



Variation of soil nematode community composition with increasing sand-fixation year of *Caragana microphylla*: Bioindication for desertification restoration



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ABSTRACT

Vegetation restoration plays an important role in controlling desertification. The effects of vegetation restoration on aboveground biodiversity are well known. However, the effects of vegetation restoration on the belowground biotic communities in sand land are still highly important and need to be explored. We examined soil nematode community composition under *Caragana microphylla* of dominant native vegetation with 0- (the drifting sand dunes), 13-, 18- and 29-year sand-fixation and natural vegetation communities in Horqin Desert, China. The result showed that total nematodes, bacterivores, fungivores and omnivores-predators were all significantly affected by sand-fixation years, with their highest values being in 29-year sand-fixation. The conversion of drifting sand dunes to shrub land resulted in significant changes in *r*-strategists with *cp*-2 and *K*-strategists with *cp*-4 of soil nematodes. Nematode genera in different sand-fixation years were clearly separated by redundancy analysis and the preference of different nematode genera to habitat was discriminative. The effect of *C. microphylla* on soil abiotic properties and nematode communities was time-dependent. The significant variation of soil abiotic properties appeared from 18-year sand-fixation, and soil nematodes increased significantly after 13-year sand-fixation. The plantation of *C. microphylla* improved nematode diversity, with markedly higher values in the later sandy land stabilization stage than the drifting sand dunes. Furthermore, it can be concluded that soil nematode communities as bioindicators reflect the progressive restoration process of the sandy ecosystems.

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1. Introduction

In sandy ecosystems, desertification may result in poor soil condition and low land productivity, which is a serious social and ecological problem (Lal, 2000). Ecosystem restoration measure is highly important for controlling desertification. For the reconstruction of ecosystem and its ecological function in sandy ecosystems, the vegetation restoration is one of the most effective ways to combat and control land desertification (Le Houérou, 2002; Ala et al., 2014; Liu et al., 2014).

In order to improve degraded sandy ecosystem, some native shrubs tolerant to nutrient-poor environment are planted on sandy

lands. *Caragana microphylla* is an important shrub species for the restoration in the Horqin Desert, which is one of the most serious land desertification areas in China. *C. microphylla* could resist the shear force of wind erosion (Su and Zhao, 2003) and prevent being grazed because of the spines on its stems (Zhang et al., 2006a). As legumes, *C. microphylla* also contributes significantly to the nitrogen cycle through N₂ fixation (Li et al., 2013). For these reasons, *C. microphylla* is widely used as the pioneer species in vegetation reestablishment in the Horqin Desert to stabilize the shifting sand (Zhang et al., 2006b; Cao et al., 2011). With increasing sand-fixation year of *C. microphylla*, the density, height, cover and biomass of vegetations increase correspondingly (Zhao et al., 2007). The vegetations become strong drivers of the structure and function of soil food webs. Feedback and interaction between plants and soil can greatly influence soil biota communities (Kardol et al., 2006; van der Putten et al., 2013).

The soil nematode assemblage as an important component of soil biota communities is an ubiquitous inhabitant in soil

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ecosystem (Pen-Mouratov et al., 2003). They occupy a central position in the detritus food web and can regulate the rates of decomposition, mineralization and nutrient cycling (Neher, 2001; Yeates, 2003; Bakonyi et al., 2007). Soil nematodes are also good indicators for evaluating soil food web structure and function because of their close relationship with soil environment and sensitivity to habitat disturbance (Neher, 2001; Wasilewska, 2006). Although the bioindication of soil nematode communities is very important for evaluating sand restoration, more attention is paid to plant community development during the restoration process (Zhang et al., 2005; Klass et al., 2012). Restoration of plant communities is of limited indicative value for belowground community development, because successful vegetation restoration does not necessarily indicate successful restoration of belowground biodiversity (Kardol et al., 2005; Parfitt et al., 2010). Korthals et al. (2001) and Hedlund et al. (2003) proposed that the belowground responses to the ecosystem restoration were slower than the aboveground due to different response rates between plants and soil organisms. Zhi et al. (2009a) reported that soil nematode abundance increased significantly after stabilizing sand dunes for 16 years. Jiang et al. (2007) reported that soil nematode was significantly higher under the canopy of the *C. microphylla* in 5-year-old plantations than that in drifting sand dune without vegetation cover at 0–10 cm depth. Klass et al. (2012) proved that soil nematode communities could indicate plant–soil interactions associated with desertification. Therefore, assessing the impact of vegetations on soil biodiversity restoration requires information on belowground community composition in order to establish proper conservation measures for restoration sites (Kardol et al., 2005).

Our objectives are to investigate the response of soil nematode community composition and diversity of the *C. microphylla* with different sand-fixation years, to analyze the effect of sand-fixation year and soil environment on soil nematode communities during restoration process, and to utilize soil nematodes as bioindicators to evaluate the contribution of sand-fixation vegetations to control desertification.

2. Materials and methods

2.1. Study site

This study was conducted at the Wulanaodu Experimental Station of Desertification (43°02'N, 119°39'E), Institute of Applied Ecology, Chinese Academy of Sciences. The station is located in western Horqin Desert of Northeast China, with a mean annual temperature and rainfall of 6.3 °C and 340 mm, respectively. The annual mean wind velocity ranges from 3.2 to 4.5 m s⁻¹. The soil is classified as Cambic Arenosols (IUSS Working Group WRB, 2007). The landscape is characterized by drifting, semi drifting and stabilized sand dunes (Jiang et al., 2007). Sand dune movement, wind erosion, and sand burial are frequent in this area. In addition, due to long-term overgrazing and overcutting, the original vegetation has been greatly changed over the past decades. Now the dominant vegetations are *C. microphylla*, *Bassia dasyphylla* and *Pennisetum flaeidum*.

