mm sieve and stored for analysis. Soil organic matter (SOM) was analyzed by dichromate oxidation and titration using ferrous ammonium sulfate. Soil samples for moisture were taken from each treatment at earring stage and filling stages of winter wheat (*Triticum aestivum* L.) in 2014. Five soil cores with 3 cm diameter were randomly collected to 20 cm depth from areas within 1.5 m of the edge after harvested and the soil moisture was determined gravimetrically after being kept at 105 °C for 24 h [23]. The wheat plant samples were collected before harvest time. There were three points for each fertilization treatment and per point was 1 m^2 quadrat included more than 50 wheat plants, which weigh fresh weight and dry weight of wheat for calculating the crop yield of wheat. The soil pH (water:soil at 2.5:1), available N (alkaline diffusion method), Olsen-P (0.5 mol/L sodium bicarbonate ($NaHCO_3$) at pH 8.5 extractable P) and available K (1 mol/L ammonium acetate (NH_4OAc) extractable K) in the samples were analyzed [24]. Total N and, P in soil were analyzed using the micro-Kjeldahl digestion and, colorimetric analysis, respectively [24].

For the soil fauna studying, soil samples were collected in the earring and filling stage of the winter wheat (*Triticum aestivum* L.) in 2014. Three replication soil samples were collected from each plot. Soil samples were collected using a self-regulating geotome (5 cm depth, 100 cm^3 for soil hygrocolous fauna and 200 cm^3 for the dry soil fauna). Macrofauna were collected by hand-sorting on site and preserved in 70% alcohol, then the collected fauna samples were extracted by the modified Tullgren funnel method in the laboratory [25,26]. The soil samples remained in the steel cylinders during the extraction and the funnels were equipped with sieves of 2 and 0.5 mm for dry and hygrocolous soil fauna, respectively. A standard 60W filament bulb, regulated with a dimmer switch, was used for extraction with light intensity gradually increased during the extraction process. Soil fauna was collected in small plastic bottles filled with 75% alcohol. Finally, the soil fauna were identified and counted under a binocular dissecting microscope equipped with double-tube anatomical lenses [25,26].

2.4. Data Analysis

Dominant groups (the group with proportion of individual numbers representing over 10% of the total sample) and common groups (the group with proportion of individual numbers representing 1%–10% of the total sample) were sorted as follows: Nematodes, Oribatida, Mesostigmata, Onychiuridae, Entomobryidae, Formicidae, Aphididae, Staphylinidae, Scaphidiidae, Lycosidae and, Oonopidae. Soil fauna community diversity was quantified using the Shannon-Wiener index (H'), Pielou evenness index (J) and, Margalef richness index (d) [27–29]. Non-metric multidimensional scaling (non-metric-MDS), another nonlinear iteration ordination technique developed recently, was widely used and adapted to analyze nonlinear data structure [30] using Euclidean distance calculated for each fertilization distance coefficient matrix in two-dimensional space using non-metric multidimensional scaling model fits from the coefficient matrix of each fertilizer treatment. This matrix was then subjected to MDS. MDS analysis of such a matrix produces a map where some grades that were often sorted together appear close together and those that were rarely sorted together appear far apart on that map. The relationship at the series grade would be indicated primarily by ecological analysis, which had been completed by separated lattices of sample components themselves, and the stress indicated the dissimilarity defined between the initial axis defined by non-metric-MDS and truth value to a certain extent, and the stress was thought to be coinciding very well with each other when it was less than 0.1000 [22]. The method of principal component analysis (PCA) was used to analyze how the major the community of soil animals were influenced by habit types under different fertilizer regimes. The analytical program CANOCO for Windows 4.5 was used [31].

Descriptive statistics of the data (e.g., application rate of N fertilizer, Olsen-P and sheep manure, *etc.*) for the long-term monitoring experiment site were obtained using Excel software (Microsoft Corporation, 2010). In the case of non-homogeneity of variances, data were log-transformed ($x + 1$) before further analysis. The data of the abundance and biodiversity indices among different fertilizer plots for ANOVA and path analysis were normalized log ($x + 1$) if required. Statistical significance was determined at $p = 0.05$ and levels of significance among the different treatments (including the fallow) were evaluated using Tukey's *post hoc* multiple comparisons test. The data were analyzed for homogeneity of variance using Levene's test of equality for error variances and asymmetry. Statistical analysis was conducted using SPSS 19.0 software [32].

