Impact of Tobacco Bacterial Wilt on Small- and Medium-Sized Soil Fauna Communities in Tobacco Fields: Postprint

Authors: Bai Yaoyu, Pang Shuai, Wei Shan, Xiao Yao, Ding Wei

Date: 2018-06-09T00:00:00+00:00

Abstract

To elucidate the impact of tobacco bacterial wilt damage on the community structure and diversity characteristics of soil meso- and micro-fauna in tobacco fields of Chongqing's tobacco-growing regions, a fixed-point experiment was conducted in Pengshui County, Chongqing Municipality, during the tobacco field fallow period in March, the vigorous growth stage of tobacco plants in June, and the tobacco leaf maturity stage in September 2015, investigating the soil meso- and micro-fauna communities in tobacco fields with consecutive bacterial wilt outbreaks and control fields without bacterial wilt damage. A total of 50,112 individuals of soil meso- and micro-fauna were captured, belonging to 33 taxa. Among these, nematodes, mites, and springtails constituted the dominant components of the soil meso- and micro-fauna in tobacco fields, playing a decisive role in shaping community characteristics. The overall abundance of soil fauna in bacterial wilt fields and control fields across different seasons followed the pattern March > June > September. The relative abundance and density of soil fauna and their main groups, as well as the community Margalef richness index, Shannon-Wiener diversity index, Pielou evenness index, and Simpson dominance concentration index, all exhibited marked dynamic variations across seasons in both field types, with significant differences detected ($P < 0.05$). Community similarity analysis revealed that the soil fauna communities of the two field types exhibited high similarity, which decreased as tobacco bacterial wilt damage intensified. Community stability results indicated that control field stability was significantly greater than that of bacterial wilt fields in both June and September. The A/C ratio of mite and springtail individuals was higher in control fields than in bacterial wilt fields, with significant differences in March and June ($P < 0.05$). Principal Component Analysis (PCA) demonstrated that bacterial wilt damage exerted substantial influences on soil fauna individual counts, soil fauna density, Mesostigmata, Oribatida, nematodes, Psocoptera, and Onychiuridae, as well as the A/C ratio of mite and springtail individuals;

these soil fauna indicators, being sensitive to bacterial wilt damage, can serve as characteristic indicators for evaluating bacterial wilt occurrence and damage severity; furthermore, ordination of soil sample collection points based on PCA scores revealed that heterogeneity in soil fauna community composition between the two field types increased with intensifying bacterial wilt damage. These results demonstrate that soil fauna community composition and diversity characteristics are closely associated with bacterial wilt occurrence and damage; to develop sustainable and effective biological control strategies for tobacco bacterial wilt in agricultural production, fundamental research on ecological relationships between this pathogen and soil meso- and micro-fauna must be continuously strengthened.

Full Text

Effects of Tobacco Bacterial Wilt on Meso-Micro Soil Fauna in Tobacco Fields of Chongqing

BAI Yaoyu, PANG Shuai, WEI Shan, XIAO Yao, DING Wei
College of Plant Protection, Southwest University, Chongqing 400715, China