2.2. Experimental design and sampling

C. microphylla, as the main sand-binding vegetation, has been gradually planted on sandy land in the Wulanaodu Experimental Station of Desertification since 1980s. The 0-year (the control without vegetation), *C. microphylla* shrubs with different sand-fixation years (13, 18 and 29 years) and natural *C. microphylla* shrubs were selected as five experimental treatments (hereafter called 0-Y, 13-Y, 18-Y, 29-Y and N-Y). For each treatment, four

(20 m × 20 m) plots were selected randomly as four sample replicates. From each plot, composite soil samples of 3 sub-samples were collected under three *C. microphylla* shrubs with similar growth conditions (or without shrubs in CK) as one replication. After removing the surface residue, soil samples (about 1000 m³) were taken at the 0–10 cm soil layer under the canopy of the shrub using a shovel in May 2013. Large roots and other debris were removed. All the samples were put into individual plastic bags and were kept at 4 °C until further analyses.

2.3. Analysis of soil physicochemical properties

Soil moisture (SM) was determined gravimetrically by drying samples at 105 °C for 48 h. Soil pH and electrical conductivity (EC) were measured in a soil–water suspension (1:2.5 and 1:5 soil–water ratio, respectively) with pH and conductivity meter (Thermo Fisher Scientific Inc., USA). Total soil organic carbon (TOC) was determined by potassium dichromate heating method and total nitrogen (TN) by Kjeldahl method (McGill and Figueiredo, 1993; Rowell, 1994).

2.4. Soil nematode extraction and identification

Nematodes were extracted from 200 g of fresh soil by a modified cotton–wool filter method (Liang et al., 2009). Nematode abundance was expressed as individuals per 100 g dry soil. 100 nematodes from each sample were identified to the genus level using an inverted compound microscope. If the total number was less than 100, all of the nematodes were identified. The nematodes were assigned to the following trophic groups characterized by feeding habits: bacterivores (BF), fungivores (FF), plant parasites (PP) and omnivores–predators (OP) (Yeates et al., 1993). Nematode life-history groups with *cp* (colonizer–persister) 1–3 were regarded as *r*-strategists and *cp* 4–5 as *K*-strategists (Bongers, 1990; Ferris et al., 2001). The nematode community indices were calculated as follows: dominance (λ), Shannon–Wiener diversity (H'), evenness (J'), richness (SR), plant parasite index (PPI) and plant parasite index/maturity index (PPI/MI) (Bongers et al., 1997; Yeates and Bongers, 1999).

2.5. Statistical analysis

Nematode abundance was $\ln(x+1)$ transformed prior to statistical analysis for normality of data. One-way ANOVA was used to evaluate the difference significance of environmental or nematode parameters among different sand-fixation years. Tukey's post hoc test was used to compare individual values among different sand-fixation years. All statistical analyses were performed by SPSS statistical software (SPSS Inc., Chicago, IL, USA). Difference at $P < 0.05$ level was considered to be statistically significant. Redundancy analysis (RDA) using CANOCO software was performed to analyze the relationship between soil nematode communities and sand-fixation year (ter Braak, 1988). Sand-fixation year was treated as nominal (0, 1) environmental variable. In order to find indicative genera to different sand-fixation years, predict on ratings were explored in our study according to RDA. The criteria of predicting ratings of nematode to different sand-fixation years were used as followed: a genus vector in RDA within the range of 45° close to the environmental variable vector was rated as positive correlation; a genus vector in RDA in the diagonally opposite quadrant was rated as negative correlation; if the genus did not fit neither of two criteria, it was regarded as no correlation (Zhao and Neher, 2013). To analyze the relationship between environmental parameters and nematode communities, the bioenv method (R-3.0.2 project) was employed using the Spearman correlation coefficient (Clarke and Ainsworth, 1993; R Development Core Team, 2006).

3. Result

3.1. Soil physicochemical properties in different sand-fixation years

The effects of sand-fixation year on total organic carbon (TOC), total nitrogen (TN), soil moisture (SM), electrical conductivity (EC) and pH were significant ($P < 0.05$) (Table 1). There were similar variation trends in the values of TOC, TN and EC, which all progressively increased with increasing sand-fixation year. Compared with those in 0-Y, the values of TOC, TN and EC increased 88.3%, 84.0% and 62.3% in 29-Y, respectively. The value of SM was significantly lower in 13-Y than in 29-Y and N-Y ($P < 0.01$). The value of pH was significantly higher in 18-Y than in 29-Y ($P < 0.05$).

3.2. Abundance of total nematodes and trophic groups in different sand-fixation years

Only in 0-Y, the total nematode abundance was less than 10 individuals per 100 g dry soil. The total nematode abundance in other treatments ranged from 200 to 600 individuals 100 g^{-1} dry soil, and reached a mean maximum density in 29-Y (Fig. 1). Significant difference in the total nematode abundance was observed among treatments ($P < 0.01$) (Fig. 1), where the total nematode abundance was significantly higher in 29-Y than in other sand-fixation years.

