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Water and fertilizer management regulates soil quality, bacterial community structure and function, and yield in Panax Notoginseng

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Abstract

Background Proper water and fertilizer management can improve soil quality, regulate soil microbial community balance, and increase crop yield. However, the overall soil quality of Panax notoginseng under different irrigation and fertilization levels are still unclear.

Methods We set up an experiment with W1F1, W1F2, W1F3, W1F4, W2F1, W2F2, W2F3, W2F4, W3F1, W3F2, W3F3, W3F4 irrigation and fertilization treatments and a non-irrigated and non-fertilized CK as a control in Panax pseudoginseng farmland during 3 consecutive years. The differences of TDS covering 13 soil physicochemical properties and biological indicators in the fruiting stage of Panax notoginseng under different irrigation and fertilization treatments were analyzed, and the effects of different irrigation and fertilization treatments on the structure and function of soil bacterial community in a phyla level were further explored. The soil MDS was selected by principal component analysis and Norm value combined with Pearson correlation analysis, and the SQI-MDS was employed to comprehensively evaluate the soil quality of Panax notoginseng under each irrigation and fertilization treatment and the corresponding yield was associated.

Results The data showed that the soil physicochemical properties and Alpha diversity index, structure, and function of bacterial in Panax notoginseng under different irrigation and fertilization treatments in three years had significant difference. In 3 years, the coupling water and fertilizer treatments compared to single fertilization or irrigation had more unique bacteria phyla, the Acidobacteriota, Actinobacteriota, Chloroflexi, and Proteobacteria were the dominant bacteria phyla in each fertilization or irrigation treatment, the Acidobacteriota and Firmicutes phylum demonstrated significant difference in the W3 and F3 treatment, respectively, and the values of multiple positive soil physicochemical indicators and bacterial functional metabolism potential under the W3F3 treatment were significantly greater than CK. In addition, the functional richness of soil beneficial bacteria in Panax notoginseng increased with the increased planting years. The soil MDS included pH and Shanno indicators, and the fitting effect between SQI-MDS-NL and SQI-TDS were better in each year. The irrigation and fertilization regimes under the top three soil quality were the same and the soil quality under the W3F3 treatment was in the top three in every year. Furthermore, the yield in Panax notoginseng under the W3F3 treatment in 2018-2019, 2019-2020， and 2021-2022 year increased by 1.63 times, 1.29 times, and 0.95 times compared with CK, respectively.

Conclusions This study provides a reference for understanding the overall soil condition of Panax notoginseng under different irrigation and fertilization regimes in the long term and formulating the optimization plan of irrigation and fertilization management increasing the yield in Panax notoginseng.

Keywords: Water and fertilizer management, Panax notoginseng, SQI-MDS, Structure and function of soil bacteria, Yield

Introduction

As a precious but limited natural resource on land, soil is a key carrier for the survival and development of human beings, plants, and animals (Kahsay et al., 2023; Elmujtar et al., 2019), and it plays an important role in ecosystem balance (Zhang et al., 2022). Excessive irrigation caused soil nutrient leaching loss and reduced water and fertilizer utilization, and excessive fertilization leaded to soil acidification and mineral excess (Liu et al., 2022; Li et al., 2020). According to the conditions of crop water and fertilizer demand, irrigation and fertilization are reasonably coordinated in time, quantity, and ways, and the negative effects of single fertilization or irrigation on soil fertility can be offset by the coupling of water and fertilizer, so as to improve soil fertility and water and fertilizer utilization efficiency (Li et al., 2021; Wang et al., 2021). In the process of sustainable agricultural development, the development of efficient irrigation and fertilization mode is the key to improving crop yield, water and fertilizer utilization efficiency, and soil quality, so scientific exploration of water and fertilizer management strategies and mechanisms is the key to achieving sustainable development for local agricultural (Wang et al., 2023). Soil quality refers to the ability of soil to maintain plant production, animal survival and reproduction, ecological environment quality, and human health within the boundary of ecosystem (Arshad et al., 2022). Effective soil quality assessment can improve soil productivity and sustainability, and promote soil ecological balance (Ma et al., 2020). Soil quality can be comprehensively reflected by physical, biological and chemical indicators (Vasu et al., 2021), soil indicators are interdependent and interact with each other, a single indicator may be one-sided and unfavorable to soil quality evaluation (Atanu et al., 2014), and while it is difficult to conduct soil quality comprehensive evaluation of with numerous indicators. Researchers construct an evaluation index system by screening indicators using qualitative (Karlen et al., 2003), quantitative (Masoud et al., 2020), and semi-quantitative methods. Semi-quantitative method means that experts select representative indicators from a large number of indicators. quantitative method is that minimum data set was quantitatively obtained by principal component analysis (Li et al., 2019), factor analysis (Liu et al., 2018), partial least squares regression (Li et al., 2023), and other statistical methods. Considering the collinear relationship among soil indicators, index acquisition cost, soil structure complexity, and other factors, the minimum data set can reduce data redundancy and reflect soil quality by the least indicators (Yuan et al., 2020). Presently, common soil quality evaluation methods at home and abroad include soil quality index (Rezapour et al., 2023), Technique for Order Preference by Similarity to Ideal Solution (Adebo et al., 2020), grey correlation analysis (Zhou et al., 2020), Analytic hierarchy Process (Shahnazari et al., 2021), principal component analysis (Jin et al., 2021), fuzzy comprehensive evaluation (Xue et al., 2021), comprehensive index (Zhang et al., 2021), and dynamic method (Hussain et al., 2019). Soil quality index method has been widely used by domestic and foreign researchers in soil quality evaluation of farmland and forest land due to its simplicity and high flexibility (Davari et al., 2020; Yang et al., 2023; Shao et al., 2020). Therefore, soil quality index method based on minimum data set can effectively evaluate soil quality.

Panax notoginseng is a medicinal plant widely cultivated in southwest China, and its extract has been increasing in the global market year by year (Tang et al., 2024). In recent years, researches have mainly focused on the pharmacological effects of Panax notoginseng (Mengnan et al., 2023), and the influences of chemical additives and different water and fertilizer management measures on soil nutrients in Panax notoginseng, and yield and quality of Panax notoginseng (Zhao et al., 2022; Tuo et al., 2023). There is no report on the soil quality evaluation in Panax notoginseng under different water and fertilizer management, and it is not clear how the optimization of water and fertilizer can increase the yield of Panax notoginseng by improving soil physicochemical properties and bacterial structure and function. Therefore, we conducted the soil collection and determination experiment of the fruiting period of Panax notoginseng under different water and fertilizer conditions in three years. This study aims to: analyze the differences of soil physicochemical properties and bacterial Alpha diversity index in Panax notoginseng under different water and fertilizer treatments; further explore the soil bacterial community structure and function in Panax notoginseng under different water and fertilizer treatments; evaluate soil quality in Panax notoginseng under different water and fertilizer treatments by SQI-MDS and compare the corresponding yield. This study will provide a reference for understanding the soil quality and bacterial community structure and function of Panax notoginseng under different water and fertilizer conditions and sustainable production in Panax notoginseng.

Materials and methods

Study area

The study area is located in Luxi County, Honghe Prefecture, Yunnan Province (Fig. 1), and which geographical location is 103°42′E and 24°24′N. It belongs to the North subtropical monsoon climate. the rainy season is from June to October, the average annual rainfall is 850 mm, the average annual sunshine is 2122 hours, the frost-free period is 272.7 days, the summer is warm and humid, and the winter is dry.

The highest altitude is 2448 m, and the lowest altitude is 824 m. The main soil type is red soil， and pH is 4.8~6.9.

