EVALUATION OF SOIL QUALITY AND ANALYSIS OF DRIVING FACTORS OF JUJUBE FORESTS IN THE LOESS HILLY AREAS WITH ABANDONED MOUNTAINS

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Abstract. The evolution mechanism of soil quality of abandoned montane jujube forests in loess hilly areas is still unclear. In this study, we analyzed the driving mechanism of soil quality (SQ) by using principal component analysis, fuzzy evaluation and partial least squares structural equation modeling PLS-SEM with different abandonment years (1, 6, 10, 15, and 20 years) in montane jujube forests and abandoned grasslands in Yanchuan County. The results showed that the number of years of abandonment significantly increased the soil quality index (SQI), and the 20-year abandonment of date palm forest reached the highest value (0.669), which was significantly higher than that of abandonment of grassland (0.331). The results of structural equation modeling showed that organic carbon (SOC), quick-acting phosphorus (AP), total nitrogen (TN) and urease activity (URE) positively drove the SQ, while soil water content (SWC) and pH had negative effects on it. Long-term abandonment promotes ecological recovery by improving soil nutrients and microbial enzyme activities, and provides a scientific basis for the management of degraded date palm forests in loess hilly areas.
Keywords: *loess area of northern Shaanxi, abandonment of hilly date palm forests, soil quality, driving factors, structural equation modeling*

Introduction

As the main native tree species in loess hilly area, jujube tree has become one of the most representative tree species in the ecological construction of the region and has been planted in a large area by virtue of its ecological adaptability and its role in promoting local economic development. However, with the accelerated urbanization process, the rural population continues to migrate to the city, resulting in a large area of abandonment. After the abandonment of date palm forests, their soil physicochemical properties and microbiological indicators changed significantly. Studies have shown that abandonment may have complex effects on soil quality: Yu et al. (2023) found that microbial carbon (MBC) and nitrogen (MBN) contents of alfalfa fields increased during abandonment; Lei et al. (2024) in the Weibei Dry Plateau showed that abandonment significantly increased soil C and N contents and improved microbial enzyme activities; while Li et al. (2024) in the Weibei dry plateau showed that abandonment significantly enhanced soil carbon and N contents and improved microbial enzyme activities. The study of Li et al. (2024) on rice terraces showed that abandonment significantly increased soil carbon (C) and nitrogen (N) contents and improved microbial enzyme activities. Changes in these soil indicators further affect soil quality. Since soil quality is regulated by multiple factors, it is mainly evaluated by a combination of soil physical, chemical and biological indicators (Luo et al., 2024).

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Specifically, SQ reflects the ability of soil to maintain biological productivity, protect environmental quality, and support ecological health, and is a comprehensive expression of soil multifunctionality, as well as a core indicator for assessing ecological security and resource sustainability.

Evaluation of the quality of landfill soils is of great significance to the rational utilization of land resources, ecological environmental protection and sustainable development of agriculture (Zhao et al., 2020). Currently, most studies focus on the effects of abandonment on soil properties and stoichiometric characteristics (Lv et al., 2024), but there is still a lack of systematic research on the soil quality of economic forest abandonment sites. With the promulgation and implementation of policies such as the Action Plan for the Special Improvement of Wasteland, the management of wasteland has become a key task for rural revitalization and an important support for the comprehensive revitalization of the countryside. In this study, we took the Qijiashan jujube experimental demonstration base in Yan Chuan County, Loess Hilly Area as the study area, selected mountainous jujube forests with different years of abandonment as the study object, and took grassland (PRG) with 6 years of abandonment as the control, and comprehensively evaluated the soil quality through soil physicochemical and microbiological indexes, and identified the key drivers by combining the Partial Least Squares Structural Equation Modeling (PLS-SEM). The results of the study can provide data support for the ecological restoration and sustainable management of abandoned jujube forests in the loess area of northern Shaanxi, as well as provide scientific support and technical paths for the promotion of comprehensive rural revitalization.

Materials and methods

Overview of the study area

Yanchuan County (109°36′20″-110°26′44″E, 36°37′15″-37°05′55″N) is located in the northeastern part of Yan'an City, Shaanxi Province, China, belonging to the city of Yan'an, and geographically situated in the middle reaches of the Yellow River in the eastern part of the Loess Plateau of northern Shaanxi Province, separated by the Yellow River in the east and Shanxi Province, and bordered by the city of Yulin, Shaanxi Province in the north (Zong et al., 2020). The climate belongs to the temperate continental monsoon climate, which is dry and has four distinct seasons. The topography of Yanchuan County is high in the northwest and low in the southeast, and the geomorphology mainly consists of residual loess, beams, mounts, and gullies, etc. (Zong et al., 2021). The study area is located in the Qijiashan jujube demonstration base, and the vegetation is dominated by jujube trees, while some economic forest species such as apples are also planted and distributed (*Fig. 1*).

Sample plot layout

The study group conducted field research and visited the experimental demonstration base of red jujube in Qijiashan, Yanchuan County in April-May 2019, and selected and set up five standard mountain jujube forests and abandoned grasslands of 20 m × 20 m with different abandonment years (1, 6, 10, 15 and 20 years) for sampling and investigation in accordance with the principles of typicality and representativeness, and the information of the sample plots is shown in *Table 1* (Zong et al., 2020).