Among the four trophic groups, BF was the most abundant trophic group, followed by OP, and FF was the least abundant group. Significant differences in the abundance of four trophic groups were found among different treatments ($P < 0.01$) (Fig. 2). The abundance of BF, FF and OP increased with increasing sand-fixation year and the highest value was found in 29-Y. The abundance of OP was significantly lower in N-Y than in 29-Y ($P < 0.01$). Except in 13-Y, the abundance of PP showed an increasing trend with increasing sand-fixation year and the highest abundance was observed in N-Y. The abundance of PP was lower in 0-Y than in other treatments ($P < 0.01$), and no significant difference in PP was found among 13-Y, 18-Y, 29-Y and N-Y.

3.3. Nematode genera in different sand-fixation years

In total, 46 genera were observed in our study. The number of nematode genera increased with increasing sand-fixation year, where 0-Y (18 genera) < 13-Y (27 genera) < N-Y (33 genera) < 18-Y (34 genera) < 29-Y (44 genera) (Table 2). *Tylencholaimus* and *Discolaimium* were dominant genera (their relative abundance >10%) only in 0-Y, and *Cervidellus* in 13-Y. *Thonus* dominated in 0-Y, 13-Y, and 18-Y, and *Acrobeles* and *Microdorylaimus* in all treatments except in 0-Y.

Results of redundancy analysis showed that eigenvalues were 0.337 ($F = 17.81$, $P = 0.002$) and 0.031 for the first and second axes, respectively, and the first two axes explained 90.4% of total genera–environment variation. Nematode genera between 0-Y and other treatments were clearly distinguished by the vertical axis (Fig. 3).

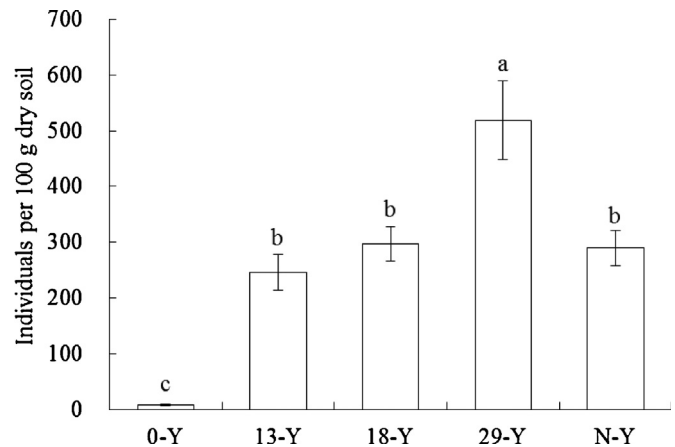


Fig. 1. Total abundance of nematode under *C. microphylla* with different sand-fixation years. Bars indicate standard errors. 0-Y, 0-year-old; 13-Y, 13-year-old; 18-Y, 18-year-old; 29-Y, 29-year-old and N-Y, natural shrubs. Different lowercase letters indicate significant differences among different sand-fixation years as assessed by Tukey's multiple range tests.

Nematode genera in 29-Y and N-Y were also distinguished from those in 13-Y and 18-Y by the horizontal axis. The predicting rating analysis proved that 12 genera in N-Y, 16 in 29-Y, 6 in 18-Y and 5 in 13-Y showed positive responses, and only one genus in N-Y, 5 genera in 29-Y, 2 in 18-Y and 2 in 13-Y showed negative responses (Fig. 3 and Table 2).

3.4. Nematode life-history group in different sand-fixation years

All nematode life-history groups showed significant differences among different sand-fixation years except nematodes with *cp-1* ($P < 0.01$) (Tables 3). Nematode life-history groups with *cp-2* to *cp-5* all increased with increasing sand-fixation year and the highest values were in 29-Y. Nematodes with *cp-2* and *cp-4* were significantly lower in 0-Y than in other treatments. The *cp-1* was only found in N-Y with a relatively low abundance. Significant differences in *r*-strategists and *K*-strategists of nematodes were also found among different sand-fixation years ($P < 0.01$) (Table 3).

3.5. Nematode ecological indices in different sand-fixation years

The values of λ , H' , J' and SR were all significantly different among different treatments ($P < 0.01$) (Fig. 4). The values of H' and SR increased progressively but those of λ decreased with increasing sand-fixation year. The values of H' and SR were higher in 29-Y and N-Y than in 0-Y ($P < 0.01$). The values of J' were significantly higher in 0-Y than in 13-Y, 18-Y and 29-Y. PPI and PPI/MI were also influenced by sand-fixation year ($P < 0.05$), with significantly lower values being in 0-Y compared with other treatments (Fig. 3).

Table 1

Soil properties under *C. microphylla* with different sand-fixation years (mean \pm SE).

	TOC (g kg^{-1})	TN (g kg^{-1})	SM	EC (ms cm^{-1})	pH
0-Y	0.28 \pm 0.06d	0.04 \pm 0.00c	2.44 \pm 0.18ab	12.72 \pm 0.29c	7.26 \pm 0.02ab
13-Y	0.74 \pm 0.12cd	0.08 \pm 0.01bc	1.78 \pm 0.18b	17.23 \pm 0.70bc	7.15 \pm 0.02ab
18-Y	1.12 \pm 0.12bc	0.11 \pm 0.01b	2.13 \pm 0.15ab	21.77 \pm 1.27b	7.29 \pm 0.05a
29-Y	2.39 \pm 0.33a	0.25 \pm 0.03a	3.01 \pm 0.25a	33.78 \pm 3.21a	7.12 \pm 0.06b
N-Y	1.69 \pm 0.09b	0.19 \pm 0.02a	3.22 \pm 0.52a	29.61 \pm 2.39a	7.19 \pm 0.03ab
F	22.62	28.85	4.26	20.63	3.47
P	0.00	0.00	0.01	0.00	0.02

Different lowercase letters in a column indicate significant differences among different sand-fixation years as assessed by Tukey's multiple range tests.