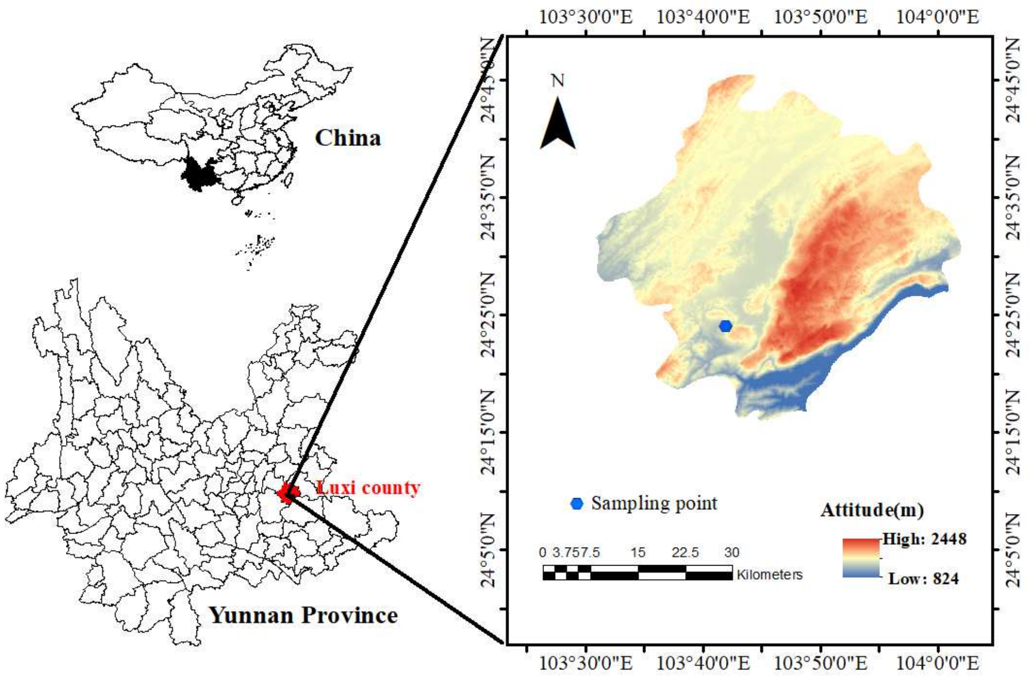

Fig.1 Location map of the study area

Sample setting and sample collection

We carried out the cultivation experiment in Panax notoginseng in Dalishu of Luxi County from 2018 to 2021. The growth period of Panax notoginseng included rooting period (November to January of the following year), seedling period (February to April), flowering period (May to July), and fruiting period (August to October). In this experiment, German-American water-soluble organic fertilizer was used, with main components N content ≥21%, P_2O_5 content ≥21%, K_2O content ≥21%, humic acid content ≥6%, B content ≥0.1%, and Mo content ≥0.007%. Furthermore, we took irrigation quantity level (W) and fertilization level (F) as control factors, the 3 irrigation levels of W1 (5 mm), W2 (10 mm), and W3 (15 mm) and the 4 fertilization levels of F1 (48.00kg·hm^{-2}), F2 (72.00 kg·hm^{-2}), F3 (93.00 kg·hm^{-2}), and F4 (120.00 kg·hm^{-2}) were set up, the 10 mm, 5 mm, and 15 mm represented 60%, 80%, and 40% of field capacity, respectively, and all combination of W and F series had W1F1, W1F2, W1F3, W1F4, W2F1, W2F2, W2F4, W3F1, W3F2, W3F3 and W3F4, with CK as the control (without irrigation and fertilization). In addition, the each of treatments set for three replicates, with a total of 39 plots, and every plot was 16.70m long and 1.50m wide and covered 5mm thick pine needles in the ground. The micro-sprinkler irrigation network was installed in the whole experimental field, the irrigation amount was controlled by the water meter and water valve of the micro-sprinkler irrigation system, and irrigation was conducted once a week. Moreover, the plastic film and a three-layer shading network were used to avoid the influence of natural precipitation and sunlight on Panax notoginseng, respectively, and at the beginning of each growth period, the required Water and fertilizer were piped to the treatment plots. In the fruiting period of the 2018-2019, the 2019-2020, and the 2020-2021, the three 1 m×1 m sampling sites were set up on the upper, middle, and lower parts of each plot, and litter and gravel on the surface in the sampling sites were removed. In addition, soil samples of 0-60 cm soil layer were collected, packed into numbered self-sealing bags, and sealed, and the soil samples were stored away from light and brought back to the laboratory as soon as possible. The part of the fresh soil sample stored at 4° was used for the determination of microbial related-indicators, the other part was used for the determination of soil moisture content, ammonium nitrogen, and nitrate nitrogen, and the air-dried sifted soil sample was used for the determination of other soil physical and chemical indicators. The three plants of Panax notoginseng with the same growth were collected in each plot, and the washed tubers were put into a kraft paper bag and green for 30 minutes at 105℃. Then the tubers dried to constant weight and their average values were measured the yield of Panax notoginseng.

Soil analysis

According to Soil Agrochemical Analysis and Environmental Monitoring, the soil moisture content was determined using the drying method (Yang et al., 2008). The total nitrogen was determined using the Kjeldahl method ((Bremner and Mulvaney, 1982), the hydrolyzed nitrogen was determined by the alkaline hydrolysis diffusion method (Li et al., 2022), the ammonium nitrogen and nitrate nitrogen were determined using the continuous flow analyzer (AA3, SEAL, Germany, Guggenberger et al., 2003), the total phosphorus was measured by the molybdate colorimetry method (Murphy et al., 1962), the available phosphorus was determined using the ammonium fluoride-hydrochloric acid extraction of molybdenum-antimony resistance colorimetric method (Olsen et al., 1954), the total potassium and available potassium were determined by the flame spectrophotometry (Pages et al., 1982), the organic carbon determined using the dichromate oxidation and titration method (Kalembasa et al., 1973), and the soil pH was measured by pH meter with the soil to water ratio was 1:2.5 (Thomas et al., 1996).

Soil microbial indicators determination

The DNA of each 0.5g soil sample was extracted by employing the E.Z.N.A. soil kit (Omega Bio-tek, Norcross, GA, U.S.). The integrity of DNA was detected by 1% agarose gel electrophoresis, and the concentration and purity of the DNA were determined and extracted, respectively, using a nano-spectrophotometer (Drop2000, Thermo Fisher Scientific, USA). The V3-V4 variable region was amplified using priming 338F(5 '-ACTCCTACGGGAGGCAGCAG-3') and 806R(5 '-GGACTACHVGGGTWTCTAAT-3') (Zhang et al., 2020). The PCR amplification procedure was initial denaturation at 95℃ for 3 min, denaturation at 95℃ for 30 s (27 cycles), annealing at 55℃ for 30 s, extension at 72℃ for 30 s, and finally extension at 72℃ for 10 min. The amplicons were extracted from 2% agarose gel and the PCR products were purified using the AxyPrep DNA gel extraction kit (Axygen Biosciences, Union City, CA, U.S.). The purified PCR products were sequenced on the Illumina MiSeq platform, then the sequence was filtered, and the sequence quality was controlled. At 97% sequence similarity level, the sequencing sequences were clustered into OUT, and finally the bacterial community composition at different classification levels was determined. The microbial DNA extraction, PCR amplification and 16S rRNA gene sequencing were conducted by Biocon Biotechnology Co., LTD. (Shanghai, China).

Yield determination of Panax notoginseng

$$Y_i = \frac{G_i \times N_i}{S_i} \qquad (1)$$

Where Yi is the yield of each water and fertilizer treatment, kg/hm^2; Gi is the weight of a single tuber in Panax notoginseng under each water and fertilizer treatment, kg; Ni is the actual planting number of panax notoginseng in each water and fertilizer treatment; Si is the effective planting area of Panax notoginseng in each water and fertilizer treatment area, hm^2.

SQI-MDS

MDS construction

The MDS of soil quality was constructed according to principal component analysis and Norm value. The specific idea is as follows: Using one-way analysis of variance to test the differences of soil indicators, 13 indicators with significant differences were taken as the TDS; Principal component analysis was performed on the indicators of the TDS, the principal component with eigenvalue ≧ 1 was extracted, and the indicator load of the same principal component was > 0.5 which divided into a group; If the index load of an indicator was higher than 0.5 in two principal components, it was classified as the group with low correlation with other indicators, the Norm values of each group were calculated respectively; The indicators within 10% of the highest Norm value of each group were selected to enter the MDS; If multiple indicators meet the condition, Pearson correlation analysis was carried out on them; when the correlation coefficient among indicators was significantly greater than 0.5, the indicator with the highest Norm value was selected to enter the MDS. When the correlation coefficient among indicators was <0.5, all indicators can be retained.

Norm value is the comprehensive load of each index in all components. The larger Norm value is, the more soil quality information is reflected.

The calculated formula of Norm value is as follows:

$$N_{mn}=\sqrt{\sum_{m=1}^{n}u^{2}{}_{mn}\lambda_{n}} \qquad (2)$$

Where N_{mn} is the comprehensive load of the m th variable on the first n principal components whose eigenvalue is greater than 1, u_{mn} is the load of the m th variable on the n th principal component; λ_n is the n th principal component eigenvalue.

SQI evaluation method

In this study, two linear models were employed to convert the measured values of soil indicators into values of 0 to 1, and two linear models were obtained by the following formulas.

$$S_L=\frac{x-l}{h-l} \qquad (3)$$

$$S_L=1-\frac{x-l}{h-l} \qquad (4)$$

Where S_L is the linear model score (0~1), x is the measured value of soil indicator, h is the maximum measured value of soil indicator, l is the minimum measured value of soil indicator.

The measured values of soil indicators are converted to 0~1 scores by nonlinear model. When soil indexes have a positive effect on soil fertility, the slope is 2.5; otherwise, the slope is -2.5. The nonlinear model is as follows:

$$S_{NL}=\frac{b}{1+\left(\frac{x}{x_0}\right)^{c}} \qquad (5)$$

Where S_{NL} is the nonlinear model score (0~1), b is the highest score, x is the measured value of soil indicator, e is the average value of soil indicator, and *c* is the slope of the equation.

The SQI of MDS and TDS were calculated according to equation 6.

$$SQI = \sum_{i=1}^{a} \omega_i S_i \qquad (6)$$

Where SQI is the soil quality indicator, ω_i is the weight of the i th indicator, and the weight of each indicator is equal to the ratio of the common factor variance of the corresponding indicator to the sum of the common factor variance of all indicators, S_i is the score of the i indicator, and a is the indicator number.

Statistical Analysis

the original data was processed using Excel 2013, a One-way ANOVA and Duncan's multiple comparison in SPSS27.0 software were employed to analyze the significance of differences in soil physicochemical and microbial indicators under different water and fertilizer treatments, the factor analysis in SPSS27.0 software was used to screen the minimum data set, Mantel analysis between microbial Alpha diversity indexes and soil physicochemical indicators was obtained by R language, and FAPROTAX function prediction of bacterial communities under different water and fertilizer treatments was obtained using the Lingbo Microclass online analysis (http://www.cloud.biomicroclass.com/CloudPlatform). In different water and fertilizer treatments, the difference diagram of soil quality evaluation index was got by Origin Pro, the composition percentage accumulation figure and the FAPROTAX function percentage accumulation figure in bacteria community were obtained by Chiplot online platform (https://www.chiplot.online), the Upset Wayne figure of bacterial community by OmicStudio online analysis platform (https://www.omicstudio.cn/tool.), the correlation network heat map of soil physicochemical properties with microbiological indicators was got by R language ggplot2, and the pyramid figure of soil quality interaction and a lollipop figure of yield were obtained by Genescloud online platform (https://www.genescloud.cn/home).

Results and analysis

Differences in soil quality evaluation indicators of Panax notoginseng under different water and fertilizer treatments

Fig. 2 shows the differences in soil physicochemical and microbial indicators of Panax notoginseng under different water and fertilizer treatments in each year. The values of SOM, TN, NH_4-N, NO_3-N, TP, AP, TK, AK, and SMC of each water and fertilizer treatment in 2018-2019, 2019-2021, and the 2020-2021 are significantly higher than CK(P<0.05). In three years, the SOM content increases by 0.75~7.00 times, the TN content increases by 0.14~1.25 times, the NH_4-N content increases by 0.67~2.29 times, the NO_3-N content increases by 0.20~1.62 times, the TP content increases by 0.31~2.90 times, the AP content increases by 0.48~3.36 times, the TK content increases by 0.24~1.04 times, the AK content increases by 0.23~1.44 times, and the SMC increases by 0.61~18.27% (Fig. 2a, 2b, 2c, 2d, 2e, 2f, 2g, 2h, 2j). The pH of CK in 2018-2019 was significantly higher compared to the W1F1, W1F2, W2F1, W2F2, W2F4, W3F1, and W3F3 treatments(P<0.05), and the pH of CK in 2019-2020 and the 2020-2021 was significantly higher than each water and fertilizer treatment (Fig. 2i). Furthermore, the microbial indicators under different water and fertilizer treatments had significant difference (P<0.05, Fig. 2k, 2l, 2m), Where Shannon index under the W3F1treatment in 2020-2021year had the smallest value, but Simpson index was the largest.