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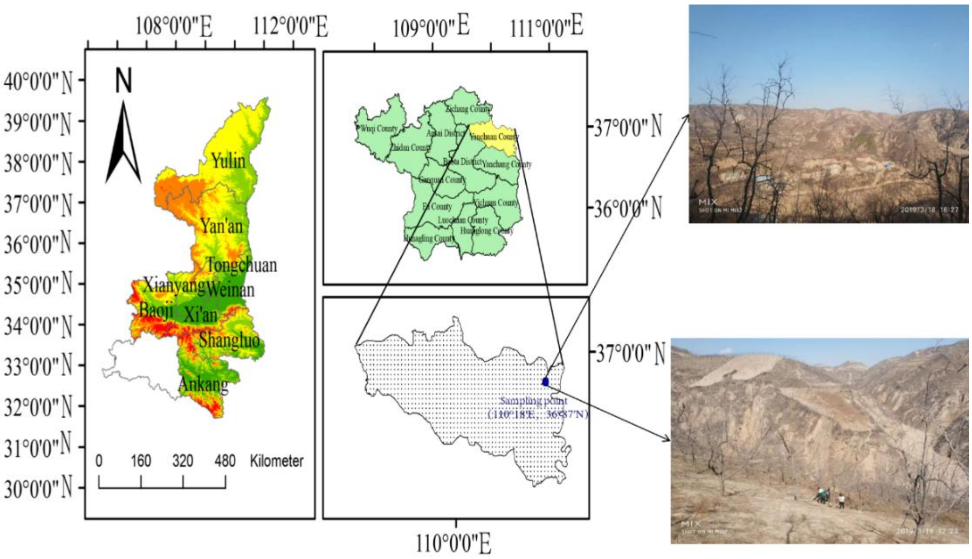

Figure 1. *Overview of the study area*

Table 1. *Sample plot information*

Serial number	Vegetation type	Elevation	Slope	Years of abandonment	Slope	Slope direction	Silvicultural density
AL1	Jujube forest	880	Downhill position	1	8	Shady slope	4×4
AL6	Jujube forest	836	Downhill position	6	15	Shady slope	4×4
AL10	Jujube forest	825	Downhill position	10	14	Shady slope	4×4
AL15	Jujube forest	812	Downhill position	15	15	Shady slope	4×4
AL20	Jujube grove	880	Downhill position	20	10	Shady slope	4×4
PRG	Grassland	860	Downhill position	6	15	Shady slopes	4×4

AL1, AL6, AL10, AL15, AL20, and PRG represent 1 year of abandonment, 6 years of abandonment, 10 years of abandonment, 15 years of abandonment, 20 years of abandonment, and grassland abandonment, respectively

Soil sample collection and index determination

According to the years of abandonment, one standard sample plot each of 20 m × 20 m was set up in August 2019 in the study area. Three 1 m-deep soil profiles were dug in each sample plot, and soil samples were taken in five layers, i.e., 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm, and three samples were taken as replicates from each layer. After soil collection, the soil was brought back to the laboratory for natural air drying, and the soil indicators were determined by soil physical property determination method and soil agrochemical analysis, and the indicator measurement methods are shown in *Tables 2* and *3*.

Soil quality evaluation methods

In this study, the soil quality index (SQI) method was used to evaluate SQ in the study area (Zhao et al., 2020). SQI is an index that can quantify the overall health and fertility of the soil, and it is widely used by many scholars to evaluate SQ. The evaluation methods are as follows:

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Selection of soil quality evaluation indicators

Based on the research results of previous researchers (Zhang et al., 2021), 15 indicators of soil physics, chemistry, and soil microorganisms in 3 categories (Liu et al., 2025) were selected as the SQ evaluation indicators of red date palm forests in mountainous areas with different abandonment years.

Calculation and evaluation of indicator weights

To avoid errors caused by subjectivity, this study used principal component analysis (PCA) to calculate the weight value (Wi) of each evaluation index (Yang et al., 2024). The common factor variance obtained by PCA reflects the degree of contribution of an indicator to the overall variance. The larger the variance of the common factor, the greater the degree of contribution to the overall variance. The weight of each evaluation indicator is determined by the ratio of the common factor variance of each indicator to the sum of all common factor variances.

Calculate the degree of affiliation of each evaluation indicator

In fuzzy comprehensive evaluation, the degree of affiliation is determined by the affiliation function associated with the evaluation indicators. The affiliation function usually includes an ascending affiliation function (*Eq. 1*) and a descending affiliation function (*Eq. 2*).

$$F(x)\begin{cases} 1.0(x \geq b) \\ \frac{0.9(x-a)}{b-a} + 0.1(a < x < b) \\ 0.1(x \leq a) \end{cases} \quad \text{(Eq.1)}$$

$$F(x)\begin{cases} 1.0(x \leq b) \\ \frac{0.9(b-x)}{b-a} + 0.1(a < x < b) \\ 0.1(x \geq a) \end{cases} \quad \text{(Eq.2)}$$

where F (x) is the affiliation value of each evaluation index, x is the measured average value of each index, a is the minimum value of each evaluation index, and b is the maximum value of each evaluation standard (Zhang et al., 2021; Luo et al., 2024).