3. Results

3.1. The Impact of Fertilization on the Soil Moisture and Crop Yield

The highest soil moisture content was found in the MNPK treatment and the lowest one was found in the S and Abandonment treatments at the earring and filling stages, respectively. The soil moisture content was significantly higher in the M and MNPK fertilizer treatments than those in the N, PK, S and SNPK treatments at the earring and filling stages ($p < 0.05$, Figure 1). However, the other fertilizer treatments showed no significant difference in soil moisture contents ($p > 0.05$, Figure 1).

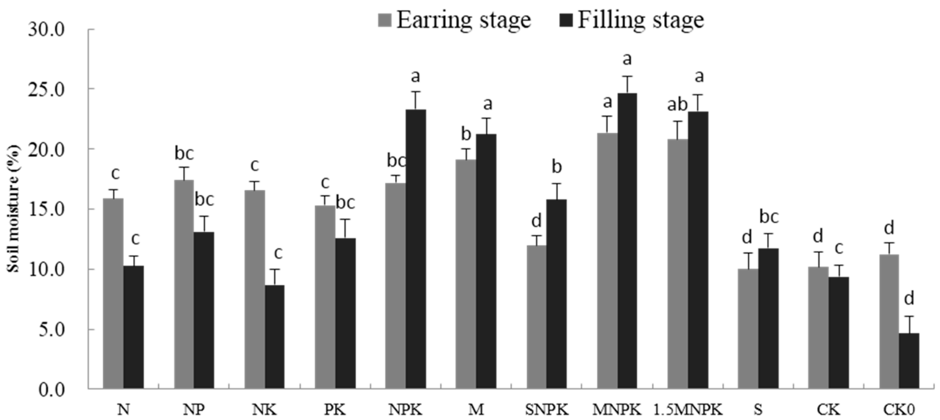

Figure 1. Soil moisture content of grey desert soil under different fertilization treatments. Treatments with the same letters (a or b) are not significantly different (ANOVA with LSD test, $p > 0.05$).

The yields of wheat for different fertilizer treatments are showed in Figure 2. The crop yields of the treatments with the long-term application of organic sheep manure (*i.e.*, M and MNPK) had a higher impact level than those obtained from the treatments with other fertilization regimes (*i.e.*, N, NPK, SNPK and S *et al.* ($p < 0.05$), Figure 2). The crop yields in the N, NP, PK and NK treatments were less impacted, not achieving statistically significant levels. Thus, these results indicated that the crop yields were significantly influenced by habit types under different fertilizer regimes. The combined application of NPK fertilizers with organic manure was an important fertilization technique in enhancing the crop yield and maintaining the quality of grey desert soil.

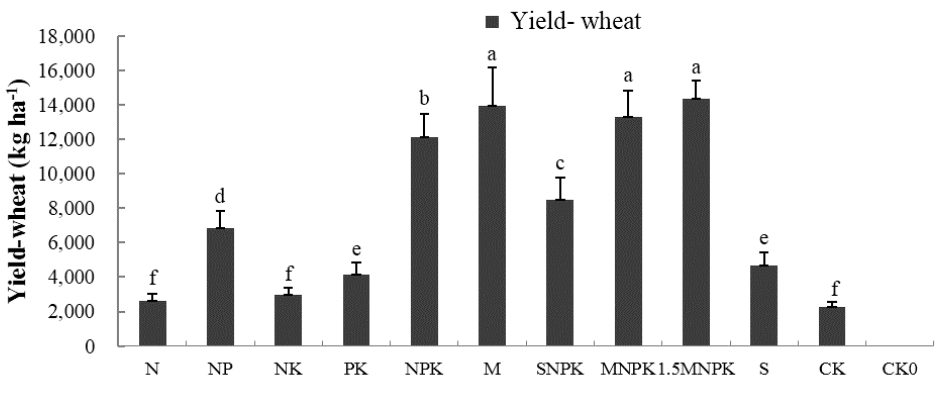

Figure 2. The yields of wheat for different fertilization treatments. Treatments with the same letters (a or b) are not significantly different (ANOVA with LSD test, $p > 0.05$).

3.2. The Impact of Fertilization on Soil Fauna Community Structure and Diversity

There were 17,788 individuals, belonging to 15 orders and 35 families, obtained from 108 soil samples and 120 pitfall traps collected in 12 plots. There were 29 families of macro fauna, with common groups Formicidae, Aphididae, Staphylinidae, Scaphidiidae, Lycosidae and Oonopidae, representing 3.29%, 1.15%, 2.48%, 1.52%, 1.52% and 2.12% of the total of fauna individuals, respectively. The meso and micro fauna were Nematodes, Oribatida, Prostigmata, Mesostigmata, Onychiuridae, Entomobryidae, Ceratocombidae, Projapygidae, and Scutigerellidae. The dominant group was Nematodes and Oribatida, which account for 60.55% and 12.64% of the total fauna, respectively. Common groups were Mesostigmata, Onychiuridae and Entomobryidae, which were 5.41%, 4.40% and 1.42% of the total of fauna individuals, respectively. The highest numbers of individuals and abundance of soil fauna community were found in the 1.5 MNPK treatment (Table 2). Compared with NPK and N, the numbers of individuals and species of soil fauna were higher in the M, S, MNPK and SNPK treatments. The application of organic materials (*i.e.*, sheep manure or crop residues) tended to increase the number of individuals in the soil fauna (Table 2).