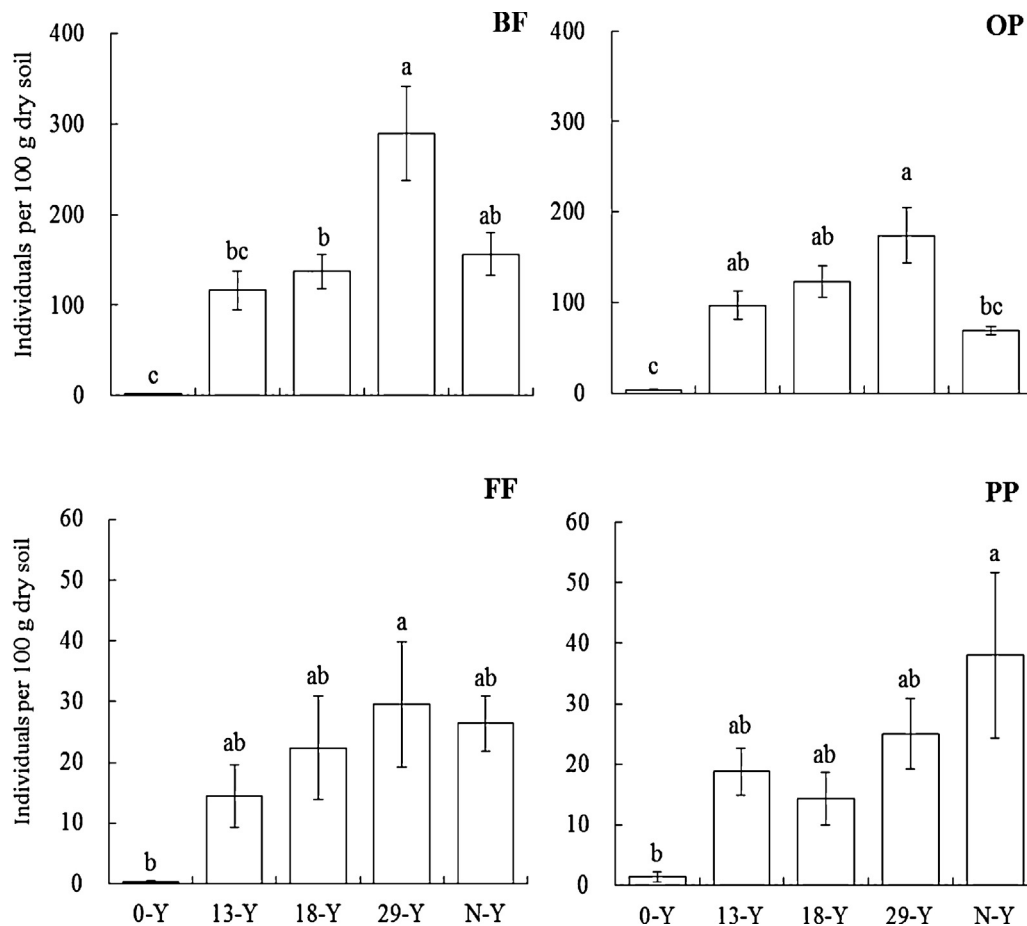


Fig. 2. Abundance of nematode trophic groups under *C. microphylla* with different sand-fixation years. Bars indicate standard errors. 0-Y, 0-year-old; 13-Y, 13-year-old; 18-Y, 18-year-old; 29-Y, 29-year-old and N-Y, natural shrubs. BF, bacterivores; OP, omnivores-predators; FF, fungivores; PP, plant parasites. Different lowercase letters indicate significant differences among different sand-fixation years as assessed by Tukey's multiple range tests.

3.6. Relationship between soil physicochemical properties and nematode communities

In our study, bioenv analysis was used to determine the environmental factors that significantly correlated with nematode community composition (taxa and trophic abundance). It was observed that the best variables to explain nematode genus composition were TN ($\rho=0.47$), TOC ($\rho=0.44$) and EC ($\rho=0.33$), and abundance was also better explained by TOC ($\rho=0.46$), TN ($\rho=0.42$) and EC ($\rho=0.31$). Of all the environmental variables examined, a combination of TOC and TN showed the highest correlation with the nematode genera and trophic groups ($\rho=0.50$ and 0.47 , respectively), while adding the other factors did not improve the correlation (Table 4).