Calculation of SQI

After obtaining the weights and affiliation degrees of each index, the weighted evaluation method was used to calculate the SQI, and the formula is as follows: the higher the value of SQI, the better the SQ of each abandonment year.

$$\text{SQI} = \sum_{i=1}^{n} Wi \times F(xi) \quad \text{(Eq.3)}$$

where SQI is the soil quality index, n is the number of evaluation indexes, Wi is the weight value of each index, xi is the value of each index, and F (xi) is the value of each index affiliation. Where BD is the descending order affiliation function, and pH is the descending order affiliation function when the soil is alkaline.

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Table 2. *Soil indicator measurement methods*

Soil indexes	Measuring method
BD	Ring knife method
pH	High precision intelligent acidity meter
maxWHC	Wet and dry weight method
CWHC	Wet and dry weight method
SWC	Dry method
EC	Multifunctional conductivity meter
SOC	Potassium dichromate volumetric method
AK	Flame photometric method
TN	Sodium sulfate-salicylate
AN	Alkali dissolution diffusion method
TP	Alkali fusion-molybdenum antimony spectrophotometry
AP	Photoelectric colorimetry
CA	Potassium permanganate titration
SUC	Sodium phenol-sodium hypochlorite colorimetric method
URE	Sodium pyrophosphate-sodium hydroxide oxidation method

BD: Soil Bulk Density; pH: Soil pH; maxWHC: Soil Saturated Water Holding Capacity; CWHC: Average Soil Water Holding Capacity SWC: Soil Water Content; EC: Electrical Conductivity; SOC: Organic Carbon; AK: Quick Potassium; TN: Total Nitrogen; AN: Quick Nitrogen; TP: Total Phosphorus; AP: Quick Phosphorus; CA: Soil Catalase; SUC: Soil Sucrase; URE: Soil urease. The high-precision intelligent acidity meter was manufactured by Chengdu New Ark Technology Co., Ltd; model: PHS-320. multifunctional conductivity meter was manufactured by Chengdu New Ark Technology Co., Ltd; model: DDS-608

Table 3. *Soil indicators of mountain date palm forests with different abandonment years*

Indicator	AL1	AL6	AL10	AL15	AL20	PRG
BD	1.2±0.11abc	1.24±0.10ab	1.26±0.02a	1.19±0.06bc	1.13±0.06c	1.18±0.07bc
pH	8.41±0.04ab	8.35±0.01cd	8.33±0.02ac	8.39±0.07bc	8.28±0.01bcd	8.44±0.03abc
maxWHC	34.69±1.16ab	39.71±1.70bc	40.49±2.60bc	40.69±3.42bc	45.46±1.64abc	36.3±1.41abc
CWHC	34.84±1.56ab	33.15±1.66bc	33.63±1.21abc	34.69±0.93a	34.23±2.22ab	32.4±0.46c
SWC	9.35±2.10bc	11.71±2.10ab	12.06±2.10ab	12.74±2.10abc	7.69±2.10bc	8.57±2.10ab
EC	72.7±2.70abc	73.87±2.70abc	75.17±2.70ab	75.87±2.70ac	72.04±2.70bc	71.42±2.70bc
SOC	7.63±1.48ab	9.77±1.48bc	9.98±1.48ac	9.7±1.48ac	9.78±1.48bc	2.25±1.48bc
AK	30.32±14.00ab	30.31±0.12ab	30.07±18.60bc	38.17±22.60ab	52.38±8.70ac	28.6±8.73ab
TN	0.29±0.04bc	0.43±0.16ab	0.41±0.13ab	0.44±0.17abc	0.36±0.20ab	0.22±0.08bc
AN	6.53±3.00ab	7.64±3.70ab	7.7±4.40ab	7.47±5.40ab	9.73±3.90a	5.57±2.05b
TP	0.22±0.01cd	0.26±0.04bc	0.28±0.10bcd	0.48±0.05ab	0.53±0.03abc	0.19±0.01cd
AP	17.69±1.50abc	19.71±5.00bc	20.25±7.70ac	20.78±7.80ab	28.56±30.00bc	11±5.30abc
CA	0.85±0.20a	0.77±0.14ab	0.74±0.12ab	0.9±0.16a	0.84±0.16ab	0.67±0.19b
SUC	6.07±1.90ab	6.07±2.00ab	6.4±2.20a	7.8±1.40ab	6.87±2.50ab	5.07±3.50a
URE	4.37±2.60bc	6.18±2.10ab	6.29±1.90ab	6.38±2.40ab	6.88±2.40ab	3.83±2.50abc

BD: soil bulk density; pH: soil acidity and alkalinity; maxWHC: soil saturated water holding capacity; CWHC: soil average water holding capacity SWC: soil water content; EC: electrical conductivity; SOC: organic carbon; AK: quick-acting potassium; TN: total nitrogen; AN: quick-acting nitrogen; TP: total phosphorus; AP: quick-acting phosphorus; CA: soil catalase; SUC: soil sucrase; URE: Soil urease

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Statistical analysis tools

In this study, Excel 2021 software was used to process the data and calculate the affiliation, weight and SQI of the soil indicators at the later stage. principal component analysis was performed using Spss27.0, and plotting was performed using Origin 2024. by constructing the partial least squares structural equation model of soil quality (PLS-SEM), the environmental factors, such as the number of years of abandonment and the physicochemical properties of the soil, were used to reveal the effect of the SQI. The structural equations were modeled using R4.2.2. The R package was mainly used PLS-PM package.

