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Spatiotemporal Evolution of Soil Quality Under Long-Term Apple Cultivation in the Taihang Mountains, China

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Abstract

The present study aims to investigate the impact of long-term apple production and orchard management practices on soil quality in gneiss mountainous regions. The microbial community (as measured by phospholipid fatty acid analysis) and soil physicochemical properties (bulk density, organic matter, nitrogen, phosphorus, and potassium) were determined in soil samples collected from apple plantations of various ages (0-, 8-, 22-, 29-, and 36-year) in Gangdi Village, Xingtai, China. The soil samples were collected from depths of 0–20, 20–40, and 40–60 cm. The findings of the present study demonstrate that with increasing duration of apple cultivation, the soil bulk density and porosity decreased and increased, respectively. Initially, the content of soil nutrients such as organic matter, nitrogen, and phosphorus increased, eventually stabilizing, accompanied by a decline in pH. The soil microbial biomass significantly increased, accompanied by discernible alterations in the composition of the microbial community. Organic matter was found to be the primary factor influencing the structure and diversity of microbial communities. It is evident from forward analysis that the soil Gram-negative and actinomycete communities were predominantly influenced by soil pH, bulk density, and total phosphorus. In contrast, the Gram-positive and eukaryote communities were less affected by soil environmental factors. Notably, the soil bacterial community presented a greater degree of sensitivity to the duration of apple cultivation than did the fungal community. A marked vertical difference in the soil quality indicators was evident, with the increase in surface soil quality exceeding that of deeper soil depths.

Keywords: apple orchard; soil quality; microbial community; sustainability

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1. Introduction

The gneiss-dominated mountainous region of the Taihang Mountains is one of the areas in China severely affected by soil erosion. The ongoing impact of human activities has resulted in significant deterioration of the forest ecosystem and substantial biodiversity loss in this region. Consequently, forest degradation has occurred, manifesting as the transformation of forests into shrub lands and grassy slopes. This phenomenon has had deleterious effects on the soil, leading to exacerbated rates of erosion and an increase in the frequency of flood disasters [1]. To increase afforestation success within the specified site conditions and improve farmers' living standards, mechanical land preparation has been utilized in recent years to manage the gneiss mountainous regions of the Taihang Mountains.

This has resulted in the development of high-standard terraced fields with sloping gullies. The aforementioned fields have been cultivated with a range of economically viable tree species, including walnuts, apples, and cherries. This approach has not only led to the reforestation of barren mountains and the optimization of land resource utilization but has also yielded substantial economic benefits. This has ensured the optimal use of limited soil, substantially increased vegetation cover in mountainous areas, and dramatically enhanced the living standards of local residents [2].

It is universally acknowledged that soil constitutes the foundation of agricultural production, supplying essential nutrients and water to crops and providing stable media for root growth. A symbiotic relationship clearly exists between plants and soil, where the cultivation of crops is contingent upon the inherent characteristics of the soil, including but not limited to, water availability, nutrient status, aeration, and temperature [3–5]. Furthermore, the cultivation of crops specifically influences the physical structure, nutrient equilibrium, and microbial community composition of the soil. The repeated cultivation of a single crop can result in a decline in the soil nutrient balance, compromised soil quality, and a reduction in microbial diversity. This, in turn, can precipitate a decline in crop yield and quality [6–8].

The management of agricultural activities has been demonstrated to have a profound effect on the composition and activity of soil microbial communities. This alteration is caused primarily by changes in the quantity and quality of plant residues entering the soil, as well as the excessive use of pesticides, fertilizers (synthetic or organic), and tillage practices. These changes in management practices have been shown to have significant consequences for soil quality, as evidenced by several studies [9–13]. A study revealed that traditional tillage reduces the stability of aggregates, decreases the proportion of macroaggregates, and increases the proportion of microaggregates [12]. The planting period significantly influences the soil aggregate structure, in addition to altering its bulk density and porosity [14]. Furthermore, the duration of crop cultivation has been demonstrated to influence the accumulation of nutrients and the flux of greenhouse gas emissions within the soil–vegetation system [15,16]. The practice of continuous cropping has been demonstrated to result in the accumulation of soil macronutrients (e.g., organic matter, nitrogen, phosphorus, and potassium). However, trace elements have been observed to exhibit differential changes, which has the potential to induce nutrient imbalance and consequently affect crop absorption, utilization, and growth health [17–20].

A growing body of evidence suggests a close correlation between soil attributes and the composition of the soil microbial community [21,22]. Rhizosphere soil microorganisms play a pivotal role in the transformation and cycling of rhizosphere ecosystems, thereby contributing significantly to the maintenance of soil health [23,24]. However, it is imperative to acknowledge the profound impact of anthropogenic activities, such as plowing, landfilling, pruning, and fertilizing, on the composition of soils. These disturbances can potentially induce changes in major physical, chemical, or biological factors, which can further result in shifts in the structure and activity of soil microorganisms. Conversely, alterations in the community structure and functional diversity of rhizosphere soil microbes have been demonstrated to impact plant growth, fruit yield, and quality [25,26].