Abstract

To understand the effects of tobacco bacterial wilt (TBW) on the community structure and diversity characteristics of meso-micro soil fauna in Chongqing tobacco-planting regions, field experiments were conducted from March to September 2015 in Runxi Town, Pengshui County, Chongqing Municipality. Two treatments were established in Baiguoping and Yingtaojing villages, representing hazard fields of tobacco wilt (HFTW) affected by TBW for more than 10 consecutive years and control fields without this hazard (CK). Modified Tullgren and Baermann’ s methods were used to extract a total of 50,112 individuals of meso-micro soil animals, belonging to 33 groups. Among them, Nematoda, Acari, and Collembola were the dominant groups. The individual numbers of soil animal communities as well as dominant groups of Nematoda, Acari, and Collembola showed a decreasing trend from March to September. The relative abundance and density of soil animals as well as dominant groups varied widely between the two treatments during different investigation periods. For example, the abundance and density of Nematoda were significantly higher in CK than in HFTW in March ($P < 0.05$); the density of Acari was significantly higher in HFTW than in CK in June ($P < 0.05$); the density of Collembola was significantly higher in HFTW than in CK during all investigation periods; and the abundance of Isotomidae in CK was significantly higher in March and lower in September compared to those in HFTW. The density of rare groups was also significantly different between the two treatments in June and September. The dynamics of several community diversity indices of soil fauna varied between HFTW and CK during different investigation periods. Although the Margalef richness index was significantly greater in CK than in HFTW in March and June, it was significantly higher in HFTW than in CK in September. The Shannon-Wiener diversity index was significantly higher in HFTW than in CK in March and September, but lower in June. The Pielou evenness index was significantly higher in CK than in HFTW in June. In March, the Simpson index was significantly higher in CK than in HFTW in the presence of Nematoda, but significantly lower in the absence of Nematoda. However, in the absence of Nematoda, the Simpson index was significantly higher in CK than in HFTW in June and September. Similarity analysis using the Sørensen index showed that the composition and structure of soil animal communities between HFTW and CK were highly similar, but the similarity declined markedly under effects of TBW with increased severity of damage level from March to September. Stability analysis showed that the structure of soil animal community in CK had higher stability than that in HFTW in June and September. The ratio of individual numbers between Acari and Collembola (A/C value) was higher in CK than in HFTW, and was significantly different in March and June. The results of principal component analysis (PCA) indicated that the occurrence and damage of TBW had a considerable effect on individual numbers and density of soil fauna, individual numbers of Oribatida, Mesostigmata, Nematoda, Corrodentia, and Onychiuridae, and values of A/C, which could be used as an indicator to monitor the environmental impacts on the disease. In addition, PCA ordination diagrams of soil collection points in tobacco fields suggested that the differences in soil animal community composition were considerably influenced by the damage and its severity of TBW from March to September. On the basis of these results, we can conclude that abundance and diversity of meso-micro soil fauna is closely related to the occurrence and severity of TBW in tobacco fields.

Keywords: tobacco bacterial wilt; fallow season; growing period; meso-micro soil fauna; community diversity

1. Study Area Overview

The study area was located in Runxi Town, Pengshui County, Chongqing Municipality, approximately 53 km southwest of the county seat. The region has a mid-subtropical humid monsoon climate with an average annual temperature of 17.6°C and average annual rainfall of 1,224 mm. The elevation ranges from 841 m to 1,498 m, with significant temperature differences between high mountains and low valleys, creating distinct three-dimensional mountain climate characteristics. The town, situated at the junction of Chongqing and Guizhou, features tobacco cultivation as its characteristic industry, with tobacco output value accounting for approximately one-third of the town' s total agricultural income. The typical TBW hazard area is located in Baiguoping Village, where tobacco fields have suffered major TBW damage for nearly 12 consecutive years, with disease incidence rates in some plots reaching up to 95% during the tobacco maturity stage. Pengshui County Tobacco Branch Company has established a 13.3

hm² demonstration area for TBW research and integrated management. The experimental TBW field selected for this study was located within this demonstration area, while a control field without TBW hazard history was selected in the nearby Yingtaojing Village tobacco-planting area.

2. Materials and Methods

2.1 Sample Plot Setup and Soil Physicochemical Properties In both the TBW-affected area and the control area, 30 m × 20 m tobacco field plots were selected as experimental sites, separated by 1.0 m wide ridge non-cultivation zones. All plots were managed according to local farmer practices for transplanting, fertilization, and water management, without chemical pesticide application for disease and pest control. After sample collection in March, the soil animals were separated and the remaining soil was used for physicochemical property determination following methods in Bao Shidan' s *Soil Agrochemical Analysis* [18]. The test soil was yellow clay loam. Other measurement results are shown in and .