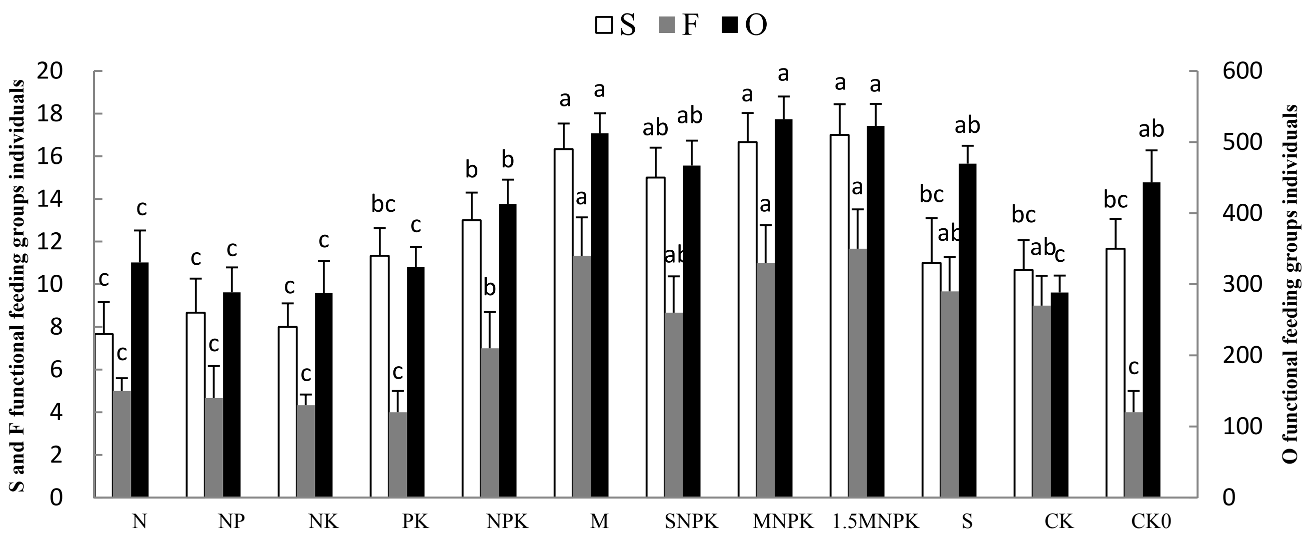

Figure 3. Saprozoic (S), fungivorous (F) and omnivorous (O) members of the soil fauna community (mean ± standard error). Treatments with the same letters (a or b) are not significantly different (ANOVA with LSD test, $p > 0.05$).

Six types of guilds were gathered, which included omnivores, saprozoic, phytophages, fungivores, predators and cadavericoles, of which those of omnivores, predators and saprozoic were greater than the others, accounting for 88.46, 4.83 and 3.68% of the total guilds, respectively (Table 2). Saprozoic, fungivores and omnivores of soil fauna were significantly higher in the M, MNPK and SNPK than in the NPK and N treatments ($p < 0.05$), whereas the other fertilization regimes showed no significant differences ($p > 0.05$) (Figure 3).

Table 2. The total number of individuals of soil fauna community in the different fertilization regimes.