As demonstrated in the extant literature, the age of the fruit tree and its physiological status significantly influence the composition of rhizosphere microorganisms. Furthermore, by manipulating cultivation techniques that influence the structure of the rhizosphere microbial community, it is possible to regulate the growth and development of fruit trees [27,28]. However, the relationships among rhizosphere soil chemical indices, microbial communities, and apple quality in different planting years remain to be elucidated.

Chronosequences have been proven to be an effective means of assessing the changing trends and rates of soil properties. This is achieved by replacing time with space under the strict control of environmental factors [29,30]. Therefore, the decision was made to select apple orchards of different stand ages for the purpose of measuring changes in the microbial community structure and identifying the factors that led to these variations. The objective of this study was to explore the interactions between rhizosphere microorganisms and environmental factors to provide a scientific basis for the sustainable management of apple orchards in fragile mountain ecosystems.

2. Materials and Methods

2.1. Study Area

The study site (ca. 1500 ha) is located in Gangdi village (114°04′–114°06′ E, 37°19′–37°22′ N; Figure 1), Neiqiu County, Hebei Province, China. This area has a warm temperate monsoon climate with average annual temperature and precipitation of 11.8 °C and 685 mm, respectively. The frost-free period is 180 days. In addition, the soils at the study site are classified as Entisols according to FAO Soil Taxonomy. Owing to its remote location, the area has not been developed and utilized for a long time (>100 years). Notably, the trial sites have similar climatic and soil conditions because of the short distances (i.e., similar geomorphologic units; hills). Since 1984, apple trees (variety 'Nagafu No. 2') have been planted in this region, and the apple plantations vary in their planting ages. The apple cultivation density was set to approximately 667–1250 plants ha^{-1}, and the row and plant spacing was 2.0–3.0 × 4.0–5.0 m. The field management measures (e.g., fertilization, pest prevention, and weeding methods) were similar among the trial sites.

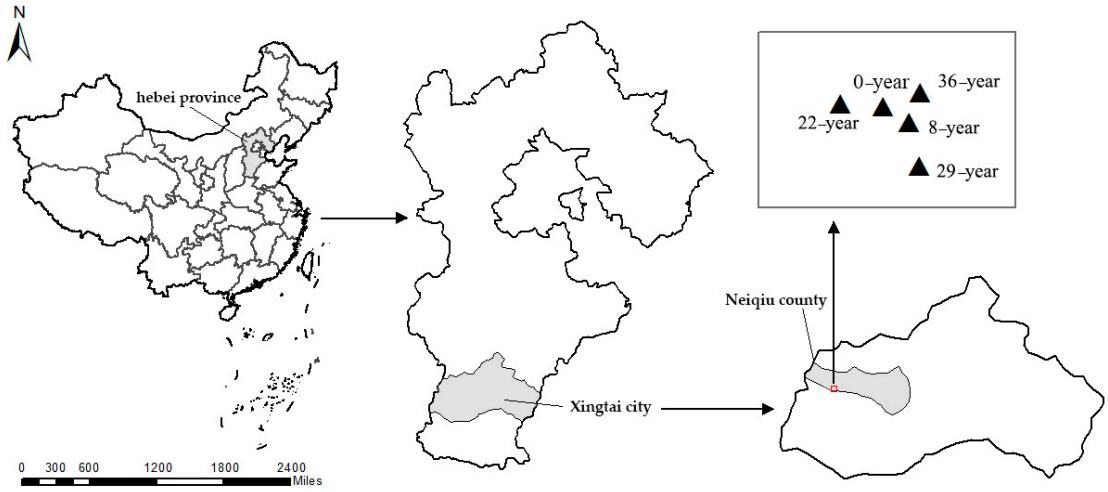

Figure 1. Location of the study area.

2.2. Soil Sampling

Space-for-time replacement, a reliable method to monitor temporal changes in soil, was applied to evaluate the change trends of soil variables (e.g., microbial characteristics) in an apple cultivation chronosequence that was situated on the same geomorphic units with similar management measures as well as soil and climatic statuses. Five chronosequence apple orchards (cultivar 'Nagafu No. 2') representing continuous cultivation durations of 0 (Not plowed), 8, 22, 29, and 36 year intervals (Figure 1) were systematically investigated to quantify pedological evolution, including microbial community composition, bulk density stratification, pH dynamics, and associated biogeochemical parameters across cultivation decades. A completely randomized block design with three replicates was used for each apple plantation (15 plots; 3 replicates × 5 treatments). The area of each plot was 100 m^2

(10 m × 10 m). On each plot, five soil cores (5 cm diameter, 20 cm depth) were obtained from three soil depths below the apple canopy (0–20, 20–40, and 40–60 cm; the major distribution area of the apple root system) using the diagonal method. These soil samples were subsequently integrated into one combined sample. In total, 45 combined samples (15 plots × 3 depths) were obtained. After the removal of plant residues, defoliation, and stones, these combined soil samples were carefully passed through a sieve (2 mm) and then divided into two parts. One part was air-dried to determine the soil physicochemical properties; the other part was stored in a freezer (−80 °C) for measurement of the soil microbe-associated characteristics.