In conclusion, there were obvious differences in soil physicochemical and biological indicators in Panax notoginseng under different water and fertilizer treatments in each year. In addition to soil pH, each water and fertilizer treatment significantly increased the values of soil positive indicators in Panax notoginseng compared with CK in each year.

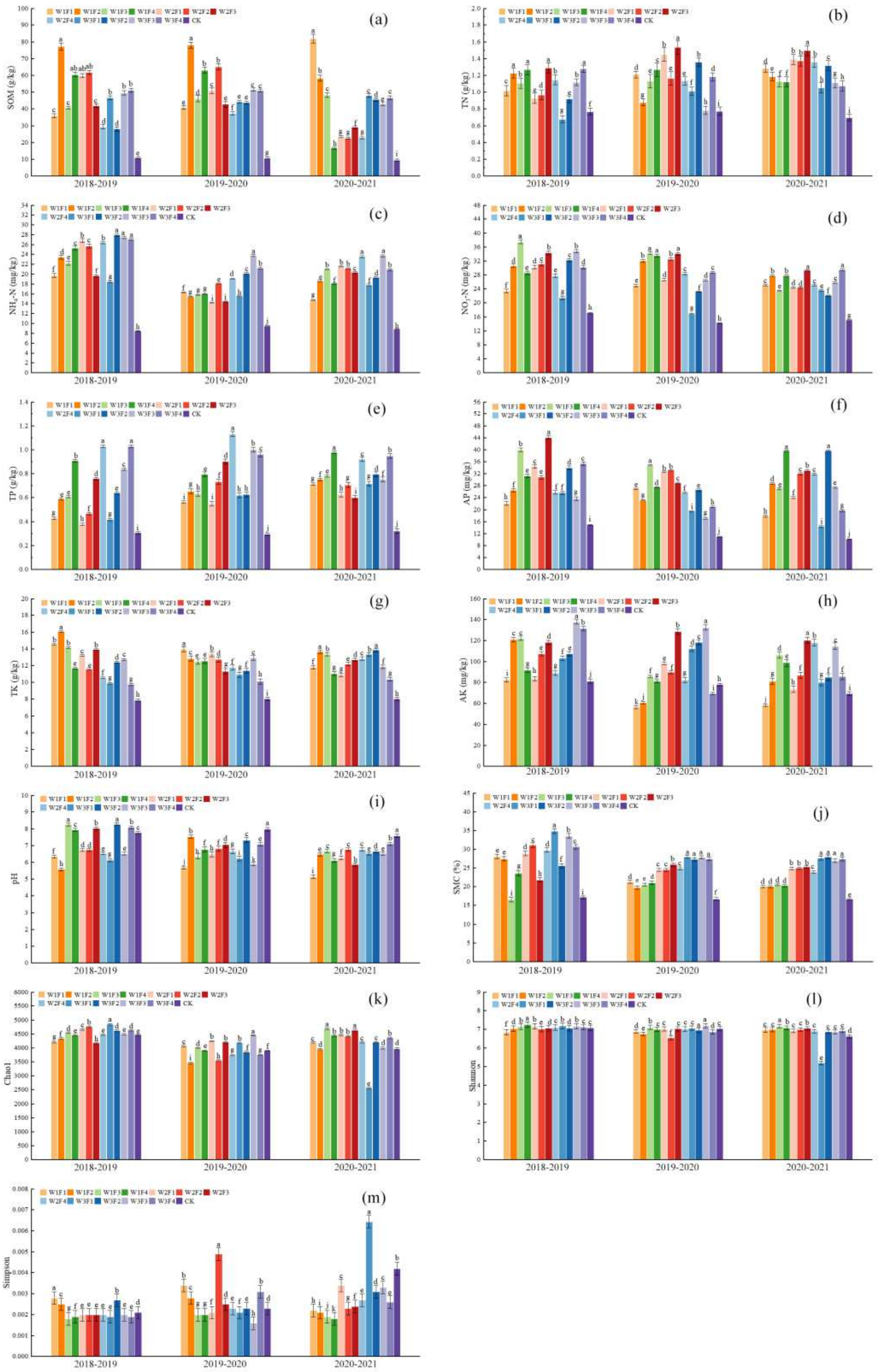

Fig. 2 Differences in soil quality evaluation indicators under different water and fertilizer treatments

Note: SOM represents organic matter, TN represents total nitrogen, NH_4-N represents ammonium nitrogen, NO_3-N represents hydrolyzed nitrogen, TP represents total phosphorus, AP represents available phosphorus, TK represents total potassium, AK represents available potassium, and SMC represents soil moisture content. different lowercase letters represent the different water and fertilizer treatments have significant differences ($P<0.05$), and the error bar is represented by standard deviation.

Effects of different water and fertilizer treatments on soil bacterial community in Panax notoginseng

Fig. 3 reflects the soil bacteria of Panax notoginseng under single irrigation, fertilization and different water and fertilizer treatments. In 2018-2019, the soil bacterial communities of the W series irrigation and CK belong to 33 phyla, the soil bacterial communities in the F fertilization series and CK belong to 31 phyla, and the soil bacterial communities in all irrigation and fertilization treatments and CK belong to 26 phyla (Fig. 3a). In 2019-2020, the soil bacterial communities in the W series irrigation and CK belong to 33 phyla, the soil bacterial communities in the F fertilization series and CK belong to 31 phyla, and the soil bacterial communities in all irrigation and fertilization treatments and CK belong to 25 phyla (Fig. 3b). In 2020-2021, the soil bacterial communities of W series irrigation and CK belong to 24 phyla, the soil bacterial communities in F fertilization series and CK belong to 24 phyla, and the soil bacterial communities in all irrigation and fertilization treatments and CK belong to 19 phyla (Figure 3c). The results show that the similarity of soil bacterial phylum under the coupling of water and fertilizer was smaller than that under single fertilization or irrigation. In addition, the similarity of soil bacterial phylum under the water and fertilizer treatment, single fertilization, and single irrigation also decreased with the increase of planting years in Panax notoginseng.

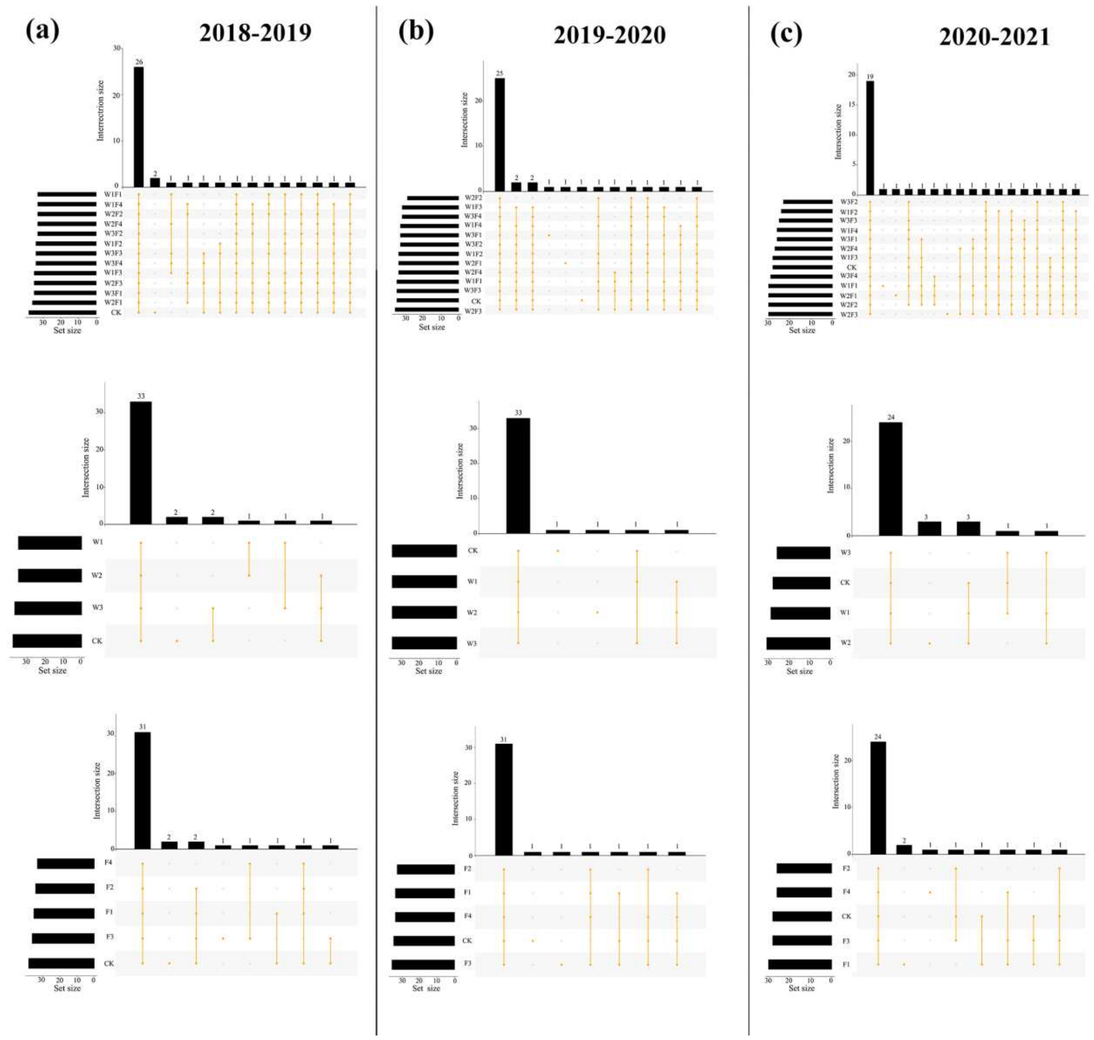

Fig. 3 Upset Wayne diagram of soil bacterial community under irrigation, fertilization, and the coupling water and fertilizer (phylum level)