Table 1. Physical and chemical properties of tobacco soils in Runxi Town, Pengshui County, Chongqing

Indexes	Hazard fields of tobacco wilt	Control fields without hazard
pH value	5.45	5.21
Organic matter content (g/kg)	17.97	13.61
Total nitrogen (g/kg)	1.128	1.12
Total phosphorus (g/kg)	0.84	0.87
Total potassium (g/kg)	15.30	13.68
Soil bulk density (g/cm³)	1.12	1.15
Water holding capacity (%)	44.07	42.36

Indexes	Hazard fields of tobacco wilt	Control fields without hazard
Cation exchange capacity (cmol/kg)	35.21	35.20

2.2 Sample Collection and Separation Sampling was conducted during three periods: March (tobacco field fallow period), June (tobacco seedling vigorous growth period, initial TBW stage), and September (tobacco leaf maturity period, post-TBW stage). Three experimental plots were established in both TBW-affected and control sites, with three replicate sampling points per plot and approximately 10 m spacing between collection points. March sampling points were selected in relatively flat areas of ridge tobacco fields with minimal human activity, while June and September sampling points were selected near the main stems of tobacco seedlings on ridge platforms to collect rhizosphere soil. At each point, three soil layers (0-5, 5-10, and 10-15 cm) were sampled simultaneously using a 5 cm diameter ring sampler. After stratified collection, soil samples from each layer were processed separately. Soil animals were separated using modified Tullgren funnels (dry funnels) for 48 hours at 30-50°C, while nematodes and other wet-dwelling animals were separated using Baermann wet funnels. Collected soil animals were preserved in alcohol in glass bottles for classification, identification, and counting. Nematodes in the funnel collection tubes were examined and counted under a microscope. Soil animals were identified under a binocular dissecting microscope using reference materials such as *Soil Fauna of China' s Subtropical Regions* and *Soil Animal Retrieval Atlas* [20], classified by major taxa, and counted. Due to taxonomic limitations, classification was performed at the group level.

2.3 Data Processing and Analysis Alpha diversity indices for soil fauna communities were calculated using the Simpson dominance index, Shannon-Wiener diversity index, Pielou evenness index, and Margalef richness index [19]. Since nematodes have very high density in soil animal communities, calculations were performed both with and without nematodes for separate statistical analysis. Beta diversity between communities was analyzed using the Sørensen similarity coefficient, which reflects the similarity degree of soil animal groups between the two habitat types. The similarity scale was defined as: 0.75-1.00 (extremely similar), 0.50-0.74 (moderately similar), 0.25-0.49 (moderately dissimilar), and 0-0.24 (extremely dissimilar). Community stability was measured using the ratio of species number to individual number. Due to the large populations of Acari and Collembola in soil animal communities and their correlation with TBW hazard, the A/C ratio (individual numbers of Acari to Collembola) was statistically analyzed across different investigation periods. Relative abundance was calculated as the percentage of individuals of each group relative to the total capture. Groups with >10% relative abundance were classified as dominant, 1.0%-10.0% as common, and <1.0% as rare groups. Soil animal density data were converted from individual counts. Before analysis, abundance and density data were transformed using arcsine square root transformation. For normally distributed data with homogeneous variance, one-way ANOVA was used; for non-normal or heterogeneous data, Mann-Whitney U tests were applied. Principal component analysis (PCA) was performed on major community characteristic indicators using CANOCO 5 software, with ordination analysis of sampling points based on dominant and common soil animal groups. All analyses and graphs were conducted using Microsoft Excel 2007, SPSS 19.0, and CANOCO 5.

3. Results

3.1 Soil Fauna Community Composition and Quantitative Characteristics A total of 50,112 meso-micro soil animals were captured, belonging to 33 groups. The dominant groups were Nematoda (80.91% relative abundance), Isotomidae (8.84%), Mesostigmata (2.39%), Prostigmata (2.17%), Entomobryidae (1.52%), and Oribatida (1.10%), while other groups were rare. In March fallow fields, Nematoda and Mesostigmata relative abundances were 66.38% and 10.88% respectively (dominant groups), followed by Isotomidae, Prostigmata, and Entomobryidae as common groups. In June vigorous growth stage, Nematoda relative abundance was 68.64% (dominant), with Isotomidae, Entomobryidae, Oribatida, and Neelidae as common groups. In September leaf maturity stage, Nematoda relative abundance was 9.95% (dominant), with Mesostigmata, Isotomidae, Entomobryidae, Coleoptera, and Neelidae as common groups.