2.3. Soil Environmental Chemistry Index Analysis

The soil bulk density (BD) was determined using a ring with an internal volume of 50 cm^3, whereas the capillary porosity (CP) and field capacity (FC) were determined using a Richards pressure plate; this was performed as described by Klute [31]. The pH of the four aggregates was measured in a soil–water mixture (1:2.5) through a compound electrode pH meter (STARTER300, Pinebrook, NJ, USA). The contents of soil organic matter (SOM) and total N (TN) were measured following the heated dichromate/titration method and the semimicro Kjeldahl method [32,33], respectively. The total P content was determined by the molybdate colorimetric method after ascorbic acid reduction [34]. The available nitrogen (AN) content was determined by the alkaline hydrolysis diffusion method [35]. Available P (AP) was extracted with 0.5 M sodium bicarbonate (pH 8.5) and measured by the Olsen method [36]. Available K (AK) was extracted with 1 M ammonium acetate and then measured by atomic absorption spectrometry (NovAA300, Analytik Jena, Germany) [37].

2.4. Soil Microbial Community PLFA Analysis

To assess the impact of soil management practices on microbial activity and diversity, soil lipid extraction and PLFA analysis were performed using a modified Bligh and Dyer method [38,39]. Briefly, 3.0 g of freeze-dried soil was placed in a 15 mL glass centrifuge tube, and 11.4 mL of chloroform–methanol–citrate buffer (1:2:0.8) was added in two portions for lipid extraction. Further, 4.8 mL of citric acid buffer and 6 mL of chloroform were added to the extract, and it was left to stand overnight in the dark. The lower organic phase was transferred to a silicic acid column for adsorption and elution to remove neutral lipids and glycolipids. After the collection was dried by N2, 200 μL of internal standard methyl nineteenth alkanoate (19:0) was added to N2 gas and dried again. The target phospholipids and internal standard were dissolved in 1 mL of 1:1 methanol–toluene mixture and incubated for 15 min at 37 °C to generate fatty acid methyls (FAMEs), which were then dissolved in n-hexane. The FAMEs and δ13C of individual PLFAs were identified and quantified at the Ningbo Urban Environment Observation and Research Station-NUEORS, Chinese Academy of Sciences. PLFA, i14:0, i15:0, α15:0, i16:0, i17:0, and α17:0 were used as indicators for G+ bacteria; 16:1ω5c, 16:1ω7c, 17:1ω8c, cy17:1ω7c, and 18:1ω7c were used as indicators for G− bacteria; 15:0, 16:0, 17:0, and 18:0 were used as indicators for universal bacteria; 18:1ω9c and 20:1ω9c were used as indicators for fungi; and 10-methyl fatty acids were used as indicators for actinomycetes [40]. The fatty acid nomenclature is described by Frostegård et al. [41].

2.5. Statistical Analysis

The data were organized using Microsoft Office 2019. One-way analysis of variance (ANOVA) with Duncan tests was conducted to assess the effects of different apple plantation ages (or soil depths) on the physicochemical and microbial variables. Duncan tests were used to determine the significance level ($p < 0.05$). Two-way ANOVA was conducted to compare the differences in these soil variables, with four apple plantation ages (0, 8, 22,

29, and 36 years) and three soil depths (0–20, 20–40, and 40–60 cm) as the main factors. SPSS 20.0 statistical software (SPSS lnc., Chicago, IL, USA) was used to perform the abovementioned statistical analyses. Additionally, CANOCO 5.0 software (Microcomputer Power, Ithaca, NY, USA) was used to evaluate the effects of the soil physicochemical properties on the microbial community through redundancy analysis (RDA).

3. Results

3.1. Spatiotemporal Evolution of Soil Physical Properties

Soil acts as a critical medium for plant root growth and material–energy exchange, and its quality significantly influences crop health. The physical properties of the soil in apple orchards with different planting durations are summarized in Table 1. As shown in Table 1, the soil bulk density at the 0–20 cm, 20–40 cm, and 40–60 cm depths decreased gradually as the number of years of apple cultivation increased. Specifically, during the first 8 years of planting, the decline was relatively rapid, with average annual reductions of 1.12%, 0.67%, and 1.43% for the respective depths. After 8 years, the changes became less pronounced, with average annual reductions of 0.40%, 0.60%, and 0.32%, respectively. The soil bulk density increases gradually with soil depth; however, this vertical gradient diminishes progressively as the number of years after apple planting increases. As the number of years of apple cultivation increased, the capillary porosity and field water holding capacity in each soil layer gradually increased. Notably, changes in the 0–20 cm soil layer were more pronounced than those in the 40–60 cm layer. The soil capillary porosity and field water holding capacity gradually increased with increasing soil depth, but this vertical difference gradually decreased with increasing apple planting duration.

Table 1. Soil physical properties of apple orchards with different numbers of years of cultivation.