Results and analysis

The affiliation characteristics of soil indicators in mountain date palm forests with different abandonment years

As shown in *Figure 2,* there are significant differences ($p < 0.05$) in the affiliation values of different sites in the study area. In AL1, CWHC, CA, AP, and SOC indicators had high affiliation, while most of the other indicators were limiting factors. The montane date palm forests with 6 years of abandonment had higher affiliation of pH, SWC, SOC, TN, and AP, while physical indicators such as BD, CWHC, and EC were limiting factors. The montane date palm forests with AL10 had higher affiliation of indicators and limiting factors that basically converged with AL6. However, in mountain date palm forests of AL15, pH indicators have lower affiliation, except pH, AK, AN, the rest of the indicators affiliation is more than 0.5. When the abandonment period of mountain date palm forests is 20 years, the chemical indicators pH, AP, TP and the physical indicators maxWHC have higher affiliation, while SWC, TN and other physical indicators are limiting factors. All the indicators except pH showed high affiliation in the abandoned grassland.

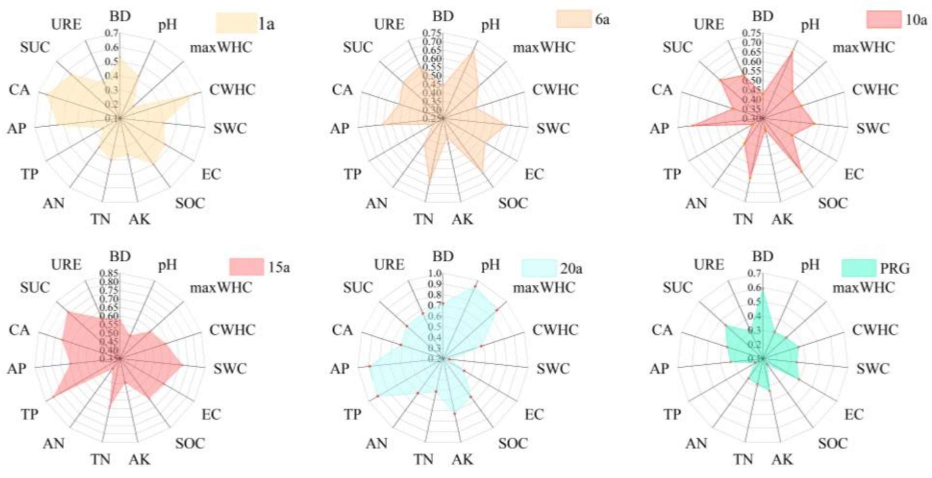

Figure 2. *Radar plot of soil indicator affiliation for date palm groves with different abandonment years. PRG: Abandoned grassland; 1a: Jujube orchard abandoned for 1 year; 6a: Jujube orchard abandoned for 6 years; 10a: Jujube orchard abandoned for 10 years; 15a: Jujube orchard abandoned for 15 years; 20a: Jujube orchard abandoned for 20 years. BD: soil bulk density; pH: soil acidity and alkalinity; maxWHC: soil saturated water holding capacity; CWHC: soil average water holding capacity SWC: soil water content; EC: electrical conductivity; SOC: organic carbon; AK: quick-acting potassium; TN: total nitrogen; AN: quick-acting nitrogen; TP: total phosphorus; AP: quick-acting phosphorus; CA: soil catalase; SUC: soil sucrase; URE: Soil urease*

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Principal component analysis of soil indicators in mountain date palm forests with different abandonment years

The results of principal component analysis of 15 soil quality indicators are shown in *Table 4,* the eigenvalues of the first four principal components are greater than 1, and the cumulative contribution rate reaches 83.258%, which fully explains the information of the original variables. The variance of the common factors of the 15 indicators ranges from 0.659 to 0.938, and the variance of the common factors is greater than 0.5. Except for CWHC, SWC, EC, TP, the variance of common factors of the rest of the indicators are greater than 0.8. This indicates that the extracted common factors effectively and completely express the information contained in the evaluation indicators of SQ. This indicates that the extracted common factors effectively and completely express the information contained in the SQ evaluation indicators.