Comparing HFTW and CK fields, differences existed in dominant and common groups and their relative abundances. In March, HFTW dominant groups were Nematoda and Isotomidae, with common groups being Oribatida, Mesostigmata, Entomobryidae, and Prostigmata; CK dominant group was Nematoda, with common groups being Isotomidae, Mesostigmata, and Entomobryidae. Among shared groups, HFTW Nematoda relative abundance was significantly lower than CK ($F = 10.577$, $P < 0.01$), while Isotomidae and Oribatida were significantly higher ($F = 4.384$, $P < 0.05$). In June, HFTW dominant groups were Nematoda and Mesostigmata, with common groups being Isotomidae, Entomobryidae, and Prostigmata; CK dominant group was Nematoda, with common groups being Oribatida, Mesostigmata, and Prostigmata. Among shared groups, HFTW Isotomidae relative abundance was significantly higher than CK ($F = 9.082$, $P < 0.01$), while Oribatida was significantly lower ($F = 6.175$, $P < 0.05$); Mesostigmata differences were not significant ($F = 0.175$, $P > 0.05$). In September, HFTW dominant groups were Nematoda and Mesostigmata, with common groups being Isotomidae, Entomobryidae, and Neelidae; CK dominant groups were Nematoda and Mesostigmata, with common groups being Oribatida, Isotomidae, and Entomobryidae. Among shared groups, HFTW Mesostigmata and Isotomidae relative abundances were significantly lower than CK ($F = 7.292$, $P < 0.01$; $F = 11.70$, $P < 0.01$), while

Entomobryidae and Neelidae differences were not significant ($F = 0.025$–3.488, $P > 0.05$).

3.2 Temporal Dynamics of Soil Fauna Community Density Total soil fauna density and Nematoda density in HFTW and CK fields showed distinct temporal patterns. In March, CK soil fauna and Nematoda densities were significantly higher than HFTW ($F = 6.77$, $P < 0.01$; $F = 8.67$, $P < 0.01$); in June and September, HFTW densities were significantly higher than CK (June: $F = 16.08$, $P < 0.01$; September: $F = 0.796$, $P > 0.05$ for total fauna; $F = 7.07$, $P < 0.05$ for Nematoda). Acari density in both field types was higher during the growing period than the fallow period. In March, HFTW Acari density was significantly higher than CK ($F = 9.31$, $P < 0.01$); in June and September, HFTW densities were also significantly higher (June: $F = 5.54$, $P < 0.05$; September: $F = 8.45$, $P < 0.01$). Collembola density was higher during the fallow period than the growing period in both habitats, with all three periods showing significantly higher density in HFTW than CK (March: $F = 18.59$, $P < 0.01$; June: $F = 9.29$, $P < 0.01$; September: $F = 11.22$, $P < 0.01$). Other rare groups showed higher density during the growing period, with significantly higher density in HFTW than CK in June and September ($F = 11.29$, $P < 0.01$), but no significant difference in March ($F = 0.013$–4.399, $P > 0.05$).

3.3 Vertical Distribution of Soil Fauna Community Density Total soil fauna density and group densities in HFTW and CK fields showed obvious variations across the three soil layers (0–5, 5–10, and 10–15 cm). In March, soil fauna and Nematoda densities were significantly higher in CK than HFTW in all three layers (0–5 cm: $F = 125.5$, $P < 0.01$; 5–10 cm: $F = 10.17$, $P < 0.01$; 10–15 cm: $F = 6.15$, $P < 0.05$). In June, densities were higher in HFTW than CK, with significant differences only in the 0–5 cm layer for soil fauna ($F = 16.63$, $P < 0.01$) and all three layers for Nematoda (0–5 cm: $F = 96.0$, $P < 0.01$; 5–10 cm: $F = 11.26$, $P < 0.01$; 10–15 cm: $F = 6.49$, $P < 0.05$). In September, densities were higher in HFTW than CK, with significant differences in the 0–5 cm and 5–10 cm layers for soil fauna ($F = 138.5$, $P < 0.01$; $F = 99.0$, $P < 0.05$) and all three layers for Nematoda (0–5 cm: $F = 137.0$, $P < 0.01$; 5–10 cm: $F = 6.89$, $P < 0.05$; 10–15 cm: $F = 6.59$, $P < 0.05$). Acari density in HFTW was significantly higher than CK in the 0–5 cm layer in March ($F = 6.34$, $P < 0.05$) and in all three layers in June and September ($P < 0.01$). Collembola density was significantly higher in HFTW than CK in the 0–5 cm layer in March ($F = 7.95$, $P < 0.01$) and in the 0–5 cm and 5–10 cm layers in June and September ($P < 0.01$). Other rare groups showed significantly higher density in HFTW than CK in the 0–5 cm layer in June and September ($F = 14.85$, $P < 0.01$; $F = 18.21$, $P < 0.01$), with no significant differences at other times.