Index	Plantation Age (T)	Soil Depths (D)			Effects		
		0–20 cm	20–40 cm	40–60 cm	T	D	T × D
BD ($g\ cm^{-3}$)	0-year	1.49 ± 0.06 a	1.55 ± 0.14 a	1.60 ± 0.23 a	**	*	NS
	8-year	1.36 ± 0.09 b	1.48 ± 0.05 ab	1.42 ± 0.13 ab			
	22-year	1.32 ± 0.06 b	1.37 ± 0.05 bc	1.47 ± 0.05 ab			
	29-year	1.25 ± 0.08 b	1.37 ± 0.08 bc	1.35 ± 0.08 ab			
	36-year	1.25 ± 0.04 b	1.30 ± 0.04 c	1.33 ± 0.08 b			
CP (%)	0-year	27.26 ± 1.02 a	26.42 ± 0.96 a	24.48 ± 1.50 b	**	NS	NS
	8-year	28.98 ± 1.23 a	28.55 ± 0.85 a	25.99 ± 1.10 b			
	22-year	31.48 ± 2.21 a	27.27 ± 0.95 a	26.68 ± 2.73 a			
	29-year	31.85 ± 2.07 ab	30.71 ± 2.82 a	31.41 ± 3.02 b			
	36-year	28.35 ± 1.79 a	28.78 ± 4.49 a	31.54 ± 1.63 a			
FC (%)	0-year	18.29 ± 0.24 d	17.17 ± 2.09 b	15.54 ± 2.70 b	**	**	NS
	8-year	21.38 ± 0.57 c	18.56 ± 2.24 ab	18.50 ± 2.28 ab			
	22-year	23.88 ± 0.59 ab	22.40 ± 2.79 a	21.33 ± 1.85 a			
	29-year	25.43 ± 1.32 a	19.87 ± 0.30 ab	19.81 ± 3.13 ab			
	36-year	22.72 ± 0.81 bc	22.17 ± 3.19 a	23.79 ± 2.08 a			

Data were shown as means of three replicates ± standard deviations. Different lowercase letters indicate significant differences ($p < 0.05$) in each column among different ages of apple plantations in the same depths. Two-way ANOVA was applied to identify the effects of apple plantation ages, soil depths, and their interaction on the above indices. *, **, and NS represent significant differences at $p < 0.05$, $p < 0.01$ and no significant difference ($p > 0.05$), respectively. BD, soil bulk density; CP, capillary porosity; FC, field capacity.

3.2. Evolution of Soil Acidity and Alkalinity

The pH of the soil solution is an important factor affecting plant growth and nutrient absorption. It can directly affect the absorption of minerals by plants and the activity of microorganisms in the soil, thereby further affecting the growth and development of plants. With increasing years of apple cultivation, the soil pH values at the 0–20 cm, 20–40 cm,

and 40–60 cm soil depths gradually decreased (Figure 2). During the first 29 years of apple cultivation, the soil pH decreased rapidly. The average annual decreases at the 0–20 cm, 20–40 cm, and 40–60 cm soil depths were 1.06%, 1.11%, and 1.12%, respectively, and the decrease gradually slowed thereafter. The soil pH gradually decreased as the depth of the soil layer increased, and this difference gradually decreased with increasing years of apple cultivation.

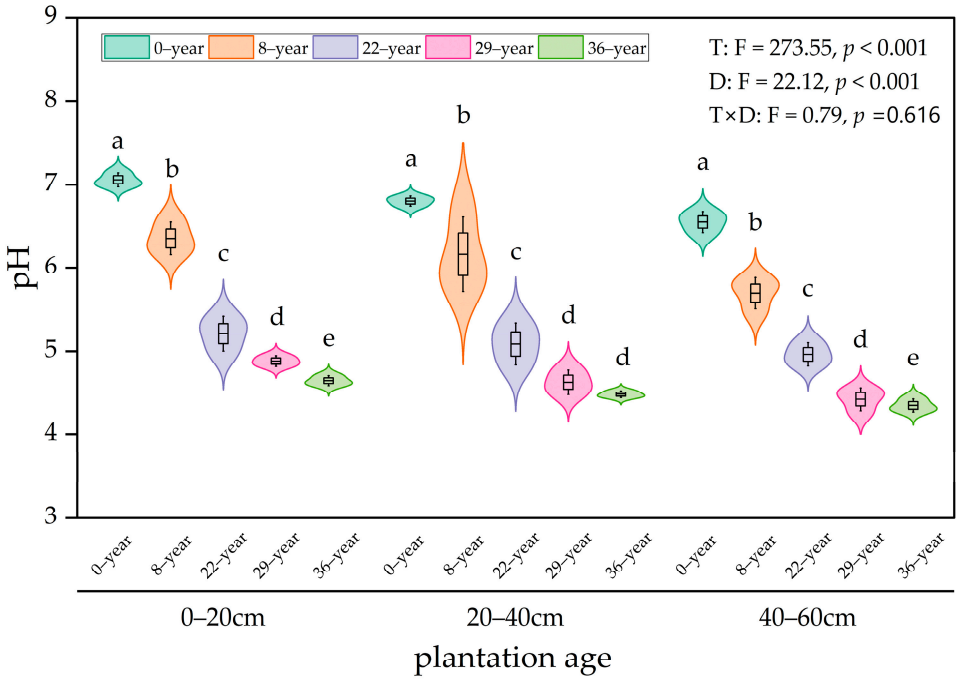

Figure 2. Soil pH of apple orchards with different numbers of years of cultivation. Different lowercase letters represent significant differences ($p < 0.05$) among different ages of apple plantations at the same depths. Two-way ANOVA was applied to identify the effects of apple plantation age, soil depth, and their interaction on the above indices (the data is shown in the upper right corner). T, apple plantation age; D, soil depth.