Fig. 4 shows the composition of soil bacterial community in Panax Notoginseng under different water and fertilizer treatment levels. In 2018-2019, the relative abundance of 10 phyla soil bacterial under each water and fertilizer treatment and CK is greater than 1.00%, and their relative abundance accounts for 93.77%-95.55% of all phyla. In 2019-2020, the relative abundance of 11 phyla soil bacterial under each water and fertilizer treatment is greater than 1.00%, and their relative abundance are 94.28%-96.72% of all phyla. In 2020-2021, the relative abundance of 8 phyla soil bacterial under each water and fertilizer treatment is greater than 1.00%, and their relative abundance accounts for 91.06%-97.92% of all phyla. The relative abundance in the dominant Acidobacteriota, Actinobacteriota, Chloroflexi, and Proteobacteria are 8.12%-

30.23%, 11.55%-30.83% and 6.55%-15.58%, 23.79%-39.64% in 2018-2019, respectively, and the relative abundance of Acidobacteriota in CK, Actinobacteriota and Chloroflexi in the W3F2 treatment, and Proteobacteria in the W3F4 treatment is the highest (Fig. 4a). The relative abundance in the dominant Acidobacteriota, Actinobacteriota, Chloroflexi, and Proteobacteria are 10.54%-22.39%, 19.71%-28.44%, 8.71%-15.87%, and 23.91%-31.87% in 2019-2020, respectively, and the relative abundance of Acidobacteriota in the W3F1 treatment, Actinobacteriota in the W2F3 treatment, Chloroflexi in the W2F2 treatment, and Proteobacteria in the W1F3 treatment is the highest (Fig. 4b). The relative abundance in the dominant Acidobacteria, Actinobacteria, Chloroflexi, and Proteobacteria are 17.42%-23.12%, 10.81%-24.59%, 5.67%-24.30%, and 28.59%-64.91% in 2020-2021, respectively, and the relative abundance of Acidobacteriota in the W1F2 treatment, Actinobacteriota in the W3F2, treatment and Proteobacteria in the W3F1 treatment is significantly higher than CK (Fig. 4c). To sum up, the Acidobacteriota, Actinobacteriota, Chloroflexi, and Proteobacteria are dominant bacteria in each water and fertilizer treatment during three years, and the coupling of water and fertilizercan increase or decrease the relative abundance of dominant bacteria phylum.

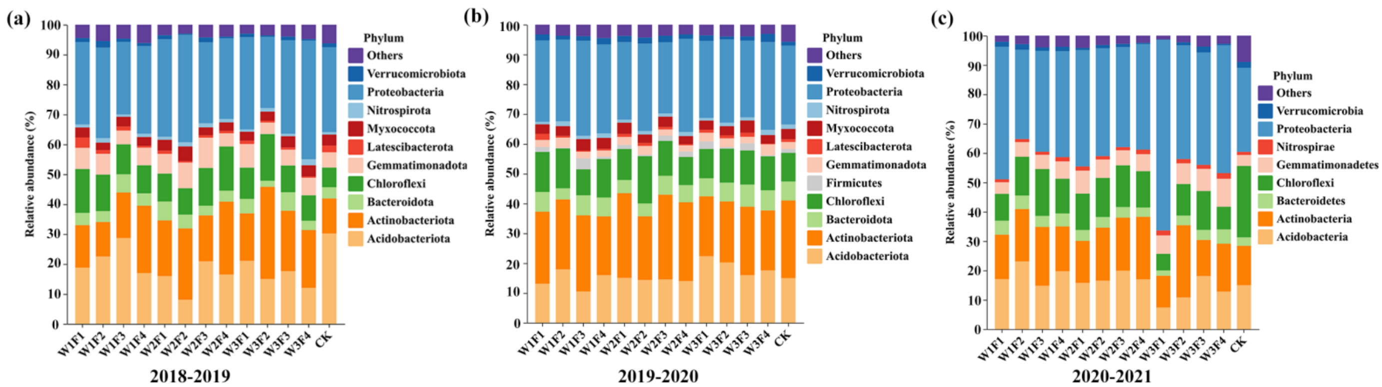

Fig. 4 Composition of soil bacterial community in Panax Notoginseng with different water and fertilizer treatments (phylum level)

LEFSE analysis is employed to confirm the soil bacteria phyla in Panax notoginseng show significant differences in irrigation and fertilization levels (Fig. 5). When the LDA score of a soil bacteria phylum exceeds 2.0, it is considered that there is a significant difference in the level of irrigation and fertilization. The Latescibacterota under the F1 treatment has significant differences in 2018-2019, (Fig. 5a). The Acidobacteriota in the level of W3 has a significant difference, the Verrucomicrobiota in the level of F4 has a significant difference, and Firmicutes in the level of F3 has a significant difference in 2019-2020 (Fig 5b). The Acidobacteriota and Verrucomicrobia in the level of W1 have a significant difference, while the Unclassified phylum in the level of F2 has a significant difference in 2020-2021 (Fig. 5c). Therefore, there was a significant difference in the performance of irrigation and fertilization treatment in the three years, and the main bacteria phyla include Latescibacterota, Acidobacteriota, Firmicutes, and Verrucomicrobia.

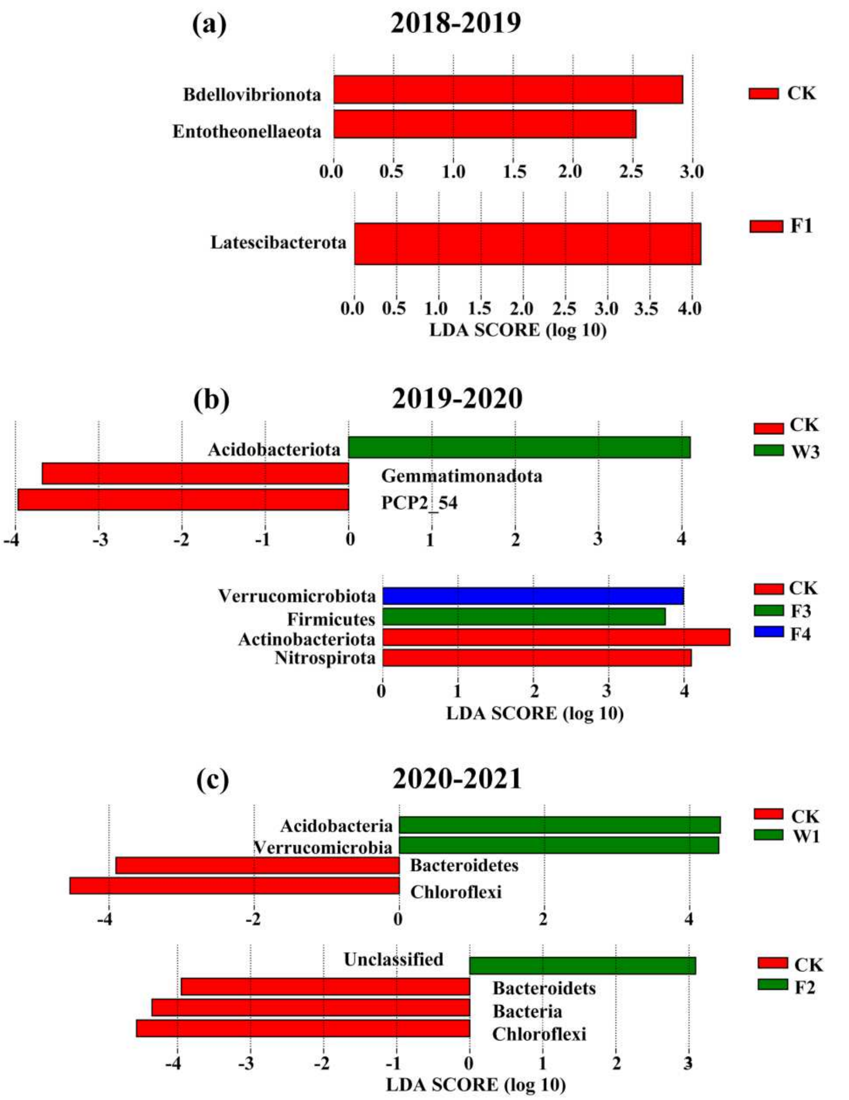

Fig. 5 Difference analysis of LEFSE of soil bacteria in Panax notoginseng after irrigation and fertilization

Fig. 6 demonstrates FAPROTAX analysis is used to predict the function of soil bacterial community in Panax notoginseng under different water and fertilizer treatments (Fig.5)., there are 7 bacterial functional relative abundances greater than 1%, and the functional relative abundance in nitrogen_fixation, the human_pathogens_pneumonia, human_pathogens_all, and animal_parasites_or_symbionts under the W1F2, W3F1, and W3F3 treatments compare to CK is significantly higher in 2018-2019 (Figure 6a). In 2019-2020, there are 9 bacterial functional relative abundances greater than 1%, and the functional relative abundance in nitrogen_fixation and aerobic_chemoheterotrophy, nitrate_reduction, and chemoheterotrophy under the W2F3, W3F1, and W3F3 treatments is significantly higher than CK (Fig. 6b). From 2020 to 2021, the 11 bacteria functional relative abundances are greater than 1%, and bacteria functional relative in handling aerobic_ammonia_oxidation and nitrification under the W2F3, W3F2, W3F3 treatments is significantly greater than that of CK, and the relative abundance of nitrogen_fixation and aerobic_chemoheterotrophy in the W3F2 and W3F3 treatments was significantly higher than that in CK (Fig. 6c). The data show that the functional metabolic potential of soil bacteria under the W1F2, W3F1, and W3F3 treatments in 2018-2019, the W2F3, W3F1 and, W3F3 treatments in 2019-2020, and the W2F3, W2F3, W3F2, and W3F3 treatments in 2020-2021 are higher than CK. In addition, with the increase of planting years of Panax notoginseng, the soil bacteria of Panax Notoginseng were more functional.