3.4 Diversity Indices and Dynamics of Soil Fauna Communities The Shannon-Wiener diversity index was significantly higher in HFTW than CK in both nematode and nematode-free conditions in March ($F\_with = 83.21$, $P <$

0.01; F_without = 17.21, $P < 0.01$) and September (F_without = 92.03, $P < 0.01$; F_without = 35.65, $P < 0.01$), but lower in June. The Pielou evenness index was only significantly higher in CK than HFTW in June (F_with = 6.69, $P < 0.05$). The Simpson dominance index was significantly higher in CK than HFTW in March under nematode conditions (F_with = 5.64, $P < 0.05$), but significantly lower in June and September under nematode-free conditions (F_without = 95.85, $P < 0.01$; F_without = 6.98, $P < 0.05$). The Margalef richness index was significantly higher in HFTW than CK in both conditions in June and September (F_without = 7.81, $P < 0.01$; F_with = 49.41, $P < 0.01$), but significantly higher in CK than HFTW in March (F_without = 47.42, $P < 0.01$).

3.5 Similarity and Stability Analysis of Soil Fauna Communities The Sørensen similarity coefficient between HFTW and CK soil fauna communities was >0.75 across all investigation periods, indicating extremely high similarity. However, the similarity declined markedly with increased TBW severity from March to September, particularly during the tobacco maturity stage. Community stability (St), measured as the ratio of species number to individual number, was higher in CK than HFTW in June and September, though the difference was small in March. The A/C ratio was consistently higher in CK than HFTW, with significant differences in March and June (March: $F = 5.65$, $P < 0.05$; June: $F = 9.96$, $P < 0.01$), indicating a close relationship between this ratio and TBW occurrence.

3.6 Principal Component Analysis of TBW Effects on Major Soil Fauna Characteristics PCA was performed on soil fauna characteristics including individual numbers, diversity indices, evenness index, richness index, dominance index, A/C ratio, and dominant/common groups across investigation periods. The first four principal components explained 74%-85% of cumulative variance for each period. Comprehensive scores were calculated by weighting each component by its eigenvalue proportion.

In March (fallow period), the top four most sensitive indicators were individual numbers, density, Mesostigmata, and A/C ratio. In June (vigorous growth period), the top indicators were density, Mesostigmata, individual numbers, and Onychiuridae. In September (maturity period), the top indicators were individual numbers, Mesostigmata, density, and Onychiuridae. These indicators could serve as reference indices for analyzing TBW effects during respective periods.

PCA ordination of sampling points based on dominant and common groups showed clear gradient clustering. In March, sampling points from both field types overlapped considerably, indicating high similarity. In June, points overlapped in only one classification region, with Prostigmata showing higher abundance in some CK samples. In September, points overlapped in only one region, with Coleoptera and Hymenoptera showing higher abundance in some CK samples, while Onychiuridae and Entomobryidae showed higher abundance in some HFTW samples. This demonstrated that community heterogeneity increased with TBW severity.

4. Discussion and Conclusion

The occurrence mechanism and control measures of TBW in various crops have been research hotspots in agricultural production. With increasing continuous cropping years in China’ s tobacco regions, the disease’ s epidemic and diffusion rates are accelerating. Successful biological control of soil-borne plant diseases requires understanding soil microbial and faunal composition and their interrelationships. Soil fauna are closely related to biotic and abiotic factors in farmland systems and can effectively indicate soil health in sustainable agriculture. Previous studies have shown significant correlations between TBW severity and rhizosphere soil Acari and Collembola occurrence.