3.3. Spatiotemporal Evolution of Soil Fertility

Soil is the cornerstone of crop growth, and its fertility directly affects the growth, development, and final yield of crops. As shown in the table, with increasing years of apple cultivation, there were significant changes in soil nutrient levels, but there were certain differences in the change patterns of different nutrients. With increasing years of apple cultivation, the SOM, TP, AN, and AK levels first tended to increase but then stabilized. Compared with those at 0-year, the SOM, TP, AN, and AK levels in each soil layer in the 36-year-old apple orchard increased by factors of 0.26–2.44, 0.86–1.41, 0.87–1.17, and 0.24–0.46, respectively. With increasing years of apple cultivation, the AP level in the soil continued to increase. Compared with that at 0 years, the AP content in the 0–20 cm, 20–40 cm, and 40–60 cm depths in the 36-year apple orchard increased 1.95-fold, 1.57-fold, and 2.90-fold, respectively. With increasing years of apple cultivation, the TN content of the soil first increased but then decreased. The TN content in the 0–20 cm layer peaked at 22-year, and that in the 40–60 cm layer peaked at 29-year. In the vertical profile, soil nutrient levels decreased as the soil depth increased. Notably, the variations in the SOM, TP, AN, and AP levels were more pronounced along the vertical gradient. Moreover, these differences gradually increased with increasing duration of apple cultivation (Table 2).

Table 2. Soil nutrient contents in apple orchards with different numbers of years of cultivation.

Index	Plantation Age (T)	Soil Depths (D) 0–20 cm	20–40 cm	40–60 cm	Effects T	D	T × D
SOM (g kg^{-1})	0-year	9.50 ± 0.80 e	8.23 ± 0.53 c	6.72 ± 0.80 b	**	**	**
	8-year	14.60 ± 1.39 d	10.43 ± 1.39 bc	7.88 ± 0.80 ab			
	22-year	21.32 ± 1.45 c	11.36 ± 2.12 bc	7.88 ± 0.80 ab			
	29-year	36.14 ± 1.21 b	12.75 ± 2.89 ab	8.69 ± 0.35 a			
	36-year	32.67 ± 1.39 a	15.99 ± 2.51 a	8.46 ± 0.72 a			
TN (g kg^{-1})	0-year	0.45 ± 0.04 a	0.51 ± 0.03 a	0.48 ± 0.07 a	**	**	**
	8-year	0.68 ± 0.09 ab	0.55 ± 0.03 a	0.59 ± 0.07 ab			
	22-year	0.82 ± 0.03 bc	0.48 ± 0.03 ab	0.37 ± 0.02 bc			
	29-year	0.77 ± 0.05 c	0.57 ± 0.01 ab	0.68 ± 0.07 c			
	36-year	0.57 ± 0.08 d	0.52 ± 0.06 b	0.46 ± 0.05 c			
TP (g kg^{-1})	0-year	0.43 ± 0.03 c	0.49 ± 0.11 c	0.40 ± 0.06 b	**	NS	NS
	8-year	0.72 ± 0.13 b	0.53 ± 0.06 c	0.49 ± 0.46 ab			
	22-year	0.97 ± 0.20 ab	0.70 ± 0.26 bc	0.64 ± 0.03 ab			
	29-year	1.10 ± 0.10 a	0.95 ± 0.13 a	0.90 ± 0.14 a			
	36-year	1.03 ± 0.15 a	0.92 ± 0.10 ab	0.90 ± 0.05 a			
AN (mg kg^{-1})	0-year	73.97 ± 11.85 b	68.13 ± 0.40 b	45.27 ± 4.28 b	**	**	NS
	8-year	80.73 ± 7.18 b	70.00 ± 4.90 b	63.93 ± 15.48 b			
	22-year	91.47 ± 14.57 b	76.30 ± 7.95 b	65.33 ± 6.80 b			
	29-year	158.20 ± 4.20 a	131.25 ± 5.95 a	96.60 ± 13.50 a			
	36-year	144.90 ± 3.50 a	127.17 ± 15.08 a	98.23 ± 25.34 a			
AP (mg kg^{-1})	0-year	47.60 ± 9.30 c	40.93 ± 0.40 b	20.41 ± 1.39 d	**	**	NS
	8-year	77.14 ± 12.69 bc	52.10 ± 4.37 b	33.43 ± 2.91 c			
	22-year	79.40 ± 59.41 bc	65.41 ± 6.30 ab	39.73 ± 1.62 c			
	29-year	122.33 ± 9.93 ab	71.93 ± 48.99 ab	54.67 ± 6.41 b			
	36-year	140.67 ± 4.24 a	105.19 ± 7.64 a	79.60 ± 13.45 a			
AK (mg kg^{-1})	0-year	230.43 ± 12.75 b	203.47 ± 22.05 c	208.37 ± 3.45 b	**	NS	NS
	8-year	198.57 ± 11.75 c	205.90 ± 13.70 c	208.37 ± 1.45 b			
	22-year	252.50 ± 9.30 b	262.30 ± 20.60 b	237.77 ± 26.95 b			
	29-year	281.90 ± 8.30 a	299.07 ± 18.65 a	291.70 ± 17.20 a			
	36-year	286.80 ± 25.50 a	296.60 ± 18.10 a	281.87 ± 27.45 a			