Table 4. *Principal component analysis and weights of soil indicators*

Norm	PC1	PC2	PC3	PC4	Common factor variance (math.)	Indicator weights
BD	-0.60	0.479	-0.285	0.391	0.828	0.06633
pH	-0.69	0.006	0.567	0.148	0.815	0.06525
maxWHC	0.79	-0.042	-0.514	-0.067	0.891	0.07133
CWHC	0.49	0.129	0.323	0.587	0.706	0.05657
SWC	0.21	0.801	0.183	-0.264	0.789	0.06316
EC	-0.28	0.728	-0.101	-0.293	0.707	0.05658
SOC	0.84	0.316	-0.12	0.261	0.894	0.07159
AK	0.92	-0.265	0.096	-0.11	0.938	0.07508
TN	0.72	0.226	-0.029	0.441	0.758	0.06067
AN	0.93	-0.144	0.17	0.063	0.918	0.07352
TP	0.72	-0.011	-0.376	-0.03	0.659	0.05276
AP	0.86	-0.011	-0.299	-0.005	0.821	0.06577
CA	0.84	0.041	0.417	-0.153	0.906	0.07255
SUC	0.86	0.135	0.384	-0.176	0.927	0.07426
URE	0.94	0.123	0.127	-0.118	0.932	0.07459

BD: soil bulk density; pH: soil acidity and alkalinity; maxWHC: soil saturated water holding capacity; CWHC: soil average water holding capacity SWC: soil water content; EC: electrical conductivity; SOC: organic carbon; AK: quick-acting potassium; TN: total nitrogen; AN: quick-acting nitrogen; TP: total phosphorus; AP: quick-acting phosphorus; CA: soil catalase; SUC: soil sucrase; URE: Soil urease

Analysis of soil quality index in mountain date palm forests with different abandonment years

As shown in *Figure 3*, the SQI values were in the range of 0.444-0.669, the SQI of AL6 was better than that of AL1, the SQI of AL10 was slightly lower than that of AL6, and the SQI values were 0.5289459 and 0.5287077, respectively, and the difference between the two values was extremely small, with a difference of only 0.0004, and the SQI values increased from AL10 to AL20, the SQI of AL15 was greater than that of AL10 and AL6, with a value of 0.619; the SQI of AL20 was greater than that of AL15, with the highest value of 0.669. The SQI values of AL10 to AL20 increased, and the SQI of AL15 was greater than that of AL10 and AL6, with a value of 0.619; the SQI of AL20 was greater than that of AL15, with the highest value of 0.669. In summary, with the increase of the abandonment

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years, the SQI values increased with the increase of the abandonment years, and the SQI of PRG was the lowest in the control group, with a value of only 0.444. The SQI of the mountain date palm grove of AL6 was significantly higher than that of the control group, with a 43% enhancement compared with that of the abandonment meadow. The SQI of AL6 mountain date palm forest was significantly higher than that of the control group of abandoned grassland, with a 43% increase. With the increase of years of abandonment, the SQI from AL10 to AL15 increased the most, and the SQI value of the latter increased by 17% compared with that of the former, while the increase from AL15 to AL20 decreased significantly, and only increased by 8%, and the SQI reached the peak after AL20, but the increase of the SQI decreased with the increase of years of abandonment.

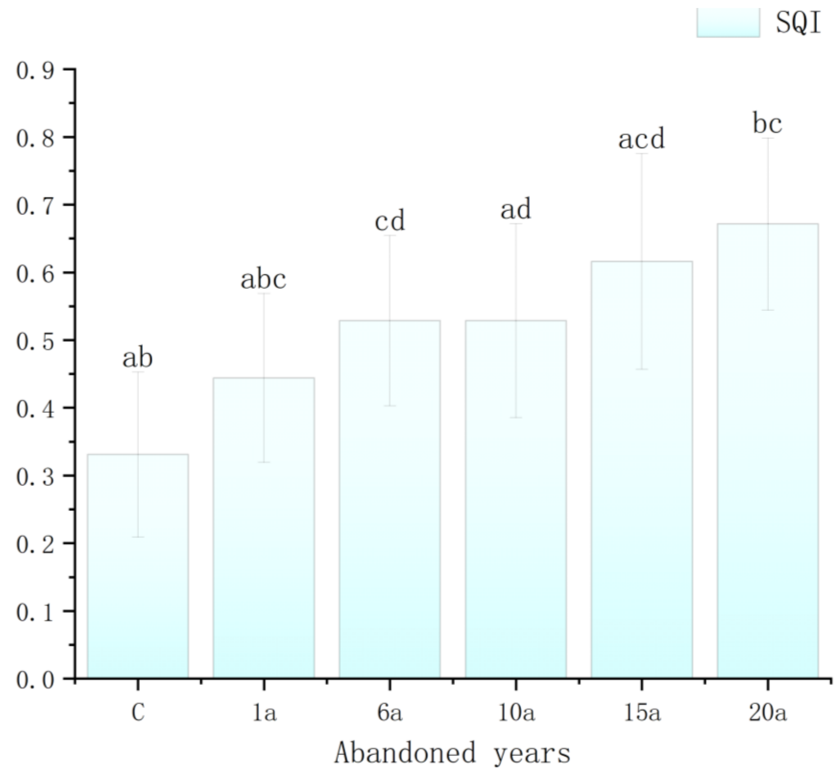

Figure 3. *SQI for different years of abandonment in montane date palm forests. C: Abandoned grassland; 1a: Jujube orchard abandoned for 1 year; 6a: Jujube orchard abandoned for 6 years; 10a: Jujube orchard abandoned for 10 years; 15a: Jujube orchard abandoned for 15 years; 20a: Jujube orchard abandoned for 20 years*