Taxa	Size	N	NP	NK	PK	NPK	M	SNPK	MNPK	1.5 MNPK	S	CK	CK_0	Pet.	Deg.	Gu.
Nematodes	Meso/micro	678	641	631	663	973	1235	1125	1295	1256	1133	644	497	60.55	***	O
Oribatida	Meso/micro	253	157	162	250	163	183	170	178	182	168	146	236	12.64	***	O
Prostigmata	Meso/micro	6	2	1	2	5		2	7		8	3	2	0.21		O
Mesostigmata	Meso/micro	58	53	44	47	122	134	88	143	152	38	37	46	5.41	**	O
Collembola																
Onychiuridae	Meso/micro	11	13	14	11	38	49	38	52	50	42	13	452	4.40	**	O
Entomobryidae	Meso/micro	5	8	7	4	17	18	22	26	34	13	11	87	1.42	**	O
Thysanoptera																
Phlaeothripidae	Macro		11	2	15	7	1	19	5	27	21	7	19	0.75		S
Hymenoptera																
Formicidae	Macro	45	47	49	46	48	52	46	45	46	53	51	58	3.29	**	O
Formicinae	Macro		13	5	5	5	2	23	1	18	2	11	4	0.50		O
Homoptera																
Aphididae	Macro	25	15	6	8	16	27	45	11	15	5	21	11	1.15	**	Ph
Coleoptera																
Nitidulidae	Macro				1		1	3	1		2		1	0.05		S
Nitidulidae larva							5	10			3			0.10		
Staphylinidae	Macro	23	26	24	34	39	49	45	50	51	33	32	35	2.48	**	S
Staphylinidae larva								2						0.01		
Scaphidiidae	Macro	15	14	13	12	21	34	26	33	35	29	27	12	1.52	**	F
Scarabaeidae	Macro		1	2	1	2	3	2	3	1			1	0.09		Ph
Lucanidae	Macro	1				8	1	3			3	1		0.10		S
Carabidae	Macro	6	2	2	2	3	2	4	2	5	2	6	1	0.21		Pr
Cicindelidae	Macro		1											0.01		Pr
Silphidae	Macro		1		1			3	1	2		3	1	0.07		Ca
Coccinellidae	Macro		4	1	1	6		6	2	6		3	1	0.17		Pr/Ph
Diptera																
Dolichopodidae	Macro	6	1	1	17		2	1	2	1	1			0.18		Pr/S

Table 2. *Cont.*

Taxa	Size	N	NP	NK	PK	NPK	M	SNPK	MNPK	1.5 MNPK	S	CK	CK_0	Pet.	Deg.	Gu.
Orthoptera																
Catantopidae	Macro	23	3		2				1	1	1			0.17		Ph
Gryllidae	Macro		1	1		1			2				3	0.04		Ph
Isopoda																
Armadillidiidae	Macro			2		1				1				0.02		O
Araneae																
Lycosidae	Macro	12	17	9	37	14	13	20	79	19	16	22	12	1.52	**	Pr
Zoridae	Macro			5	6			8	2	1	4	2	10	0.21		Pr
Oonopidae	Macro		20	3	87	3	52	52	21	120	7	7	5	2.12	**	Pr
Heteropodidae	Macro			2	1	3	2	7	1	1		2	2	0.12		Pr
Prodidomidae	Macro	1		1	2	1	1	4	1	5		1		0.10		Pr
Philodromidae	Macro	2		1	1					3				0.04		Pr
Zoropsidae	Macro		1		1	1	1		2	1				0.04		Pr
Leptonetidae	Macro	4							1					0.03		Pr
Liphistiidae	Macro					1	1		2					0.02		Pr
Oxyopidae	Macro			1		1	1							0.02		Pr
Gnaphosidae	Macro								2	3			1	0.03		Pr
Opiliones																
Phalangiidae	Macro			1								1		0.01		Pr
Hemiptera																
Ceratocombidae	Meso/micro		1	1	3			1	1		1			0.04		Ph
Diplura																
Projapygidae	Meso/micro		1								1	2		0.02		O
Symphyla																
Scutigerellidae	Meso/micro	10			1		1	3	1	1	1	1	3	0.12		S
Total group		19	25	27	29	25	25	28	31	27	24	24	24			
Total Individuals		1184	1054	991	1261	1499	1870	1778	1973	2037	1587	1054	1500	17788		

[a] Pet., percent; Deg., degree; Gu., guild; [b] Meso/micro., meso and micro fauna; Macro., macro fauna; [c] O, omnivores; S, saprozoic; Ph, phytophage; F, fungivorous; Pr, predators; Ca, cadavericoles; [d] *** dominant group; ** common group.

The indexes *d*, *H*' and *J* were used to analyze the impacts of fertilization regimes on diversity of soil fauna (Figure 4). The highest *d* of soil fauna were for the 1.5 MNPK treatment, with an average of 4.45 ± 0.16. The highest *H*' and *J* of soil fauna were for the M treatment, with averages of 2.73 ± 0.12 and 0.59 ± 0.06, respectively. The highest soil fauna *d* was obtained in the 1.5MNPK treatment and it was significantly higher than results of the other treatments, especially S and SNPK treatments ($p < 0.05$, Figure 4). The *H*' of soil fauna was significantly higher in the M and MNPK treatments than in the NK and S treatments ($p < 0.05$, Figure 4), whereas the other fertilization regimes showed no significant difference ($p > 0.05$, Figure 4). The soil fauna *J* in the MNPK treatment was significantly higher than that in both the application of N and S treatments ($p < 0.05$, Figure 4). However, the other fertilization regimes showed no significant difference in soil fauna *J* ($p > 0.05$, Figure 4).