Data are shown as means of three replicates ± standard deviations. Different lowercase letters indicate significant differences ($p < 0.05$) in each column among different ages of apple plantations at the same depths. Two-way ANOVA was applied to identify the effects of apple plantation age, soil depth, and their interaction on the above indices. **, and NS represent significant differences at $p < 0.01$, and no significant difference ($p > 0.05$), respectively. SOM, soil bulk density; TN, total N; TP, total P; AN, available N; AP, available P; AK, available K.

3.4. Spatiotemporal Evolution of Soil Microbial Quantity and Species

Soil microorganisms are indispensable components of soil and play an important role in maintaining soil ecological balance and biodiversity. With increasing years of apple cultivation, the total PLFA content of the soil microbial communities at the 0–20 cm and 40–60 cm soil depths gradually increased, with Gram-positive and Gram-negative bacteria contributing relatively more PLFAs. The total PLFA content of the soil microbial community in the 20–40 cm soil layer fluctuated, and Gram-positive bacteria and Gram-negative bacteria contributed more significantly (Figure 3). The total PLFA content of the soil microbial community gradually decreased as the soil layer depth increased. However, with increasing years of apple cultivation, the difference between the 0–20 cm and 20–40 cm soil depths gradually increased, whereas the difference between the 20–40 cm and 40–60 cm soil depths gradually decreased.

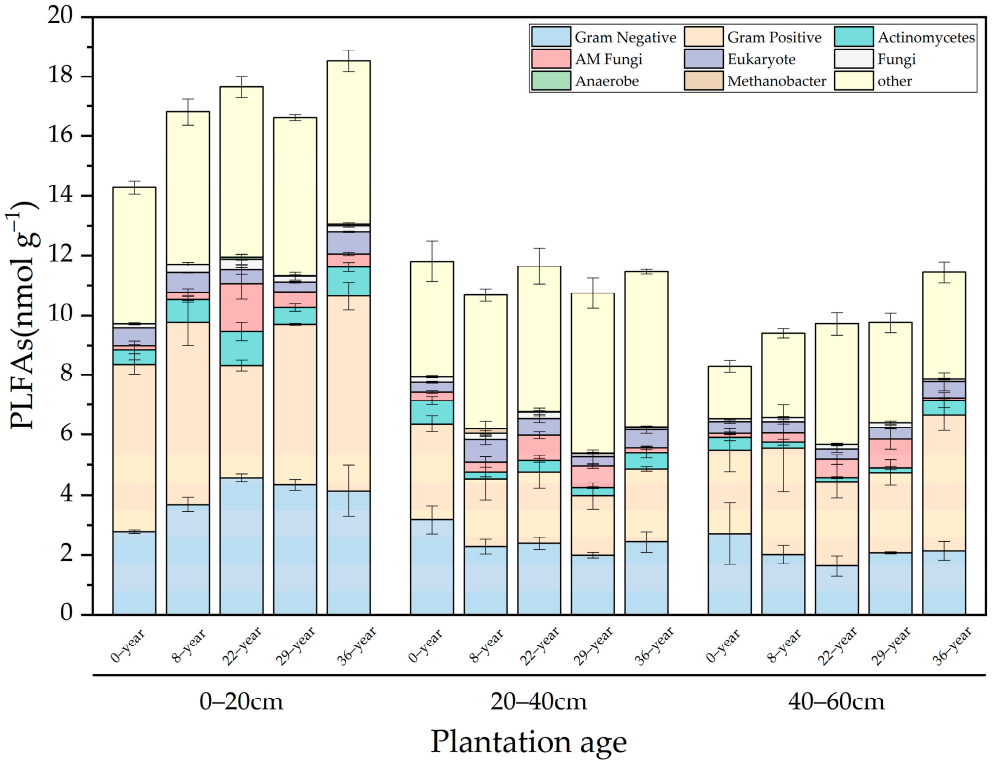

Figure 3. Soil microbial PLFA levels in apple orchards with different numbers of years of cultivation.