Analysis of soil quality drivers for different years of abandonment in montane date palm forests

The relationship between SQ and soil physical and chemical properties and soil microbial indicators of mountain date palm forests with different years of abandonment was analyzed by PLS-SEM, and the results were shown in *Figure 4*, the SQ of mountain date palm forests with different years of abandonment was affected by the combination of abandonment year, soil chemical indicators (except pH), soil water content (SWC) in soil physical indicators, and soil microbial indicators, and the soil chemical indicators (except pH) had a significant positive effect on SQ of abandonment mountain date palm forests, and its path coefficient was as high as 0.91.

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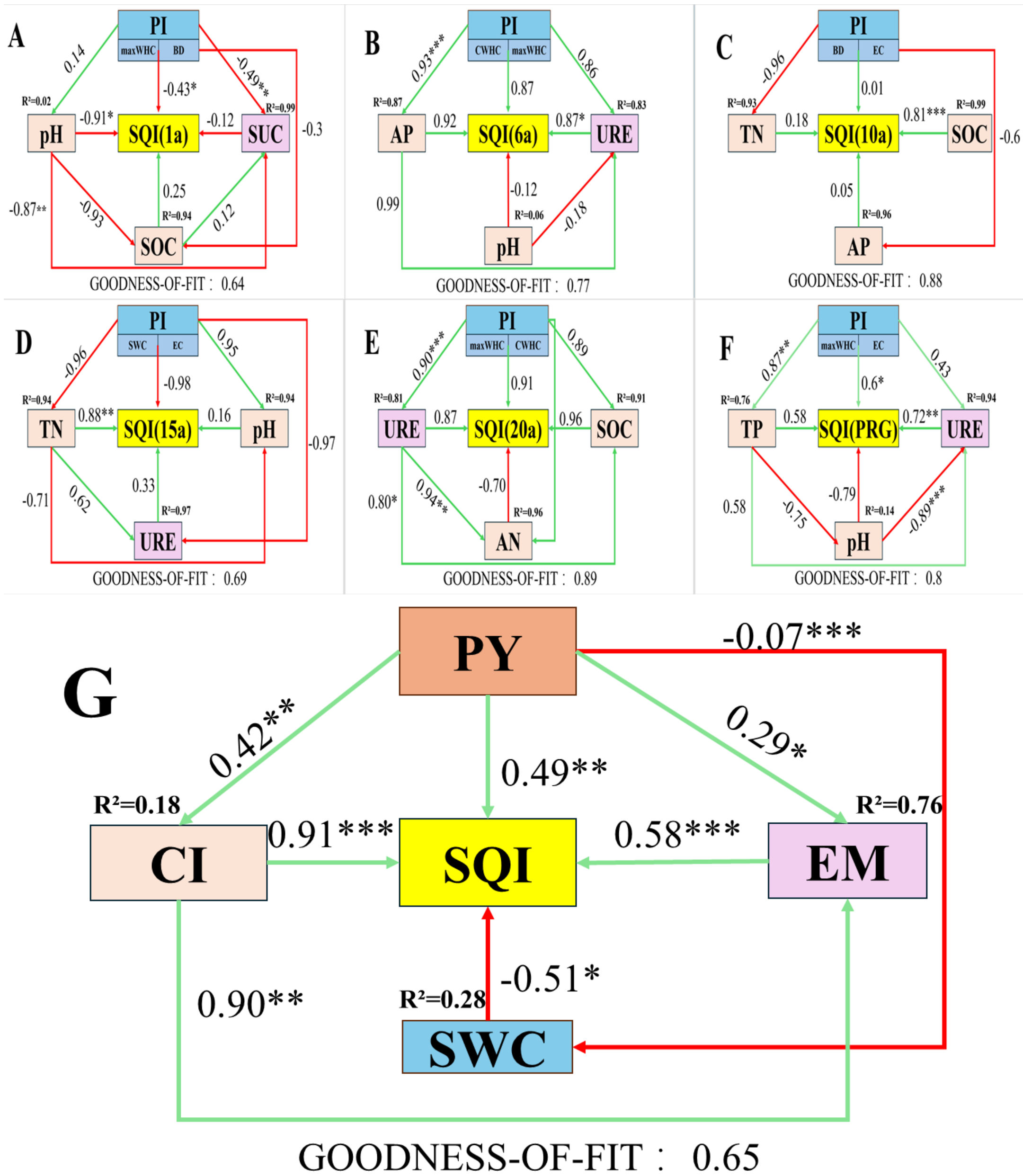

Figure 4. *Impact of different drivers on SQI. A-E represent the impacts of different indicators on SQI of the abandoned mountain date palm forests in 1, 6, 10, 15 and 20 years, F represents the impacts of different indicators on SQI of the abandoned grassland, and G represents the impacts of different indicators on SQI of the abandoned mountain date palm forests, respectively. Red arrows represent negative impacts, green arrows represent positive impacts, and the numbers labeled on the arrows are path coefficients (P-values), which indicate the magnitude of the impacts. *** indicates significant correlation at the 0.001 level, ** indicates significant correlation at the 0.01 level, and * indicates significant correlation at the 0.05 level. N: years of abandonment; PI: physical indicators; CI: chemical indicators (except pH); EM: soil microbial indicators; SWC: soil water content*