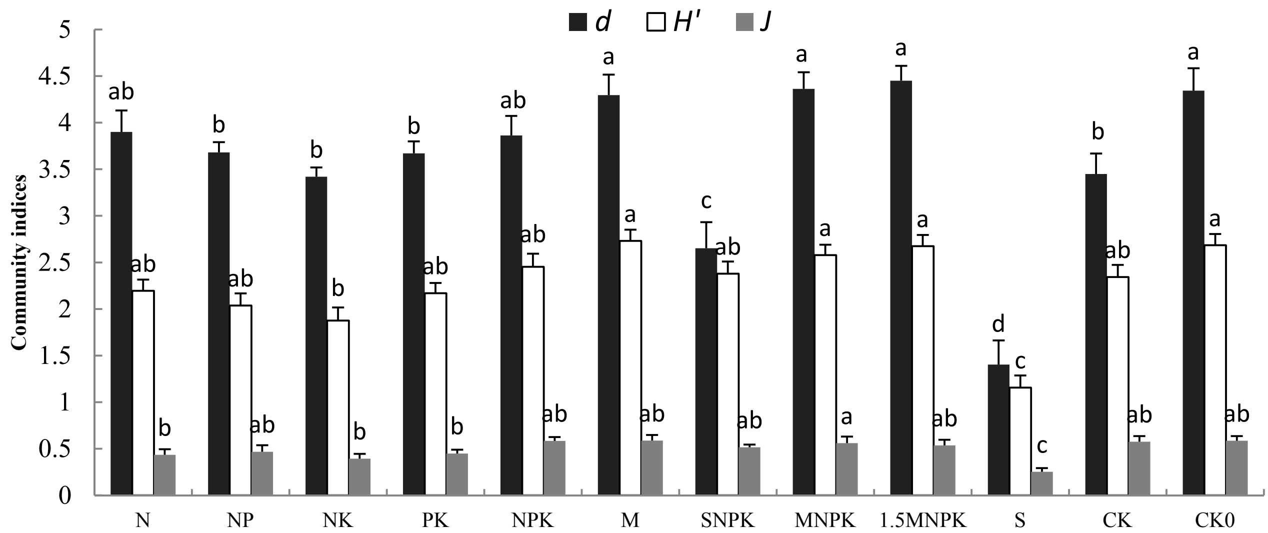

Figure 4. Richness, diversity and evenness of the soil fauna community (mean ± standard error). Treatments with the same letters (a or b) are not significantly different (ANOVA with LSD test, $p > 0.05$).

The number of individuals of Nematodes, Collembola (Onychiuridae and Entomobryidae), Staphylinidae, Mesostigmata, Lycosidae, and TI were significantly positively correlated with soil moisture and crop yield (Table 3). As decomposers, these soil faunas performed important functions in nutrient cycling, and they exhibited the most sensitive response to the changes in the habit types under different fertilizer regimes.

Table 3. Person correlation coefficients among main groups of soil fauna, soil moisture and crop yield.

Factors	Nem.	Ony.	Sta.	Pros.	Meso.	Lyco.	Ent.	Oono.	Sca.	TI.	TG.
SM	0.799 **	0.382 **	0.749 **	0.028	0.927 **	0.665 *	0.170 *	−0.062	0.613 *	0.684 *	0.448
CY-W	0.855 **	0.330 **	0.811 **	−0.104	0.946 **	0.727 **	0.103 *	0.036	0.659 *	0.757 **	0.444

SM., soil moisture; CY-W., crop yield-wheat; *Nem*., Nematodes; *Ony*., Onychiuridae; *Sta*., Staphylinidae; *Pros*., Prostigmata; *Meso*., Mesostigmata; *Lyco*., Lycosidae; *Ent*., Entomobryidae; *Oono*., Oonopidae; *Sca*., Scaphidiidae; *TI*., total individuals; *TG*., total groups. * $p < 0.05$; ** $p < 0.01$.

3.3. Soil Fauna Classification and Sorting

The number of dominant and common group individuals was grouped together was counted and this data formed a similarity matrix (Table 4, Figure 5). The stress value of 0.0825 (<0.1000) and the linear fit scatter plots (R^2 = 0.9728) in this research showed very good matching between arable soil fauna and habit types under different fertilizer regimes and clearly indicated a good relationship in the two-dimensional non-metric multidimensional scaling (NM-MDS) ordinal configuration.

Table 4. Optimal Euclidean distance coefficient matrix of different fertilization regions.