4. Discussion

4.1. Effect of sand-fixation vegetation on soil physicochemical properties

The establishment of sand-fixation vegetation is of great importance to the restoration of desertified lands (Li et al., 2006; Okin et al., 2001). Our results showed that soil total nitrogen, organic carbon and electrical conductivity increased with increasing sand-fixation year of *C. microphylla*. *C. microphylla* as a nitrogen-fixing legume could increase soil N level in the sandy ecosystem (Zhang et al., 2006b). The increase in the content of soil organic carbon was due to the increasing litter inputs and the

decreasing soil erosion rate after the establishment of *C. microphylla* (Cao et al., 2008). The plantation of *C. microphylla* on sandy land facilitated the formation of fertile islands in soil beneath the shrub canopy (Zhao et al., 2007; Liu et al., 2011). The increasing EC values were probably related to the enhancement in soil nutrient or fertility condition (Su and Zhao, 2003; Pen-Mouratov et al., 2010; Cao et al., 2011). The establishment of vegetation had an important role in improving soil properties (Zhao et al., 2007; Liu et al., 2011), but the effect of *C. microphylla* on soil environment was time-dependent. Soil properties in 18-Y were obviously distinguished from those in 0-Y, which reflected that the effect of *C. microphylla* on soil properties was only measurable or significant after 18-year sand-fixation. With increasing sand-fixation year, shrub formed an important component of net primary productivity, and its rapidly growing plants and litters provided an important input into the mobile sandy soil (Mun and Whitford, 1998).

4.2. Effect of sand-fixation vegetation on soil nematode community composition

Extremely low abundance of total nematodes (less than 10 individuals per 100 g dry soil) was found in the drifting sand dunes without vegetation (0-Y). Similar results were also found in the previous studies in Negev Desert and Tengger Desert, which indicated that the harsh environmental conditions and scarce food resources in the sandy land without vegetation did not benefit soil nematodes' survival (Pen-Mouratov et al., 2003; Zhi et al., 2009b). The abundance of total nematodes, bacterivores, fungivores and

Table 2
Relative abundance (%) of soil nematode genera and their responses to different sand-fixation years.

	<i>c-p</i>	Genus	0-Y	13-Y	18-Y	29-Y	N
Bacterivores	3	<i>Achromadora</i>	0.0	0.0	0.0	0.6	0.0
	2	<i>Acrobeles</i>	1.1–	30.8	24.4+	24.1	20.0
	2	<i>Acrobeloides</i>	1.0+	3.0–	2.9	4.8	6.1
	4	<i>Alaimus</i>	0.0	1.1	3.0	2.6+	2.6
	2	<i>Cephalobus</i>	0.0	0.0	0.0	0.6+	0.5+
	2	<i>Cervidellus</i>	4.5–	10.0+	9.2+	6.4	9.6
	2	<i>Chiloplacus</i>	0.6+	9.9	8.9–	4.9	9.0
	2	<i>Chromadorita</i>	0.0	0.8	1.4	8.0+	3.4+
	2	<i>Drilocephalobus</i>	0.0	0.1	0.0	1.6+	0.5+
	2	<i>Eucephalobus</i>	0.0	0.0	0.3–	0.4+	0.0
	2	<i>Eumonhystera</i>	0.0	0.0	2.8	0.46+	4.0+
	2	<i>Heterocephalobus</i>	0.0	0.0	0.0	0.5+	0.3+
	2	<i>Microaimus</i>	0.0	0.0	0.1	0.4+	0.1+
	2	<i>Plectus</i>	0.3+	0.0	0.3	1.8	0.5
	1	Rhabditidae	0.0	0.0	0.0	0.0	0.3
	2	<i>Wilsonema</i>	0.0	0.3	0.8	2.3+	2.1+
Fungivores	2	<i>Aphelenchoides</i>	0.0	0.8	0.3	0.5	0.5
	2	<i>Aphelenchus</i>	0.0	0.0	0.0	1.6+	0.9+
	2	<i>Ditylenchus</i>	0.3+	0.4	0.3	0.3–	0.3
	4	<i>Leptonchus</i>	0.0	0.6	0.1	0.0	0.6
	2	<i>Paraphelenchus</i>	0.1+	0.0	0.3	0.0	0.5
	4	<i>Tylencholaimus</i>	0.4–	4.8	6.4	3.5+	6.1
Plant parasites	3	<i>Amplimerlinius</i>	0.0	0.3	0.4	0.0	0.4
	5	<i>Dorylaimellus</i>	0.3	2.6	2.0	3.5+	3.1+
	2	<i>Filenchus</i>	0.0	0.0	0.4	0.0	0.4
	3	<i>Helicotylenchus</i>	0.0	0.0	0.0	0.1	0.9
	3	<i>Heterodera</i>	0.0	1.0	0.0	0.3+	0.8
	3	<i>Macroposthonia</i>	0.0	0.1–	0.0	0.3+	0.8+
	2	<i>Neothada</i>	0.0	0.0	0.0	0.0	0.6
	3	<i>Pararotylenchus</i>	0.0	0.0	0.0	0.0	0.5
	2	<i>Paratylenchus</i>	0.0	0.0	0.4	0.0	0.0
	3	<i>Rotylenchus</i>	0.0	0.0	0.8	0.8+	2.5+
	3	<i>Telotylenchus</i>	0.9	0.0	0.0	0.4	0.8+
	3	<i>Tylenchorhynchus</i>	2.3+	3.6	1.4	0.0	0.4
Omnivores-predators	5	<i>Aporcelaimellus</i>	0.0	0.4+	0.6+	0.0	0.1
	4	<i>Bathyodontus</i>	0.3	1.9	0.6	0.0	0.6–
	5	<i>Carcharolaimus</i>	0.0	0.6+	0.1+	0.0	0.5
	5	<i>Discolaimium</i>	1.6+	4.0	3.4	2.6–	2.0
	5	<i>Discolaimus</i>	0.0	1.5	1.1	2.4+	1.6
	4	<i>Dorydorella</i>	0.3	3.6+	3.5+	2.1	2.5
	4	<i>Eudorylaimus</i>	0.6+	1.0	1.0	2.5	1.5
	4	<i>Microdorylaimus</i>	1.19–	13.5+	16.5+	14.0	7.5
	5	<i>Paraxonchium</i>	0.4+	0.0	1.0	0.1	0.6
	4	<i>Thonus</i>	2.4+	12.3	12.4	9.8–	8.4
	5	<i>Torumanawa</i>	0.0	0.1	0.4	0.0	0.0
	3	<i>Trischistoma</i>	0.0	0.0	0.6	0.9	0.0