Among the main driving factors, soil chemical indicators (except pH) had a significant positive effect on the SQ of abandoned montane date palm forests, with a path coefficient as high as 0.91; the path coefficients of abandonment years and soil microbial indicators

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on the SQ of abandoned montane date palm forests were 0.49 and 0.58, respectively, both of which were positive; and the overall change of the SWC in soil physical indicators had a negative effect on the SQ, with a path coefficient of -0.51. In addition, the driving factors of SQ of mountain date palm forests with different abandonment years also differed from one another, and the path coefficient of the SWC in soil physical indicators was -0.51. drivers of different abandonment years were also different. pH had a significant negative effect on the SQI of AL1, with a path coefficient of -0.91. AP had a greater positive effect on the SQI of AL6, with a path coefficient of 0.92; the soil microbial indicator URE activity also had a significant positive effect, with a path coefficient of 0.87. SOC had a significant positive effect on the SQI of AL10, with a path coefficient of 0.81. TN had a significant positive effect on the SQI of AL10, with a path coefficient of -0.81. 0.81. TN had a positive effect on the SQI of AL10, with a path coefficient of 0.88; while PIs (BD, EC) had a more significant negative effect, with a path coefficient of -0.98. The SQI of AL20 was mainly affected by the positive effects of SOC and URE, with path coefficients of 0.96 and 0.87, respectively. The main driver of positivity in the put down of wasteland grassland was URE, with a path coefficient of 0.72.

Discussion

Analysis of soil quality in mountain date palm forests with different abandonment years

In this study, SQI increased with the increase of years of abandonment, which indicated that abandonment could promote the improvement of soil quality (Guo et al., 2022), which was in line with the results of the study by Wang et al. (2023), the reason was that the negative impacts of anthropogenic factors, such as stepping, tilling, and planting before abandonment, and the chain effects of the negative impacts on SQ gradually weakened until disappeared as the number of years of abandonment increased. The reason is that the negative effects and chain reaction of human factors such as trampling and plowing and planting on SQ before abandonment gradually decreased with the increase of abandonment years (Mikha et al., 2024), and therefore, the SQ of date palm forests in mountainous areas gradually improved with abandonment years. Studies have shown that anthropogenic trampling can make soil particles more tightly arranged (Zhang et al., 2023), reduce the air pores in the soil, resulting in a compact soil structure and reduced porosity (Yang et al., 2018), which further leads to a decrease in soil nutrients and a decrease in microbial population and diversity (Yang et al., 2018; Zhang et al., 2023), and a decrease in soil microbial enzyme activity. Soil microbial enzyme activity decreased, and these changes negatively affected the soil quality of montane jujube forests; in addition, anthropogenic activities such as plowing and planting damaged the soil structure to a certain extent (Ma et al., 2023) thus affecting the transformation and accumulation of soil nutrients, and all of the above changes negatively affected the SQ of montane jujube forests; after the abandonment of montane jujube forests in the study area, the negative impacts of anthropogenic factors gradually weakened until the disappearance of the negative effects of anthropogenic factors. After the abandonment of the hill jujube forests in the study area, the negative impacts of human factors gradually weakened until they disappeared, and the jujube forests began to recover themselves, which led to the improvement of the soil structure, and the aeration and infiltration capacity of the soil improved significantly, and the soil structure became more and more stable. Reduced soil nutrient loss prompted the continuous accumulation of nutrient elements in the soil, which

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further promoted the transformation and accumulation of soil organic matter, thus improving SQ (Ren et al., 2025); in addition, during the natural abandonment of the hilly date palm forests, the microbial population increased due to the accumulation of soil nutrients, thus improving the soil structural condition, which led to the effective restoration of soil fertility, and further improved the SQ (Yu et al., 2023). The SQI of AL6 was significantly larger than that of PRG, and the study showed that woody plants have more developed root systems, which can fix the soil better than herbaceous plants (Fan et al., 2024), increase soil aeration and permeability, and improve the soil structure, which further affects the SQ, and therefore, the SQ of woody plants is better than that of herbaceous plants. With increasing years of abandonment, the increase in SQI of montane jujube forests tended to decrease after 15 years of abandonment, which was different from the study of abandonment in tropical rainforests, and might be related to moisture limitation under arid conditions in loess areas, indicating the role of regional climate in regulating abandonment recovery. In this study, the maximum abandonment period of the mountain date palm forest was 20 years, and how the soil quality in the study area will change with the further increase of abandonment period has not been addressed in this study.