Treatments	N	NP	NK	PK	NPK	M	SNPK	MNPK	1.5MNPK	S	CK	CK_0
N	0											
NP	0.923	0										
NK	0.951	0.577	0									
PK	0.951	0.951	1.247	0								
NPK	1.247	0.712	0.951	1.357	0							
M	2.093	1.667	2.093	2.093	0.825	0						
SNPK	1.666	1.357	1.971	1.668	0.951	0.712	0					
MNPK	3.211	2.709	2.952	2.709	1.375	1.357	1.667	0				
1.5MNPK	2.709	2.227	2.709	2.093	1.247	0.712	1.247	1.247	0			
S	1.666	0.951	0.923	1.666	0.712	1.157	1.666	1.668	1.668	0		
CK	1.247	0.577	0.712	1.357	0.712	1.247	1.247	2.093	2.093	0.577	0	
CK0	3.570	3.241	2.709	3.908	3.211	3.908	4.271	4.411	4.411	2.709	2.952	0

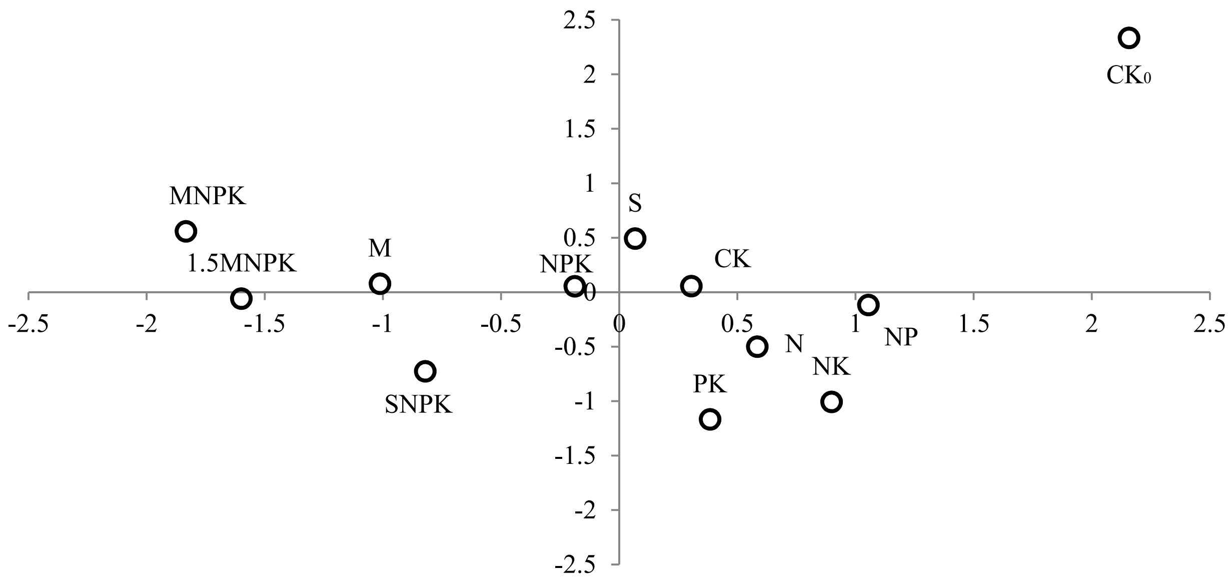

Figure 5. The two-dimensional non-metric multidimensional scaling ordinal configuration of the soil fauna (stress = 0.0825).

Principal component analysis (PCA) showed that balanced fertilizer with application of organic materials had much more effect on soil fauna than synthetic fertilizer alone and there was a positive correlation trends between them.

4. Discussion

4.1. The Link between Soil Fauna and Different Fertilization Regimes

The application of sheep manure and crop residues significantly affected soil moisture and crop yield (Figures 1 and 2), which in turn affected the diversity and abundance of soil fauna. Meanwhile, a higher soil fauna biodiversity were obtained when sheep manure was added to the soil (Table 2, Figure 4). The quantities of soil fauna individuals and groups in the treatment of fertilizer or/and sheep manure (M or MNPK treatment) were much larger than those in the other treatments (Table 2, Figure 4). These results may be explained by the fact that soil fauna ingested decomposed organic matter such as sheep manure with high nutrients and content of soil humus. This process, in turn, likely affected the bacterivorous (*i.e.*, Nematodes) and fungivorous (*i.e.*, Onychiuridae and Entomobryidae) soil fauna and increased the diversity and abundance of soil fauna [33,34], which is in accordance with the findings of this research (Table 2, Figure 3). However, compared with the results found in grey desert soil area in September 2004 in Xinjiang Province [22], the individuals and communities of soil fauna (especially Nematodes, Collembola, Oribatida and Mesostigmata) in this study were significantly increased with the combination of inorganic fertilizer and organic manure or crop residues returning. Therefore, these results indicate that the combined application of synthetic NPK fertilizers with organic manure increased crop yields greatly, which, in turn, changes the community of soil animals.