+ or – represent nematode genus that showed positive or negative response to sand-fixation year. Numbers in bold indicate dominant genus in all the treatments.

omnivores-predators increased with increasing sand-fixation year. Favorable conditions for nematodes were formed after the sandy lands were stabilized gradually (Zhi et al., 2009a). Changes in quantity and quality of shrubs with increasing sand-fixation year strongly affected soil nematode communities through bottom-up (resource control) effect (Cesarz et al., 2013; Eisenhauer et al., 2013). The effect of *C. microphylla* on soil nematodes was also time-dependent. Our result showed that soil nematode abundance started to increase significantly after 13-year sand-fixation. Compared with the significant variation of soil abiotic properties from 18-year sand-fixation, soil nematodes responded more quickly to the establishment of *C. microphylla*.

Bacterivores were the most dominant trophic group in our study. Bacterivores grazed on primary decomposers, excreted ammonium and immobilized nitrogen in live biomass (Ferris et al., 1998; Neher, 2001), and therefore, contributed to the decomposition of soil organic matter and nitrogen mineralization (Ferris and Matute, 2003). The close relationship between bacterivores and soil nutrients may be the reason for the quick response of bacterivores to the improved soil condition with increasing sand-

fixation year (Stephan et al., 2000; Viketoft et al., 2005). Omnivores-predators were significantly lower in 0-Y and N-Y than in 29-Y. Omnivores-predators belonging to *K*-strategists with relatively higher *cp* values exhibited great sensitivity to environmental disturbance (Ruan et al., 2012; Zhang et al., 2012). More disturbances, such as wind erosion occurred in sandy land without vegetation, and grazing or excess reclamation in natural shrub communities (Munsom et al., 2011; Liu et al., 2012), which had negative influences on omnivores-predators with sensitive responses. The significant increase of omnivores-predators in 29-Y indicated relatively stable soil environment gradually formed after long-term vegetation establishment. Additionally, higher trophic level organisms might be affected by bottom-up forces from those with the lower trophic levels (De Ruiter et al., 1995). In our study, the increase of omnivores-predators with higher trophic levels of soil food web in 29-Y might also be due to the increase in the number of their preys such as bacterivores and fungivores.

The analysis on nematode ecological indices showed a gradually increasing trend in *H'* with increasing sand-fixation year, while an opposite trend in λ . The establishment of vegetation

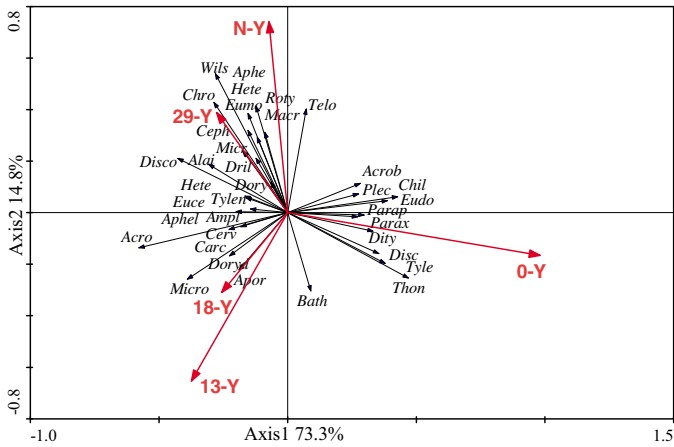


Fig. 3. Bi-plot of redundancy analysis on soil nematode genera and treatment variables 0-Y, 0-year-old; 13-Y, 13-year-old; 18-Y, 18-year-old; 29-Y, 29-year-old; N-Y, natural shrubs. Triangles represent soil nematode genera. *Aphel*, *Aphelenchoides*; *Tylet*, *Tylencholaimus*; *Doryd*, *Dorydorella*; *Acrob*, *Acrobeloides*; *Parax*, *Paraxonchium*; *Parap*, *Paraphelenchus*. The abbreviations of other genera are the first four letters of their full name.

improved nematode diversity through increasing food resource supply and providing suitable habitats, the relatively complicated soil ecosystem was developed (Li et al., 2009; Klass et al., 2012). The PPI and PPI/MI increased significantly after the establishment of *C. microphylla*. Analysis on PPI based on the community composition of plant parasites indicated the increased levels of primary production as the plant growth provided plant parasites more chance to feed on higher plants (Bongers, 1990; Urzelai et al., 2000; Ugarte et al., 2013). However, no significant differences in PPI and PPI/MI was found in 13-Y, 18-Y, 29-Y and N-Y, and the progressive variation among different sand-fixation years was not reflected by PPI and PPI/MI, but by H' and λ . Therefore, H' and λ were relatively sensitive ecological indices to indicate the gradual rehabilitation process of desertification.