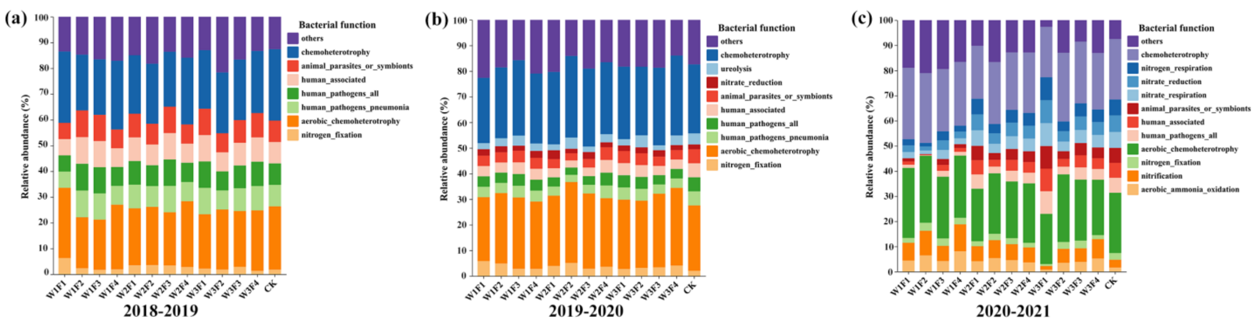

Fig. 6 Relative abundance of bacterial community function based on FAPROTAX under different water and fertilizer treatments

Determining the MDS

To eliminate the information overlap caused by too many indicators, the principal component analysis of 13 indicators was carried out. The results of principal component analysis and Norm values of each index are shown in Table 1. The first 3 PC eigenvalues of 2018-2019, and the first 4 PC eigenvalues of 2019-2020 and 2020-2021 are all>1. The cumulative variance in 2018-2019 is 66.865%, and the cumulative variance in 2019-2020 and 2020-2021 are 70.762% and 75.238%, respectively, indicating that they can represent most of the information of soil quality. In Table 1, the absolute value of the indicator load of each component is higher than 0.5, and no absolute value of the indicator load is greater than 0.5 in many components. Thus, we obtain the primary indicator according to the range in maximum Norm value of 10%. In 2018-2019, the primary indexes of the first group are TN, NH_4-N, NO3-N, NO_3-N, AP, and AK, the second group has Chao1 and Shannon, and the third group has pH and SMC. In 2019-2020, the primary indicators of the first group have NO_3-N, AP, and AK, the second group has Chao1 and Shannon, and the third group has pH and SMC. In 2020-2021, the primary indicators of the first group are TN, NH_4-N, NO_3-N, NO3-N, TP, AP, and AK, the second group has Chao1, Shannon, and Simpson, and the third group has pH and SMC. We further screened MDS based on the correlation analysis (Fig. 7). In 2018-2019, TN has the largest Norm value and the correlation coefficient with AP is less than 0.5. So TN and AP are selected into MDS. The correlation coefficient between Shannon and Chao1 in the second group is significantly close to 0.5. However, Shannon has the highest Norm value, it is chosen to MDS. the Norm value of pH in the third group is largest, but SMC is significantly negatively correlated with pH, and pH is selected as MDS. In a similar way, The MDS indicators in 2019-2020 have NO_3-N, AK, Shannon, pH, SMC, and TK, and the MDS indicators in 2020-2021 have AK, NH_4-N, Shannon, pH, SMC, and SOM. In sum up, the MDS indicators of soil quality evaluation in three years are Shannon and pH, and SMC is also selected as MDS in the last two years. The annual index screening filter is more than 50% larger, which can effectively simplify the evaluation index system.

Table 1 Load matrix and Norm values of each index

Year	Indicator	PC1	PC2	PC3	PC4	Group	Norm
2018-2019	TN	0.819	-0.197	-0.071		1	**1.728**
	NH4-N	0.727	0.106	0.394		1	1.615
	NO3-N	0.829	-0.031	0.012		1	1.720
	TP	0.785	0.147	-0.035		1	1.644
	AP	0.754	0.060	-0.162		1	**1.583**
	AK	0.750	-0.002	0.042		1	1.556
	TK	0.598	-0.456	0.257		1	1.517
	Chao1	-0.130	0.764	0.283		2	1.280
	Shannon	0.172	0.858	-0.063		2	**1.382**
	Simpson	-0.173	-0.816	0.160		2	1.336
	SOM	0.274	0.058	0.633		3	1.0601
	pH	0.378	0.200	-0.732		3	**1.332**
	SMC	-0.118	0.205	0.825		3	1.229
	Eigenvalues	4.299	2.410	1.983			
	Variance %	33.072	18.541	15.252			
	cumulative variance %	33.072	51.613	66.865			
2019-2020	TN	0.688	0.124	-0.306	-0.035	1	1.338
	NH4-N	0.562	0.270	0.460	-0.218	1	1.300
	NO3-N	0.821	-0.06	-0.131	0.249	1	**1.538**
	TP	0.587	0.298	0.389	-0.229	1	1.317
	AP	0.745	0.014	-0.297	0.132	1	1.424
	AK	0.534	0.495	-0.352	-0.161	1	**1.395**
	Chao1	-0.164	0.861	-0.007	0.204	2	1.521
	Shannon	-0.294	0.888	-0.203	0.155	2	**1.643**
	Simpson	0.265	-0.782	0.252	-0.191	2	1.476
	pH	0.394	-0.227	-0.664	-0.276	3	**1.234**
	SMC	0.276	0.475	0.568	-0.415	3	**1.295**
	TK	0.415	0.0350	0.304	0.650	4	**1.114**
	SOM	0.325	-0.273	0.282	0.455		0.977
	Eigenvalues	3.342	2.931	1.727	1.187		
	Variance %	25.706	22.548	13.285	9.134		
	cumulative variance %	25.706	48.254	61.538	70.672		
2020-2021	TN	0.706	0.014	0.355	0.125	1	1.523
	NH4-N	0.672	0.180	0.327	-0.331	1	**1.515**
	NO3-N	0.760	0.208	-0.139	0.095	1	1.623
	TP	0.773	0.248	-0.167	0.016	1	1.666
	AP	0.737	-0.119	0.116	-0.130	1	1.550
	TK	0.515	0.354	0.071	0.391	1	1.301
	AK	0.772	0.221	-0.349	-0.136	1	**1.697**
	Chao1	0.421	-0.86	0.121	-0.041	2	1.7357
	Shannon	0.421	-0.869	0.076	0.062	2	**1.7467**
	Simpson	-0.313	0.901	0.046	-0.102	2	1.6987
	pH	0.482	0.279	-0.641	-0.137	3	**1.343**

SMC	0.191	0.504	0.687	-0.269	3	**1.281**
SOM	0.148	0.230	0.144	0.845	4	**1.048**
Eigenvalues	4.273	3.018	1.347	1.143		
Variance %	32.871	23.216	10.361	8.789		
cumulative variance %	32.871	56.087	66.448	75.238		

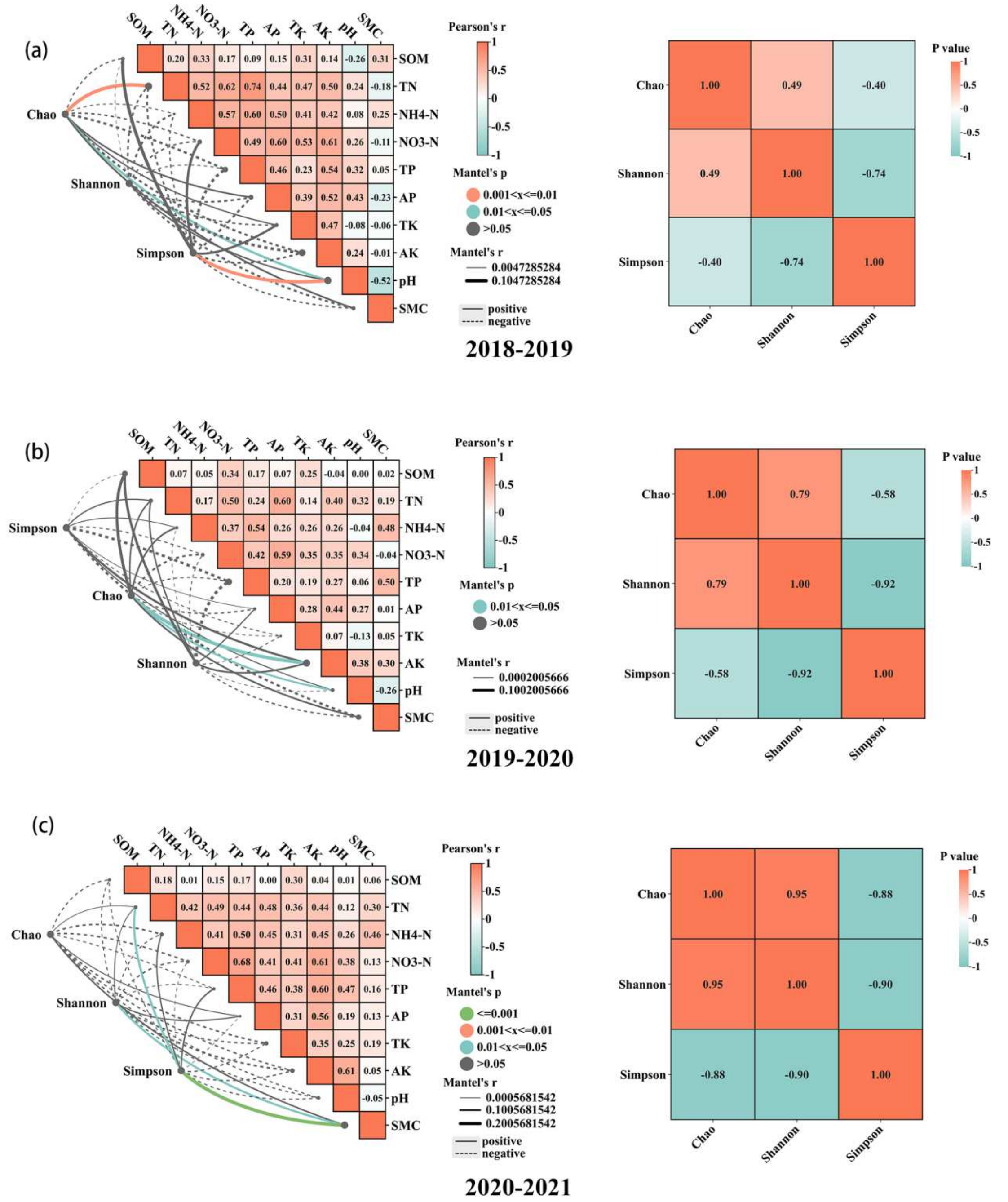

Fig. 7 Correlation relationship between soil evaluation indicators

Indicators Weight

The weights of TDS and MDS were calculated using common factor variance (Table 2). From 2018 to 2019, the weight of Shannon in MDS is 0.306, and the weight of pH, AP, and SMC are all above 0.200. In 2019-

2020, the weights of AK and pH rank first and second, while the weights of TK, NO3-N, SMC, and Shannon rank last four. The weight of SMC, NH4-N, and Shannon in 2020-2021 is 0.204, 0.198, and 0.195, respectively, and SOM has the least weight in MDS. It can be seen from the above that both Shannon and pH in the past three years have effects on the soil quality of Panax Notoginseng, indicating that bacterial diversity and soil pH play an important role in the long-term stability of soil quality.