3.5. Correlations Between Soil Physical and Chemical Properties and Soil Microbial Communities

To further elucidate the correlation between soil physicochemical properties and microbial community characteristics, redundancy analysis (RDA) was conducted using soil microbial components and soil physicochemical properties as variables. The RDA results (Figure 4) revealed that in the 0–20 cm soil layer, RDA1 and RDA2 explained 59.86% and 22.96% of the variation, respectively, with a cumulative contribution rate of 82.82%. In the 20–40 cm soil layer, RDA1 and RDA2 explained 53.93% and 21.64% of the variation, respectively, with a cumulative contribution rate of 75.57%. In the 40–60 cm soil layer, RDA1 and RDA2 explained 39.53% and 22.40% of the variation, respectively, with a cumulative contribution rate of 61.93%. In terms of the microbial community composition at the sampling points, except at 8 years, the soil sampling points of apple orchards in other planting years were distributed on the symmetrical 0-year plane. These findings indicate that the duration of apple cultivation has a significant effect on the community structure of soil microorganisms. Regardless of the soil layer, the Gram-positive community was consistent with or similar to that at the 36-year soil sample point. According to forward analysis, the soil Gram-negative and Actinomycetes communities were influenced mainly by pH, BD, and TP, whereas the Gram-positive and Eukaryote communities were less affected by soil environmental factors.

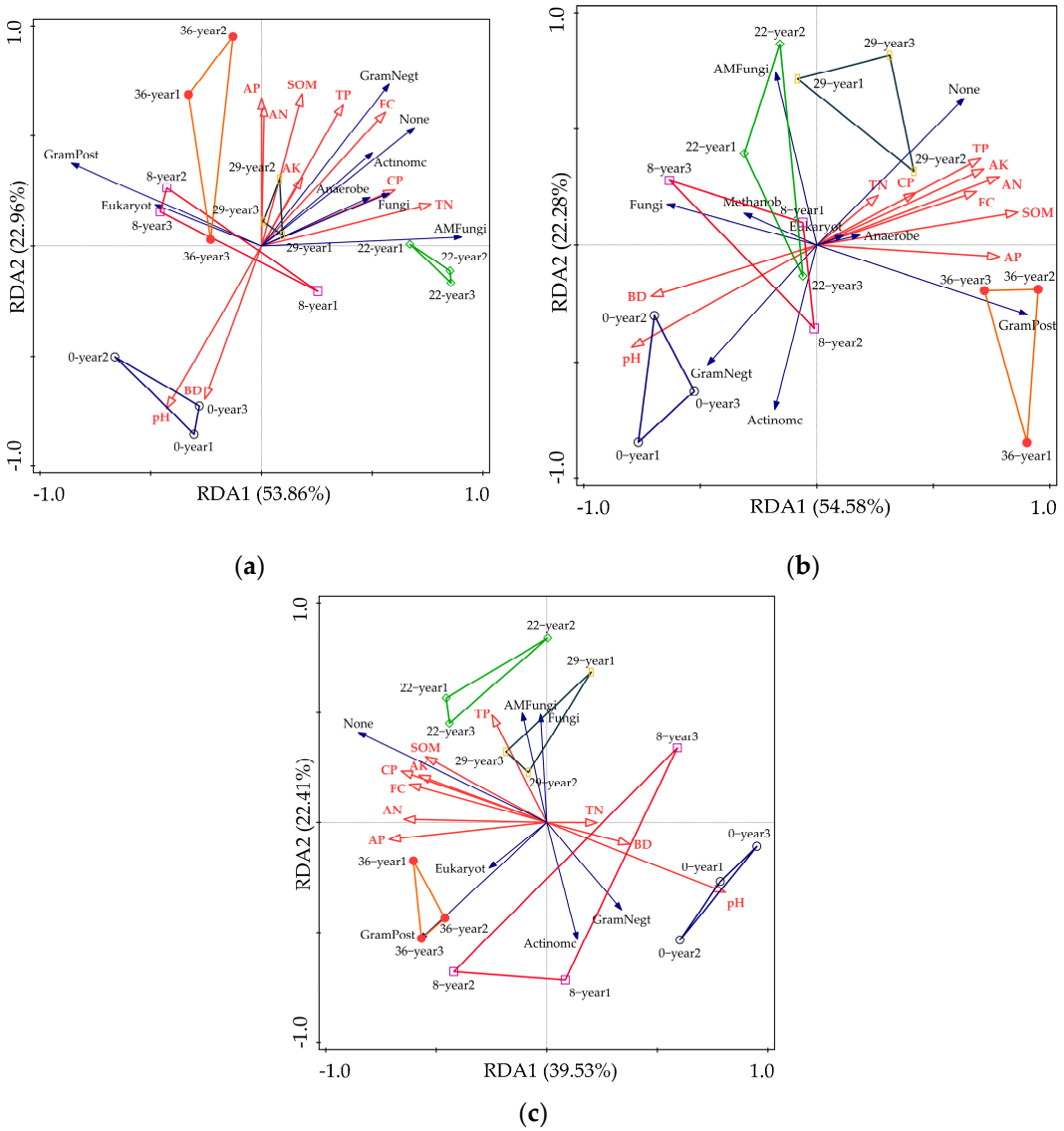

Figure 4. RDA of soil physicochemical properties and the microbial community. (**a**) 0–20 cm; (**b**) 20–40 cm; and (**c**) 40–60 cm.