Analysis of the driving factors of soil quality changes in montane date palm forests with different abandonment periods

This study demonstrates that the duration of abandonment significantly impacts soil quality in mountain jujube forests. By analyzing the path coefficients between the Soil Quality Index (SQI) and influencing factors through structural equation modeling, it was revealed that the soil quality of the overall mountain jujube forests is affected by a combination of various indicators. Soil water content (SWC) exerts a negative influence on soil quality (SQ). As abandonment duration extends, SWC decreases, leading to a progressive exacerbation of SWC deficiency in abandoned lands. In the Loess Plateau region, moisture is a critical limiting factor for SQ (Li et al., 2014), and its reduction triggers a series of cascading reactions that negatively affect SQ. Conversely, soil chemical indices (excluding pH) and soil microbial enzyme activities, such as catalase (CA) and urease (URE), significantly positively influence SQ. The extension of the abandonment period results in increased soil nutrient content. Soil nutrient levels, such as soil organic carbon (SOC), available phosphorus (AP), and total nitrogen (TN), all increase with the lengthening of abandonment duration, which is consistent with the findings of Huang et al. (2024); soil microbial enzyme activity also enhances with the increase in abandonment years, and Lei et al. (2024) showed that soil microbial enzyme activity is a key factor influencing overall SQ, reflecting changes in the soil environment and playing an important regulatory role in the cycling, utilization, and flow of soil nutrients and energy. In summary, changes in soil available nutrient content and microbial enzyme activity with the number of years of abandonment will affect and improve soil nutrient content, soil fertility characteristics, and soil structure, thereby further influencing the SQ of abandoned mountain jujube forests. This study also found differences in the main drivers of soil quality in abandoned mountain jujube forests with varying durations of abandonment. Soil pH significantly negatively affects the SQ of mountain jujube forests and grasslands abandoned for one year. In this study, the pH of mountain jujube forests and grasslands with different abandonment durations was greater than 7, indicating alkaline soil conditions, and the pH value tended to increase with the increase in abandonment years. Alkaline soil conditions inhibit the transformation of soil

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elements and nutrients and reduce the activity of soil biological enzymes, thus negatively driving SQ (Xiang et al., 2003). The soil chemical index SOC significantly positively affects the SQ of mountain jujube forests abandoned for 10 and 20 years, with a tendency to increase with the increase in abandonment duration; on one hand, since SOC is an important indicator of soil fertility, its content gradually increases with the increase in abandonment years, which helps promote the formation of soil aggregates (Ren et al., 2025) and improves soil structure to some extent; on the other hand, the increase in SOC can enhance soil fertility (Yang et al., 2025), which is the primary energy source for soil microorganisms, thereby improving soil nutrient cycling capacity and availability, and all these changes will have a positive driving effect on SQ. The two chemical indicators, AP and TN, significantly positively affect the SQ of hilly jujube forests abandoned for 6 and 15 years, respectively; AP can improve soil fertility, enhance soil conservation, and improve soil structure, thereby positively driving SQ; soil TN accumulation can help enhance soil fertility, and studies have shown that in semi-arid regions, soil nitrogen elements can regulate soil nutrients and enzyme activity to affect SQ; in addition to some soil physicochemical indices, soil enzyme activity also positively impacts the SQ of mountain jujube forests with different abandonment durations. The SQ of mountain jujube forests with different abandonment durations is also significantly positively affected; URE activity has a significantly positive driving effect on the SQ of mountain jujube forests abandoned for 6 and 20 years; with the increase in abandonment years, soil URE activity continuously increases, and enzyme promotion is enhanced, which accelerates the transformation of soil nutrients (Márton et al., 2017; Mukherjee et al., 2016); the regulatory effect of URE leads to a more optimized physical structure of some soils, resulting in more stable soil properties (Mbuthia et al., 2015), and all these changes positively affect the SQ of abandoned mountain jujube forests.

Conclusion

In this study, based on 15 soil physicochemical bioindicators, we analyzed and calculated the SQI of mountain date palm forests with different years of abandonment and the control group of abandoned grassland, and found that abandonment had a significant enhancement effect on the SQ in the loess area of northern Shaanxi, and increased with the increase of years of abandonment. Structural equation modeling showed that the overall SQ of the abandoned hilly date palm forests was positively affected by the number of years of abandonment, soil chemical indicators (except pH), and soil microbial enzyme activities; among them, the positive effect of soil chemical indicators (except pH) was the most significant, while the negative effect of SWC among soil physical indicators was stronger. The drivers of soil quality were different in different years of abandonment. pH had a highly significant negative effect on mountain date palm forests in the early stage of abandonment; URE had a significant positive effect on mountain date palm forests in the early stage of abandonment; and SOC had a significant positive effect on the soil quality of mountain date palm forests in the early stage of abandonment and had a tendency to increase. This study systematically investigated the change of soil quality of date palm forests in the loess area of northern Shaanxi with the number of years of abandonment, and clarified the influence of the main driving factors of the soil quality index after abandonment; provided data support and scientific basis for the management and transformation of abandonment of date palm forests in loess area of northern Shaanxi and similar areas in the future, and provided technical guidance for the

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comprehensive revitalization of the countryside, and in the future, should be included in the eco-compensation mechanism of abandonment date palm forests, and optimize the policy of returning farmland to forests. In the future, the abandoned date palm forests should be included in the ecological compensation mechanism to optimize the policy of returning farmland to forest.

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