Table 2 Common factor variance and weight of TDS and MDS

Year	Indicator	TDS common factor variance	Weight	MDS common factor variance	Weight
	SOM	0.479	0.055		
	TN	0.715	0.082	0.659	0.234
	NH4-N	0.696	0.080		
	NO3-N	0.688	0.079		
	TP	0.639	0.073		
	AP	0.599	0.069	0.706	0.251
2018-2019	TK	0.686	0.079		
	AK	0.564	0.065		
	pH	0.719	0.083	0.589	0.209
	SMC	0.737	0.085		
	Chao1	0.682	0.078		
	Shannon	0.770	0.089	0.860	0.306
	Simpson	0.721	0.083		
	SOM	0.467	0.051		
	TN	0.583	0.063		
	NH4-N	0.648	0.071		
	NO3-N	0.758	0.0825	0.749	0.169
	TP	0.637	0.069		
	AP	0.661	0.0719		
2019-2020	TK	0.689	0.0750	0.774	0.174
	AK	0.691	0.0752	0.871	0.196
	pH	0.724	0.079	0.85	0.192
	SMC	0.797	0.087	0.608	0.137
	Chao1	0.81	0.088		
	Shannon	0.941	0.102	0.584	0.132
	Simpson	0.782	0.085		
	SOM	0.809	0.083	0.131	0.030
2020-2021	TN	0.639	0.065		
	NH4-N	0.701	0.072	0.869	0.198
	NO3-N	0.649	0.066		

TP	0.687	0.070		
AP	0.588	0.060		
TK	0.549	0.056		
AK	0.785	0.080	0.808	0.184
pH	0.74	0.0757	0.829	0.189
SMC	0.834	0.085	0.895	0.204
Chao1	0.934	0.096		
Shannon	0.942	0.096	0.858	0.195
Simpson	0.923	0.094		

SQI-MDS confirmation

Generally, the total data set can obtain high accuracy for soil quality evaluation, but there are many indicators, which is easy to make the experiment complicated and time-consuming. Therefore, it is necessary to establish the minimum data set to simplify the evaluation index and ensure the reliability. The linear and nonlinear scoring methods are used to evaluate SQI-TDS and SQI-MDS, the determination coefficients between SQI-MDS and SQI-TDS of the nonlinear models in 2018-2019, 2019-2020, and 2020-2021 are 0.779, 0.746, and 0.767, respectively, and the determination coefficients between SQI-MDS and SQI-TDS of the linear model are 0.600, 0.702 ,and 0.619, respectively, indicating that the fitting accuracy of SQI-MDS and SQI-TDS under the nonlinear model is high (Fig. 8a, 8b, 8c). Therefore, SQI-MDS-NL can better evaluate the soil quality in Panax Notoginseng.

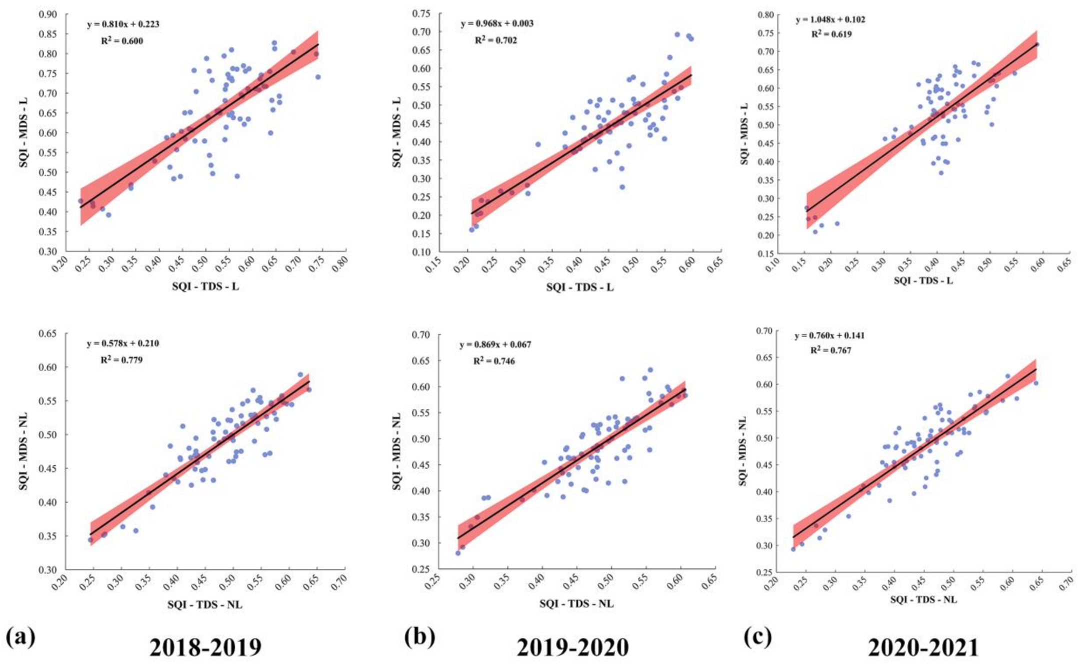

Fig. 8 Comparison between SQI-TDS and SQI-MDS under linear and nonlinear models

Note: SQI-MDS-NL indicates soil quality index of minimum data set under linear model, and SQI-MDS-NL indicates soil quality index of minimum data set under nonlinear model.

Soil quality and yield of Panax Notoginseng under different water and fertilizer treatments

Fig. 9 shows the SQI-TDS and SQI-MDS-NL of Panax Notoginseng under different water and fertilizer regimes. In 2018-2019, the top three SQI-TDS are W3F1, W3F3, and W1F2, while the top three SQI-MDS-NL are contrary it. In 2019-2020, the top three SQI-TDS are W3F3, W3F1, and W2F3, and the top three SQI-MDS-NL are W3F3, W2F3, and W3F1. The top three SQI-TDS and SQI-MDS-NL in 2020-2021 are W3F3, W2F3, and W3F2, respectively. In short, the top three water and fertilizer treatments of SQI-TDS and SQI-MDS-NL are the same in each year, and the W3F3 treatment has been in the top three.

Yield is an important index to measure soil fertility, and the yield of Panax Notoginseng in each water and fertilizer treatment is greater than CK (Fig. 10). From 2018 to 2019, W1F2>W3F3>W3F1 are the first three outputs in Panax Notoginseng under different water and fertilizer regimes, which are 1.78 times, 1.63 times, and 1.40 times higher than CK, respectively. In 2019-2020, W3F3>W2F3>W2F1>W3F1 are the top four outputs in Panax Notoginseng under different water and fertilizer treatments, respectively, which increase by 1.29 times, 1.20 times, 1.16 times, and 1.13 times compared with CK. In 2020-2021, W3F3>W2F3>W3F2 are the top three outputs in Panax Notoginseng under different water and fertilizer treatments, which are 0.95 times, 0.88 times, and 0.81 times higher than CK, respectively.

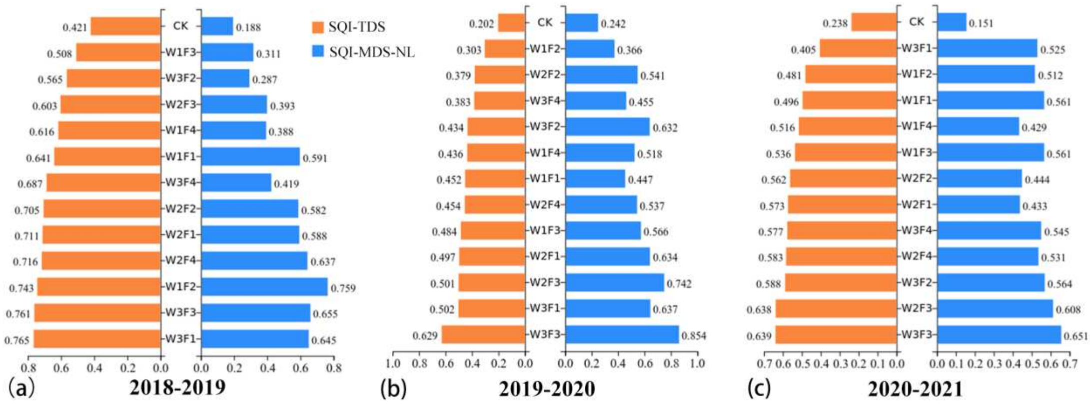

Fig. 9 Soil quality of Panax Notoginseng under different water and fertilizer regimes