4.3. Bioindication of soil nematode community composition to desertification restoration

The RDA analysis clearly separated nematode genera of 0-Y from other treatments. The change in nematode community composition indicated that the quantity and quality of potential food resources had changed in the sandy land with vegetation compared with those without or with a few vegetation cover (Williamson et al., 2005; Sánchez-Moreno et al., 2010). The nematode genera in 29-Y and N-Y was in the same quadrant and separated from those in 13-Y and 18-Y, which indicated that soil nematode community composition under natural shrub communities was more similar to that after the 29-year sand-fixation. There was relatively high plant species diversity and vegetation cover in sandy land with natural restoration communities, which

Table 3

Abundances of nematode life-history (*c-p*) group under *C. microphylla* with different sand-fixation years (mean \pm SE).

	0-Y	13-Y	18-Y	29-Y	N-Y	F	P
<i>cp-1</i>	0.00a	0.00a	0.00a	0.00a	0.92 \pm 0.92a	1.00	0.42
<i>cp-2</i>	2.24 \pm 0.49c	113.05 \pm 22.52b	127.36 \pm 19.07b	243.91 \pm 46.85a	145.33 \pm 22.22ab	10.45	<0.01
<i>cp-3</i>	1.22 \pm 0.77b	13.18 \pm 3.50b	14.86 \pm 5.69b	57.00 \pm 14.92a	38.16 \pm 12.27ab	5.99	<0.01
<i>r-strategists</i>	3.46 \pm 1.05c	126.22 \pm 22.80bc	142.22 \pm 18.79b	300.91 \pm 54.98a	184.41 \pm 26.99ab	12.44	<0.01
<i>cp-4</i>	2.58 \pm 0.43c	98.04 \pm 17.50b	128.82 \pm 17.09ab	175.67 \pm 25.17a	82.76 \pm 10.21b	15.27	<0.01
<i>cp-5</i>	1.16 \pm 0.49b	21.75 \pm 3.67b	25.87 \pm 5.18ab	41.88 \pm 11.54a	22.23 \pm 5.19ab	5.25	<0.01
<i>K-strategists</i>	3.74 \pm 0.66c	119.80 \pm 19.99b	154.69 \pm 20.58ab	217.55 \pm 32.33a	104.99 \pm 10.85b	15.4	<0.01

Different lowercase letters in a line indicate significant differences among different sand-fixation years as assessed by Tukey's multiple range tests.

Table 4

The soil physicochemical factors that significantly correlated with nematode communities were listed below. The correlations coefficients (ρ) were determined by bioenv analyses between nematode communities and environmental variables

Nematode taxa		Nematode trophic abundance	
Selection of variables	Correlation (ρ)	Selection of variables	Correlation (ρ)
TOC	0.44	TOC	0.46
TN	0.47	TN	0.42
EC	0.33	EC	0.31
SM	0.06	SM	-0.08
pH	-0.05	pH	-0.06
TOC, TN	0.50	TOC, TN	0.47
TOC, TN, SM	0.47	TOC, TN, EC	0.44
TOC, TN, SM, EC	0.45	TOC, TN, SM, EC	0.37
TOC, TN, SM, EC, pH	0.35	TOC, TN, SM, EC, pH	0.27

Number in bold indicate the highest correlation coefficients for the selected combinations of soil properties.

provided diversified food resources and living conditions for soil fauna, and thus stimulated soil nematode diversity (Mekuria et al., 2007; Bastow, 2012). Meanwhile, we found that there was a significant higher nematode abundance in 29-Y than in N-Y. Both the diversity and the abundance of nematodes improved after 29-year sand-fixation, which proved that long-term shrub plantation was more beneficial for the development of soil biota communities. It is obvious that the longer the shrubs were established, the more stable and diverse the soil ecosystem was.

The response of soil nematode communities to environmental change was genus-dependent (Zhang et al., 2012). According to the predicting ratings, some nematode genera, for example, *Tylencho-rhynchus*, *Discolaimium* and *Thonus*, were more abundant in drifting sand dunes. However, with the increasing sand-fixation year, these genera markedly decreased in abundance or even disappeared. There are two possible reasons to explain this phenomenon. Firstly, the competition for resources was intense with the increasing abundance and diversity of nematode, and the resource was not abundant but limited for each genus in sandy ecosystem (Wardle and Yeates, 1993). Therefore, uncompetitive genera decreased or disappeared. Additionally, the patchy distribution of some genera was probably another reason of disappearance in our sample. However, *Acrobelles* and *Microdorylaimus* were the predominant genera in all sand-fixation years except in 0-Y, which may be regarded as the indicative genera to discriminate between sandy lands with shrubs and without shrubs. The other nematode genera exhibited different preferences to sandy land with different sand-fixation years. Some genera such as *Cervidellus* and *Aporcelaimellus* increased in the early sandy land stabilization stage (13-Y and 18-Y). The *r*-strategists including *Cephalobus*, *Heterocephalobus* and *Aphelenchus* only appeared in 29-Y and N-Y, which might prefer the environment with enriched nutrients (Ferris et al., 2001; Zhao et al., 2013). Nematodes could migrate to their recognized habitat when the soil environment changed and the preference of different nematode genera to the habitat was discriminative (Zhang et al., 2007).