The effect of fungivorous soil fauna on agricultural productivity has been increasingly brought to attention [35]. Among the 12 treatments, the individuals of saprozoic and fungivorous soil fauna in the treatments with organic materials (M, S, MNPK and SNPK) were more than those in synthetic fertilizer treatments (N, PK and NPK *et al.*) (Figure 3), which was in accordance with the trends of crop yield found in the present study (Figure 2). These results indicated that saprozoic and fungivorous soil fauna were the dominant community in the grey desert soil with the treatment in this study and performed important functions in nutrient cycling, increasing the availability of nutrients [36,37] and exhibited the most sensitive response to the changes in crop yields, which was in accordance with the results found in grey desert soil area in Xinjiang Province, China [38].

All soil fauna indices in different fertilization regimes with sheep manure (treatments of M and MNPK) were significantly higher than those in synthetic fertilizer treatments only (N, PK and NPK *et al.*) (Table 2, Figure 4). The results showed that the decomposed organic materials may be of the utmost importance for the diversity and abundance of soil fauna, especially in the studied grey desert soil lacking soil organic matter and available soil nutrients. However, there were no significant increases in soil fauna indices between S and SNPK fertilization regimes applied with crop residues returned, which differed from the findings of purple soil [26]. Such a difference is that soil fauna attributed to the diverse exogenous nutrients [39]. Therefore, the crop yield was affected obviously in habit types under different fertilizer regimes, which leads to the changes of the community of soil animals. However, further study about the influent mechanism of soil fertility is needed.

4.2. The Link between Soil Fauna and Habit Types under Different Fertilization Regimes

There was a significant correlation among soil animals, soil moisture and crop yield in habit types under different fertilizer regimes, such as TI and the individuals' abundance of Nematodes, Onychiuridae, Entomobryidae and Mesostigmata (Table 3, Figure 7). This result indicated that the composition and abundance of soil animals were relatively sensitive to the soil moisture and crop yield. In this study, which was carried out at the earring and filling stage of wheat, the acute day/night temperature fluctuations in grey desert soil area under a typical continental arid climate will dramatically change the soil moisture, which would affect the individuals of some high humidity found soil fauna, such as Onychiuridae and Nematodes. The crop yields of the treatments with the long-term application of organic sheep manure (*i.e.*, M and MNPK) had a higher impact level than those fertilization regimes (*i.e.*, N, NPK, S *et al.* ($p < 0.05$), Figure 2), indicating that M alone represents recycling and sustainable agriculture and then NPK added represent conventional, exploitative farming practice. Here, the crop yield afforded soil fauna food sources [20].

There was a good relationship between soil fauna and habit types under different fertilizer regimes (Figures 5–7). The map showed the effects of fertilization with organic matters, synthetic fertilizer and crop residues returned, unbalanced fertilization on the community of soil animals, respectively. These results suggest that the distribution of soil fauna was related to characteristics of habit types under different fertilizer regimes.

The exogenous organic matter was the utmost energy source for the soil fauna, and the composition and abundance of soil fauna would change with the mineralization and decomposition of soil organic matter. A long-term fertilization experiment in the grey desert area indicated that organic fertilizer was the most effective means to improve or maintain the organic matter and crop yield [40]. In the present study, this research showed that the highest diversity and abundance of soil animals and the crop yield were in the MNPK treatment. Although these communities of soil animals showed a relatively sensitive response to changes of crop yield, these findings suggest that further studies are needed to determine whether soil fauna can be suited to the changes of soil fertility, which indicate soil fertility/quality changes in grey desert soil. Therefore, the functions soil fauna play in regard to changes in soil fertility require further study.