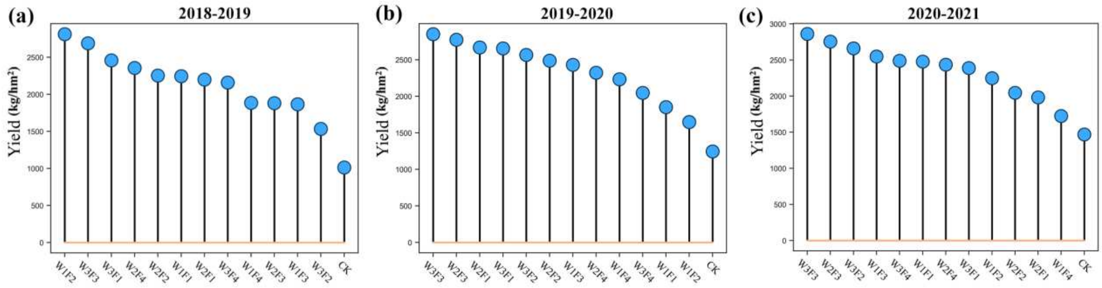

Fig. 10 Yield of Panax Notoginseng under different water and fertilizer regimes

Discussion

Soil quality evaluation indicators under different water and fertilizer treatments

Water and fertilizer are two single factors that affect soil fertility, and their interaction causes significant differences in soil nutrients. Shen et al. (2014) explored the effects of different water and fertilizer schemes on soil physicochemical properties, microbial community structure and function in Panax Notoginseng, and found that there were significant differences in soil physicochemical properties under different water and fertilizer treatments. Yang et al. (2023) studied the effects of water-fertilizer coupling on the ecological environment and yield of muskmelon and found that under the same fertilization level, soil nitrate nitrogen and available phosphorus contents showed an increased trend followed by decreased trend with the increase of irrigation, while available potassium showed an increasing trend. Cheng et al. (2024) set different irrigation and nitrogen fertilizer levels, and found that there were significant differences in the response of organic matter and nitrate nitrogen to the coupled combination of water and fertilizer. Wang et al. (2018) demonstrated that different irrigation and nitrogen, phosphorus, and potassium ratio fertilizers had significantly different effects on soil chemical properties and cotton yield. In this study, there were significant differences in soil physicochemical indicators in Panax Notoginseng under different water and fertilizer treatments in three years. Soil acidification in China is often caused by nitrogen input (Zhu et al., 2018), Shi et al. (2022) found that long-term application of organic fertilizer can reduce soil pH. In this study, the soil pH value in Panax Notoginseng under the W3F1 treatment in three years was lower than CK. This is due to the fact the large nitrogen content of organic fertilizer applied in W3F1 treatment, the nitrate formed by nitrogen fertilizer under leaching would take away the soil calcium and magnesium plasma, resulting in the weakening of soil pH. Soil microbial diversity plays an important role in improving soil health and ecological function (Chou et al., 2024; Zhou et al., 2024). In this study, the positive index values in soil nutrient under W3F1 treatment were lower than CK, and the available substrate of bacteria decreased, resulting in a lower Shanno index in bacteria. In addition, in this study, there were differences in the bacterial Alpha diversity index under different water and fertilizer conditions, which is because physical and chemical processes are indispensable for soil formation (Mcbratney et al., 2024). Soil physicochemical properties differences under different water and fertilizer conditions led to differences in soil microorganisms. It is often insufficient to only describe the Alpha diversity of bacterial. This study further analyzed the structure and function of soil bacterial phylum in Panax Notoginseng under the water and fertilizer treatments, and we found that the dominant bacterial phyla in the coupled water and fertilizer were Acidobacteriota, Actinobacteriota, Chloroflexi, and Proteobacteria. Wu et al. (2016) found that Actinobacteriota and Proteobacteria had the maximum relative abundance when comparing the rhizosphere bacterial structure and function of healthy and root rot Panax Notoginseng. In this study, by Lefse method, we identified soil bacteria phyla in Panax Notoginseng with significant differences in different irrigation and fertilization treatments, and the bacterota, Acidobacteriota, Firmicutes, and Verrucomicrobia had significant differences in the irrigation and fertilization treatments in the three years. Shen et al. (2024) analyzed the soil microbial structure in Panax Notoginseng under the coupled water and fertilizer under different growth stages, they demonstrated the main phyla affecting the variation of bacterial community structure and composition in irrigation and fertilization treatments were Actinobacteria, Gemmatimonadota, Proteobacteria, Nitrospirae, Acidobacteria, Chloroflexi, Verrucomicrobia, and Firmicutes. It is worth noting that the functional richness of soil bacteria in Panax Notoginseng under different water and fertilizer treatments were compared by FAPROTAX function prediction in this study, and we founded the relative abundance of function in nitrogen_fixation, human_pathogens_pneumonia, human_pathogens_all, and animal_parasites_or_symbionts in the first year and nitrogen_fixation, aerobic_chemoheterotrophy, nitrate_reduction, chemoheterotrophy, aerobic_ammonia_oxidation, and nitrification in the last two years was significantly higher than CK. Furthermore, with the increase of planting years, soil bacterial community function in Panax Notoginseng under W3F3 treatments was more abundant. This indicated that the proper water and fertilizer treatments could change the harmful function to the beneficial function of the soil bacteria community in Panax Notoginseng, and the longer the stage stayed in the soil, the functional richness of soil bacteria also increased.

Soil quality under different water and fertilizer treatments

Soil is an extremely complex and variable system, and soil quality plays an important role in maintaining environmental quality and animal and plant health, often reflecting soil quality through the integration of chemical, physical, and biological processes (Zhang et al., 2021; Valani et al., 2020). Many scholars evaluate soil quality through comprehensive evaluation index system covering physical, chemical, and biological factors (Yu et al., 2023; Marion et al., 2022). The TDS can evaluate soil quality information more comprehensively, but too many indicators lead to overlapping soil quality information and increase the time and cost (Teng et al., 2024). In this study, principal component, Norm value and combined correlation analysis were used to screen MDS, which is widely used in soil quality evaluation by reducing collinearity between indexes and retaining a large amount of soil quality information. We found the MDS indicators of soil quality evaluation in Panax Notoginseng in 2018-2019 included TN, AP, Shannon, and pH; in 2019-2020, there are NO_3-N, AK, Shannon, pH, SMC, and TK; in 2020-2021, there are AK, NH4-N, Shannon, pH, SMC, and SOM. The results showed that there were no soil physical indicators in the first year of MDS, but there were soil physical, chemical, and biological indexes in the second two years of MDS. The reason is that soil SMC and soil pH of Panax Notoginseng in the first year showed a significant negative correlation and the correlation degree was higher, and the pH can respond to soil quality information better, so soil SMC was excluded. Biological indicators react rapidly to the environment and are widely concerned (Chen et al., 2022), Tuo et al. (2024) Select the optimal water and fertilizer scheme based on soil microbial carbon and nitrogen and enzyme activities for Panax Notoginseng cultivation and recommend W3F4 treatment as the optimal water and fertilizer regime. However, soil quality information cannot be accurately reflected by biological indicators alone. Yu et al. (2023) established MDS with unstable carbon components, TK, sediment content, and Shanno index to accurately evaluate soil quality after afforestation in southwest China. In this study, bacterial Alpha index was used as the biological index, and bacterial Shanno index was selected as the soil MDS in Panax Notoginseng under different water and fertilizer. Moreover, based on soil quality index method, the comprehensive evaluation of soil quality in Panax Notoginseng under different water and fertilizer treatments showed that the fitting effect of SQI-MDS-NL, SQI-MDS-L and SQI-TDS was good, but SQI-MDS-NL was better. This is consistent with the conclusion of Teng et al. (2024) that the best model for soil quality assessment in tobacco was SQI-MDS-NL. The SQI-MDS evaluation under different water and fertilizer treatments was only carried out in this study area. However, its applicability in different study areas requires more research.

conclusions

In this study, water and fertilizer treatment led to differences in soil physicochemical indexes of Panax Notoginseng, and which further affected the structure and function of soil bacteria in Panax Notoginseng, resulting in significant differences in overall soil quality. The MDS indicators of soil quality evaluation in 2018-2019 included TN, AP, Shannon, and pH, the 2019-2020 were NO_3-N, AK, Shannon, pH, SMC, and TK, and the 2020-2021 were AK, NH_4-N, Shannon, pH, SMC, and SOM. The SQI-MDS-NL better represented soil quality information than SQI-MDS-L. By evaluating soil quality under different water and fertilizer treatments in Panax Notoginseng based on SQI-MDS-NL, the top three soil quality in Panax Notoginseng in 2018-2019 were W3F1, W3F3, and W1F2; The top three in 2019-2020 were W3F3, W3F1, and W2F3, and the top three in 2020-2021 were W3F3, W2F3, and W3F2, where W3F3 treatment has been in the top three, and the corresponding output of W3F3 treatment was also in the forefront. Thus, W3F3 regime should be recommended first in the long-term planting of local Panax Notoginseng.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Arshad M.A., Martin S., 2002. Identifying critical limits for soil quality indicators in agro-ecosystems. Agriculture, Ecosystems & Environment. 88(2): 153-160.

Adebo B.O., Aweto A.O., Ogedengbe K., 2020. Assessment of Soil Quality under Different Agricultural Land Use Systems:

A Case Study of the Ibadan Farm Settlement. International Journal of Plant & Soil Science. 05: 89-104.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen-Total. In: Page, A.L. (Ed.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy, Soil Science Society of America. E-Publish Inc., New York, 595–624.

Chen S., Zhang S., Li H., 2024. Optimizing irrigation and nitrogen management improves soil soluble nitrogen pools and reduces nitrate residues in a drip-fertigated apple orchard on the Loess Plateau. Agricultural Water Management. 295: 108770.

Chou M.Y., Pavlou D., Rice P.J., 2024. Microbial diversity and soil health parameters associated with turfgrass landscapes. Applied Soil Ecology. 196: 105311.

Chen T., Jiao J., Zhang Z., 2022. Soil quality evaluation of the alluvial fan in the Lhasa River Basin, Qinghai-Tibet Plateau. CATENA. 209: 105829.

Davari M., Gholami L., Nabiollahi K., 2020. Deforestation and cultivation of sparse forest impacts on soil quality (case study: West Iran, Baneh). Soil and Tillage Research. 198: 104504.

Guggenberger G., Kaiser K., 2003. Dissolved organic matter in soil: challenging the paradigm of sorptive preservation. Geoderma. 113(3-4): 293-310.