This study further demonstrates that meso-micro soil fauna in Chongqing mountainous tobacco fields are mainly composed of Nematoda and arthropods, with dominant and common groups playing important roles in TBW pathogen reproduction and infection. TBW occurrence significantly affects community composition and structure, particularly soil nematodes, Acari, and Collembola, which have important indicative value. While numerous studies have examined relationships between TBW and soil microorganisms, few have investigated soil fauna relationships. Soil fauna actively participate in soil processes and functions, regulating rhizosphere microbial processes and significantly affecting plant growth. Their ecological functions are realized through direct feeding on fungi and plant litter and indirect effects on soil physicochemical properties and microbial community structure.

Seasonal investigations revealed distinct seasonal characteristics in soil fauna community composition. Total soil fauna and nematode densities were higher during the fallow period than the growing period, while Acari and other groups showed higher densities during the growing period, and Collembola showed higher density during the fallow period. These patterns were primarily influenced by temperature, rainfall, soil nutrients, and agricultural management practices, which significantly affect soil physicochemical properties and ultimately determine soil fauna occurrence. Plant roots, as major rhizosphere regulators, also significantly impact soil microbial and faunal distribution and structure.

Community diversity indices reflect within-community stability. This study found that TBW fields had higher total soil fauna, Acari, and Collembola abundances than control fields, particularly during the tobacco growing period. The A/C ratio was closely related to TBW occurrence, with control fields showing higher values. Diversity indices showed significant seasonal variations between field types, with Shannon-Wiener and Margalef indices generally higher in TBW fields, while Pielou and Simpson indices showed more complex patterns. These changes were closely related to TBW effects on nematodes, Acari, and Collembola.

Beta diversity indices reflect environmental heterogeneity between communities. Similarity analysis showed high species composition similarity between TBW and control fields, but heterogeneity was significantly affected by TBW severity, particularly during the maturity stage. Community stability was higher in control fields than TBW fields during most periods, indicating more balanced species distribution and stronger interspecific constraints in control fields. These differences can be explained by trophic cascading interactions or bottom-up/top-down theory, where above-ground tobacco plant weakening due to TBW (bottom-up effect) and subsequent changes in root growth affect below-ground biota (top-down effect), creating differences in soil fauna community composition.

PCA results further identified season-specific sensitive indicators for TBW effects, including individual numbers, density, Mesostigmata, Onychiuridae, and A/C ratio. The ordination of sampling points confirmed high community similarity between field types but increasing heterogeneity with TBW severity. These findings suggest that soil fauna can serve as effective bioindicators for TBW occurrence and severity.

In agricultural practice, sustainable and effective biological control of TBW should strengthen basic research on ecological relationships between the pathogen and meso-micro soil fauna. Soil fauna directly participate in rhizosphere ecosystem material cycling and energy flow, significantly influencing plant growth and disease resistance. For example, combined inoculation of TBW pathogen and root-knot nematodes causes severe plant wilting, with disease symptoms appearing earlier. Some Collembola species can reduce soil-borne pathogen inoculum viability and disease incidence, while fungivorous mites can stimulate beneficial bacterial reproduction. The complex trophic and non-trophic relationships between soil fauna and microorganisms, including TBW pathogen, warrant further investigation to develop effective biological control strategies.

References

[1] Hayward A C. Biology and epidemiology of bacterial wilt caused by *Pseudomonas solanacearum*. *Annual Review of Phytopathology*, 1991, 29(1): 65-87.

[2] [Reference details omitted for brevity]

[3] [Reference details omitted for brevity]

[4] Swift M J, Heal O W, Anderson J M. *Decomposition in Terrestrial Ecosystems*. Oxford: Blackwell Scientific Publications, 1979.

[5] Büchs W. Biotic indicators for biodiversity and sustainable agriculture—introduction and background. *Agriculture, Ecosystems & Environment*, 2003,

98(1/3): 1-16.

[6] [Reference details omitted for brevity]

[7] [Reference details omitted for brevity]

[8] Niu J J, Rang Z W, Zhang C, Chen W, Tian F, Yin H Q, Dai L J. The succession pattern of soil microbial communities and its relationship with tobacco bacterial wilt. *BMC Microbiology*, 2016, 16: 233.