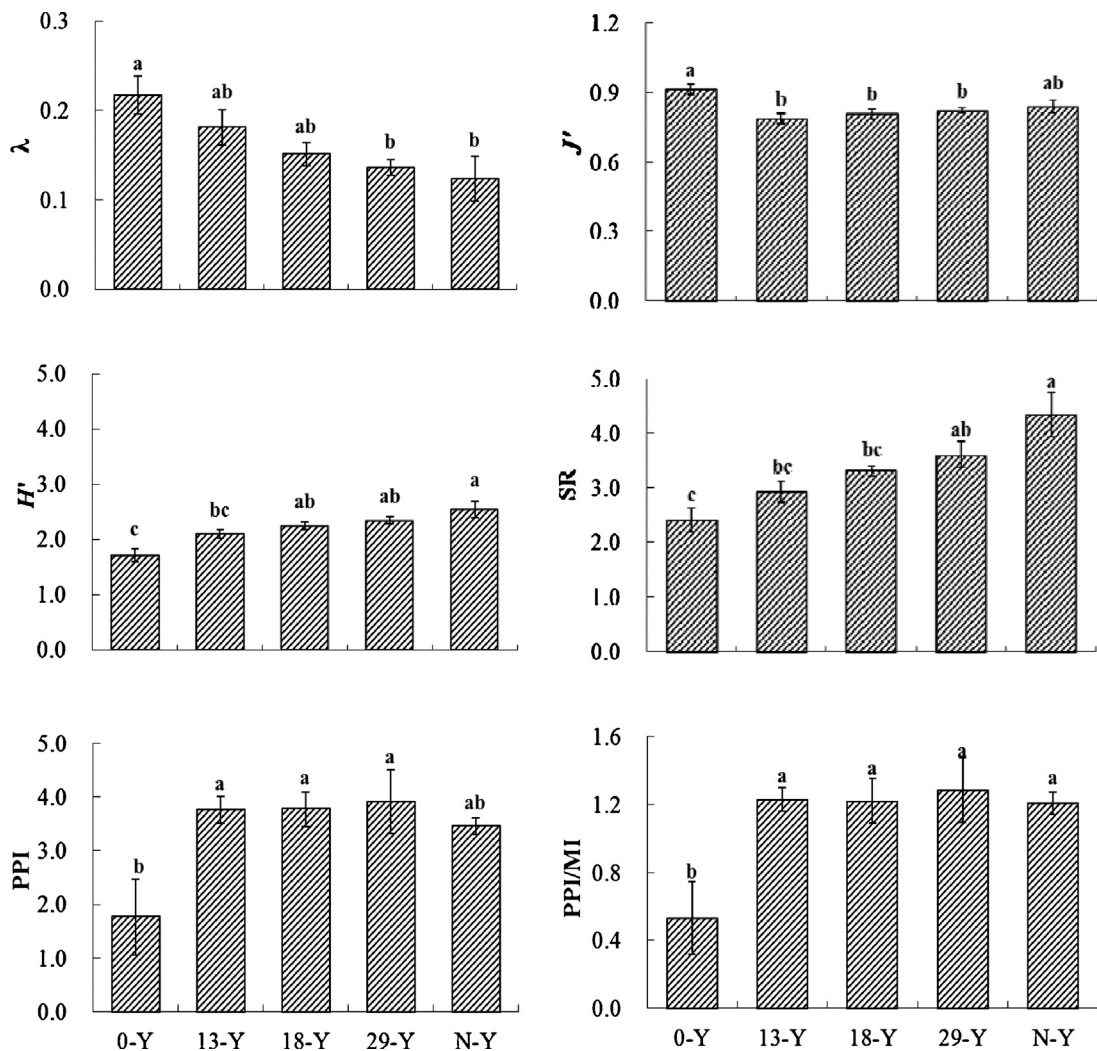


Fig. 4. Nematode ecological indices in different *C. microphylla* sand-fixation years. Bars indicate standard errors. 0-Y, 0-year-old; 13-Y, 13-year-old; 18-Y, 18-year-old; 29-Y, 29-year-old; N-Y, natural shrubs. λ , Simpson index; H' , Shannon–Weiner diversity index; J' , evenness; SR, species richness; PPI, plant parasite index; PPI/MI, plant parasite index/maturity index. Different lowercase letters indicate significant differences among different sand-fixation years as assessed by Tukey's multiple range tests.

In our study, soil organic carbon and total nitrogen as main abiotic factors were improved markedly during the development of the shrubs, which had important contributions in explaining nematode community structure and composition. Similarly, Zhi et al. (2009a) found that changes in soil abiotic factors led to the variation in nematode composition and abundance in Tengger Desert. Changes in soil properties along the sand-fixation year were accompanied by corresponding changes in soil nematode community structure. The establishment of vegetation exerts a direct effect on nematode communities by changing the quantity and quality of resource input (Wall et al., 2002; De Deyn et al., 2004) and an indirect effect through their influence on the soil conditions (Wei et al., 2012).

5. Conclusion

The effect of *C. microphylla* on total nematodes, bacterivores, fungivores and omnivorous predators was significant. The shifts in the generic composition of soil nematodes following the conversion of drifting sand dunes to shrub land altered soil nematode community structure. Soil organic carbon and total nitrogen were the most important soil abiotic factors determining soil nematode composition. The variation of soil nematode communities as

bioindicators reflected the gradual restoration process after *C. microphylla* establishment in the sandy ecosystems.

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