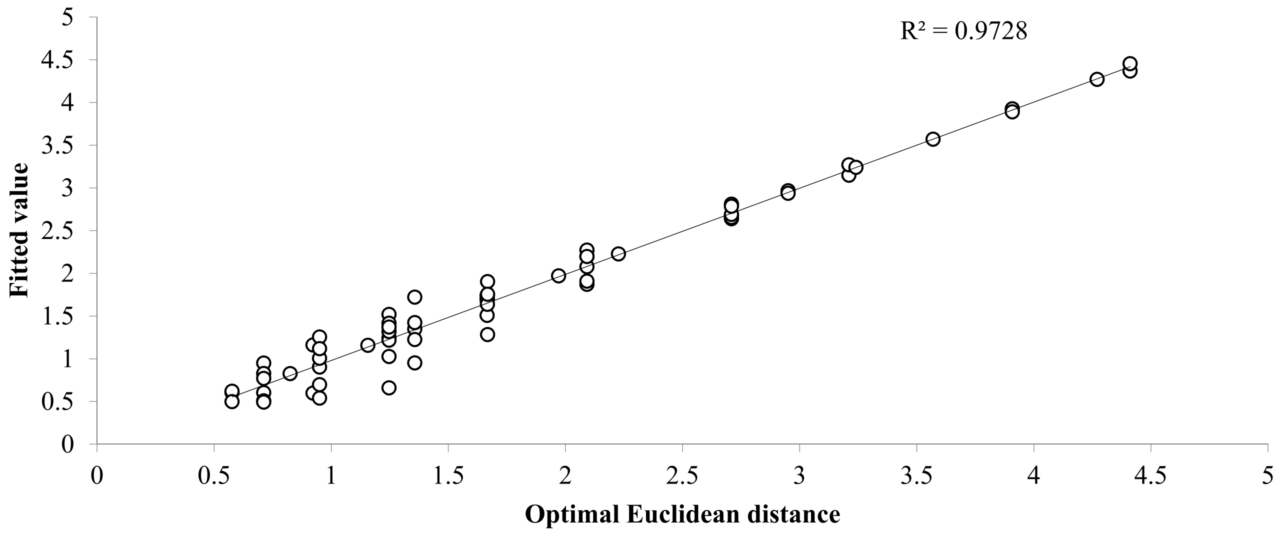

Figure 6. The linear fit scatter plots for the two-dimensional NM-MDS ordinal configuration ($R^2 = 0.9728$).

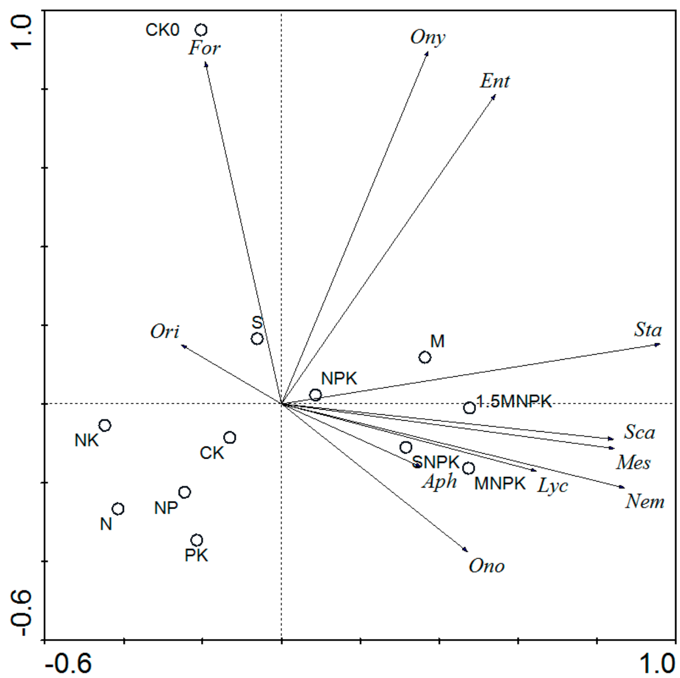

Figure 7. Results of principal component analysis of major communities of soil fauna in association with habit types under different fertilizer regimes. Circles represent habit types labeled as a reference to Table 1. Arrows represent communities of soil fauna labeled as a reference to Table 3.

5. Conclusions

Long-term fertilization offers stable soil conditions for soil fauna. In this study, the communities of soil animals in grey desert soil were investigated in the National Long-term Monitoring Network of Soil Fertility and Fertilizer Effects. Balanced fertilization tended to increase the abundance of soil animals compared with no fertilizer and unbalanced fertilization such as N, NK, NP and PK. The addition of crop residues and organic sheep manure in combination with NPK substantially increased the abundance of individuals and communities. The finding that soil fauna abundance is significantly positively correlated with soil moisture and crop yield may mean the effects of fertilizer applications on soil animals were partly masked by the soil moisture and crop yield.

The grey desert soil region is an extremely arid climate, which is located on the alluvial plain of the Tianshan Mountains, and comprehensive fertilization and water management are vitally important to maintain soil fauna biodiversity as well as soil function and agricultural sustainability in this region.

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Author Contributions

Maibo Jiang performed research of soil fauna and wrote the paper. Xihe Wang performed the implementation of field management. Yunhao Liusui analyzed the data. Xueqing Sun performed the field sampling. Chengyi Zhao and Hua Liu designed research. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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