[9] [Reference details omitted for brevity]

[10] [Reference details omitted for brevity]

[11] Bonkowski M, Cheng W X, Griffiths B S, Alphei J, Scheu S. Microbial-faunal interactions in the rhizosphere and effects on plant growth. *European Journal of Soil Biology*, 2000, 36(3/4): 135-147.

[12] Bonkowski M, Villenave C, Griffiths B. Rhizosphere fauna: the functional and structural diversity of intimate interactions of soil fauna with plant roots. *Plant and Soil*, 2009, 321(1/2): 213-233.

[13] [Reference details omitted for brevity]

[14] Smrž J, Čatská V. The effect of the consumption of some soil fungi on the internal microanatomy of the mite *Tyrophagus putrescentiae* (Schrank) (Acari: Acaridida). *Acta Universitatis Carolinae-Biologica*, 1989, 33: 81-93.

[15] Lartey R T. Dynamics of soil flora and fauna in biological control of soil inhabiting plant pathogens. *Plant Pathology Journal*, 2006, 5(2): 125-142.

[16] Wolfarth F, Schrader S, Oldenburg E, Weinert J. Nematode-collembolan interaction promotes the degradation of *Fusarium* biomass and deoxynivalenol according to soil texture. *Soil Biology and Biochemistry*, 2013, 57: 903-910.

[17] [Reference details omitted for brevity]

[18] Bao Shidan. *Soil Agrochemical Analysis*. Beijing: China Agriculture Press, 2000.

[19] [Reference details omitted for brevity]

[20] [Reference details omitted for brevity]

[21] [Reference details omitted for brevity]

[22] [Reference details omitted for brevity]

[23] Pankhurst C E, Hawke B G, McDonald H J, Kirkby C A, Buckerfield J C, Michelson P, O' Brien K A, Gupta V V S R, Doube B M. Evaluation of soil biological properties as potential bioindicators of soil health. *Australian Journal of Experimental Agriculture*, 1995, 35(7): 1015-1028.

[24] ShiomI S, Yamamoto M, Nakamura R, Inaba A. Expression of ACC synthase and ACC oxidase genes in melons harvested at different stages of maturity. *Journal of the Japanese Society for Horticultural Science*, 1999, 68(1): 10-17.

[25] [Reference details omitted for brevity]

[26] [Reference details omitted for brevity]

[27] [Reference details omitted for brevity]

[28] [Reference details omitted for brevity]

[29] [Reference details omitted for brevity]

[30] [Reference details omitted for brevity]

[31] [Reference details omitted for brevity]

[32] Ferris H, Tuomisto H. Unearthing the role of biological diversity in soil health. *Soil Biology and Biochemistry*, 2015, 85: 101-109.

[33] [Reference details omitted for brevity]

[34] Carpenter S R, Kitchell J F, Hodgson J R. Cascading trophic interactions and lake productivity: fish predation and herbivory can regulate lake ecosystems. *BioScience*, 1985, 35(10): 634-639.

[35] McQueen D J, Post J R, Mills E L. Trophic relationships in freshwater pelagic ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences*, 1986, 43(8): 1571-1581.

[36] A' Bear A D, Johnson S N, Jones T H. Putting the 'upstairs-downstairs' into ecosystem service: what aboveground-belowground ecology can tell us? *Biological Control*, 2014, 75: 97-107.

[37] Wardle D A, Bardgett R D, Klironomos J N, Setälä H, van der Putten W H, Wall D H. Ecological linkages between aboveground and belowground biota. *Science*, 2004, 304(5677): 1629-1633.

[38] [Reference details omitted for brevity]

[39] Lucas G B. *Diseases of Tobacco.* 3rd ed. Raleigh, NC: Biological Consulting Associates, 1975.

[40] Dromph K M, Borgen A. Reduction of viability of soil borne inoculum of common bunt (*Tilletia tritici*) by collembolans. *Soil Biology and Biochemistry*, 2001, 33(12/13): 1791-1795.

Acknowledgments: Professor Qisheng Song, University of Missouri, USA, assisted with manuscript preparation.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.