Hussain I., Olson K.R., Wander M.M., 1999. Adaptation of soil quality indices and application to three tillage systems in southern Illinois. Soil and Tillage Research. 50(3): 237-249.

Jin H., Shi D., Lou Y B., 2021. Evaluation of the quality of cultivated-layer soil based on different degrees of erosion in sloping farmland with purple soil in China. CATENA. 198: 105048.

Kahsay A., Haile M., Gebresamuel G., 2023. Assessing land use type impacts on soil quality: Application of multivariate statistical and expert opinion-followed indicator screening approaches. CATENA. 231: 107351.

Karlen D.L., Ditzler C.A., Andrews S.S., 2023. Soil quality: why and how? Geoderma. 114(3-4): 145-156.

Kalembasa S.J., Jenkinson D.S., 1973. A comparative study of titrimetric and gravimetric methods for the determination of organic carbon in soil. J. Sci. Food Agric. 24 (9): 1085–1090.

Liu H., Du X., Li Y., 2022. Organic substitutions improve soil quality and maize yield through increasing soil microbial diversity. Journal of Cleaner Production. 347: 131323.

Li G., Zhao B., Dong S., 2022. Controlled-release urea combining with optimal irrigation improved grain yield, nitrogen uptake, and growth of maize. Agricultural Water Management. 227: 105834.

Li Y., Liu X., Fang H., 2021. Exploring the coupling mode of irrigation method and fertilization rate for improving growth and water-fertilizer use efficiency of young mango tree. Scientia Horticulturae. 286: 110211

Li P., Shi K., Wang Y., 2019. Soil quality assessment of wheat-maize cropping system with different productivities in China: Establishing a minimum data set. Soil and Tillage Research. 190: 31-40.

Liu H., Yu X., Liu Z., 2018. Occurrence, characteristics and sources of polycyclic aromatic hydrocarbons in arable soils of Beijing, China. Ecotoxicology and Environmental Safety. 159: 120-126.

Li K., Wang C., 2023. Multiple soil quality assessment methods for evaluating effects of organic fertilization in wheat-maize rotation system. European Journal of Agronomy. 150: 126929.

Li Q., Zhang D.Q., Song Z.X., Ren L.R., Jin X., Fang W.S., 2022. Organic fertilizer activates soil beneficial microorganisms to promote strawberry growth and soil health after fumigation. Environmental Pollution. 295: 118653.

Mujtar E.V., Muñoz N., Prack M., 2019. Cormick B., Role and management of soil biodiversity for food security and nutrition; where do we stand? Global Food Security. 20: 132-144.

Ma W., Li J., Gao Y., 2020. Responses of soil extracellular enzyme activities and microbial community properties to interaction between nitrogen addition and increased precipitation in a semi-arid grassland ecosystem. Science of The Total Environment. 703: 134691.

Mukherjee A., Lal R., 2014. Comparison of Soil Quality Index Using Three Methods. Plos One. 9(8): e105981.

Masoud D., Leila G., Kamal N., Mehdi H., Hamed J.J., 2020. Deforestation and cultivation of sparse forest impacts on soil quality (case study: West Iran, Baneh). Soil and Tillage Research. 198: 104504.

Mengnan L., Xianwen Y., Shuyan Z., 2023. Homotherapy for heteropathy of Alzheimer's disease and anemia through reducing the expression of toll-like receptor and TNF by steamed Panax notoginseng. Biomedicine & Pharmacotherapy. 165: 115075.

Murphy J., Riley J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta. 27, 31–36.

Marion L.F, Schneider R., Cherubin M.R., 2022. Development of a soil quality index to evaluate agricultural cropping systems in southern Brazil. Soil and Tillage Research. 218: 105293.

Mcbratney A.B., Hartemink A.E., 2024. Define soil. Soil Security. 14: 100135.

Olsen S.R., 1954. Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate (No. 939). US Department of Agriculture, USA.

Pages A.L., Miller R.H., Dennis R.K., 1982. Methods of Soil Analysis. Part 2 Chemical Methods. Soil Science Society of America Inc., Madison.

Rezapour S., Alamdari P., Kalavrouziotis I.K., 2023. Response of soil health index to untreated wastewater irrigation in selected farms under different vegetable types. Agricultural Water Management. 290: 108592.

Shahnazari A., Pourdej H., Kharage M.D., 2021. Ranking of organic fertilizer production from solid municipal waste systems using analytic hierarchy process (AHP) and VIKOR models. Biocatalysis and Agricultural Biotechnology. 32: 101946.

Shao G., Ai J., Sun Q., 2020. Soil quality assessment under different forest types in the Mount Tai, central Eastern China. Ecological Indicators. 115: 106439.

Shen F., Fei L., Tuo Y., 2024. Effects of water and fertilizer regulation on soil physicochemical properties, bacterial diversity and community structure of Panax notoginseng. Scientia Horticulturae. 326: 112777.

Shi R., Wang S., Xiong B., 2022. Application of bioorganic fertilizer on Panax notoginseng improves plant growth by altering the rhizosphere microbiome structure and metabolism. Microorganisms. 10(2): 275.

Tang J.K., Yang Q.L., Liang J.P., Wang H.D., Yue X.L., 2024.Water management, planting slope indicators, and economic benefit analysis for Panax notoginseng production decision under shaded and rain-shelter cultivation: A three-year sloping fields experiment. Agricultural Water Management. 291: 108635.

Tuo Y.F., Wang Z., Zheng Y., 2023. Effect of water and fertilizer regulation on the soil microbial biomass carbon and nitrogen, enzyme activity, and saponin content of Panax notoginseng. Agricultural Water Management,. 278: 108145.

Thomas, G.W., 1996. Soil pH and soil acidity. Methods of soil analysis: part 3 chemical methods. 05: 475-490.

Teng L., Jiang G., Ding Z., 2024. Evaluation of tobacco-planting soil quality using multiple distinct scoring methods and soil quality indices. Journal of Cleaner Production. 441: 140883.

Tuo Y., Tan H., Liang J., 2024. Optimization of water and fertilizer management of Panax pseudoginseng based on changes in soil microbial biomass carbon and nitrogen and enzyme activities. Applied Soil Ecology. 196: 105282.

Vasu D., Tiwari G., Sahoo S., 2021. A minimum data set of soil morphological properties for quantifying soil quality in coastal agroecosystems. CATENA. 198: 105042.

Valani G.P., Vezzani F.M., Cavalieri-polizeli M.V., 2020. Soil quality: Evaluation of on-farm assessments in relation to analytical index. Soil and Tillage Research. 198: 104565.

Wang H., Cheng M., Zhang S., 2021. Optimization of irrigation amount and fertilization rate of drip-fertigated potato based on Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation methods. Agricultural Water Management. 256: 107130.

Wang N., Zhang T., Cong A., 2023. Integrated application of fertilization and reduced irrigation improved maize (Zea mays L.) yield, crop water productivity and nitrogen use efficiency in a semi-arid region. Agricultural Water Management. 289: 108566.

Wang H., Wu L., Cheng M., 2018. Coupling effects of water and fertilizer on yield, water and fertilizer use efficiency of drip-fertigated cotton in northern Xinjiang, China. Field Crops Research. 219: 169-79.

Wu Z.X., Hao Z.P., Sun, Guo Y.Q., 2016. Comparison on the structure and function of the rhizosphere microbial community between healthy and root-rot Panax notoginseng. Applied Soil Ecology. 107: 99-107.

Xue Y.J., Liu S.G., Hu Y.M., 2010. Soil Quality Assessment Using Weighted Fuzzy Association Rules. Pedosphere. 20(3): 334-341.

Yuan P., Wang J., Li C., 2020. Soil quality indicators of integrated rice-crayfish farming in the Jianghan Plain, China using a minimum data set. Soil and Tillage Research. 204: 104732.

Yang E., Zhao X., Qin W., 2023. Temporal impacts of dryland-to-paddy conversion on soil quality in the typical black soil region of China: Establishing the minimum data set. CATENA. 231: 107303.

Yang J.H., Wang C.L., Dai H.L., 2008.Soil agrochemical analysis and environmental monitoring. Beijing: China Land Press.

Yang Z., Kong T., Xie J., 2023. Appropriate water and fertilizer supply can increase yield by promoting growth while ensuring the soil ecological environment in melon production. Agricultural Water Management. 289: 108561.

Yu P., Liu J., Tang H., 2023. Establishing a soil quality index to evaluate soil quality after afforestation in a karst region of Southwest China. CATENA. 230: 107237.

Yu P., Liu J., Tang H., 2023. Establishing a soil quality index to evaluate soil quality after afforestation in a karst region of Southwest China. CATENA. 230: 107237

Zhang Y., Wang L., Jiang J., 2022. Application of soil quality index to determine the effects of different vegetation types on soil quality in the Yellow River Delta wetland. Ecological Indicators. 141: 109116.

Zhou Z., Andersen M.N., Plauborg F., 2016. Radiation interception and radiation use efficiency of potato affected by different N fertigation and irrigation regimes. European Journal of Agronomy. 81: 129-137.

Zhang Y., Xu X., Li Z., 2019. Effects of vegetation restoration on soil quality in degraded karst landscapes of southwest China. Science of The Total Environment. 650: 2657-2665.

Zhao L., Xu W., Guan H., 2022. Biochar increases Panax notoginseng's survival under continuous cropping by improving soil properties and microbial diversity. Science of The Total Environment. 850: 157990.

Zhang J.Y., Cun Z., Wu H.M., 2020. Integrated analysis on biochemical profiling and transcriptome revealed nitrogen-driven difference in accumulation of saponins in a medicinal plant Panax notoginseng. Plant Physiol. Biochem. 154: 564–580.

Zhu Q., Vries W.D., Liu X., 2018. Enhanced acidification in Chinese croplands as derived from element budgets in the period 1980-2010. Science of the Total Environment. 618: 1497-1505.

Zhou S., Chang T., Zhang Y., 2024. Organic fertilizer compost alters the microbial composition and network structure in strongly acidic soil. Applied Soil Ecology. 195: 105263.

Zhang Z., Ai N., Liu G., 2021. Soil quality evaluation of various microtopography types at different restoration modes in the loess area of Northern Shaanxi. CATENA. 207: 105633.