To disentangle drivers of soil microbial communities, a Structural Equation Model (SEM) was constructed to quantify the effects of year (temporal gradient) and depth (vertical gradient), mediated by the soil's physical and chemical properties (Figure 5). Exogenous variables (Year and Depth) influenced latent variables: Physical Property (represented by bulk density (BD), porosity (CP), field capacity (FC)) and Chemical Property (via pH, soil organic matter (SOM), total nitrogen (TN), etc.). Key pathways showed that Year positively affected both Physical Property (path coefficient = 0.668, $p < 0.001$) and Chemical Property (0.338, $p < 0.01$), while Depth negatively impacted Physical Property (-0.916, $p < 0.001$) but positively affected Chemical Property (0.361, $p < 0.001$). Critically, Chemical Property exerted a strong negative direct effect on microbes (-0.935, $p < 0.001$), whereas Physical Property showed no significant influence (path = -0.008, $p > 0.05$). Soil chemical properties serve as the primary drivers of microbial community structure, with temporal and vertical gradients influencing these communities indirectly through their effects on soil chemistry.

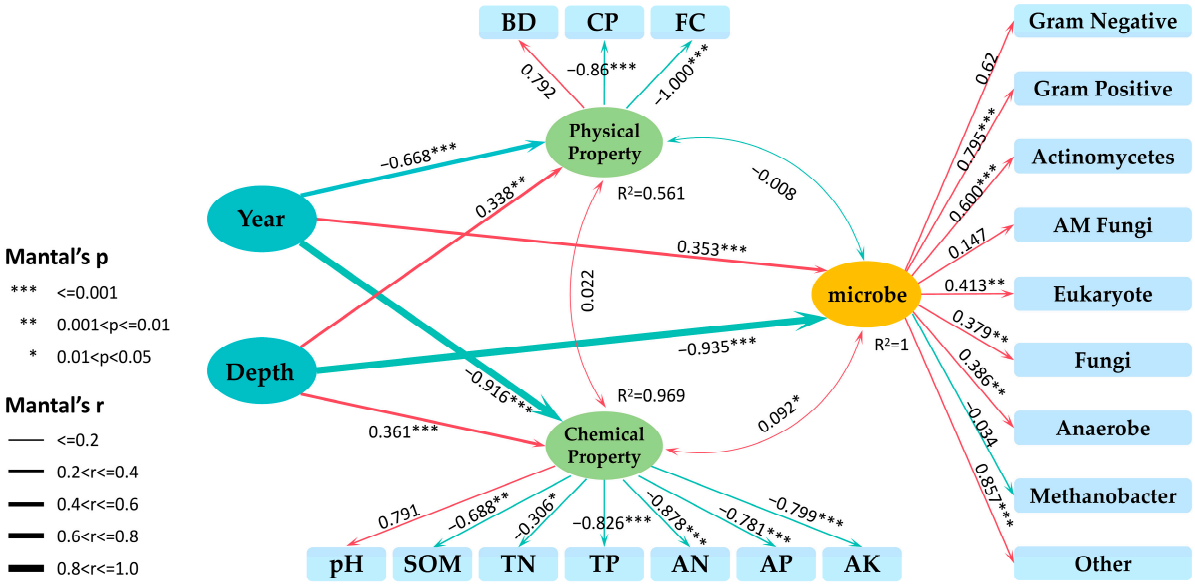

Figure 5. Structural Equation Model Illustrating Microbial Community Assembly Driven by Temporal (Year) and Vertical (Depth) Gradients, Mediated by Soil Physical and Chemical Properties.

4. Discussion

Soil, which serves as the fundamental medium for plant root development and material–energy exchange, modulates crop health via the synergistic interactions of physical, chemical, and biological processes [42]. Simultaneously, the interaction between crops and soil can modify the physicochemical characteristics and microbial community structure of the soil [43]. This study investigated the spatiotemporal dynamics of soil quality in the gneiss mountainous regions of the Taihang Mountains under apple cultivation. By conducting multidimensional analyses of orchard soils with varying planting durations, a range of intricate and significant change patterns was elucidated.

With increasing apple planting duration, significant changes in the soil physical properties occurred. Specifically, the soil bulk density decreased as the porosity increased. These alterations are attributed primarily to orchard management practices, including deep plowing and fertilization, as well as root growth activities. The penetration of root systems and the secretion of root exudates improve the soil aggregate structure, thereby increasing the soil porosity and reducing the bulk density [44,45]. Owing to the accumulation of SOC and TM, the physical structure of the soil improves, and the nutrient content increases gradually [46,47]. However, our findings are slightly different from those of [48]. That study showed that as the number of planting years increased, the soil porosity in the goji berry orchards continuously decreased. This phenomenon is primarily associated with the reduction in SOC within goji berry orchards. Specifically, deep plowing, weeding, and fruit picking operations conducted between rows in goji berry orchards disrupted the soil aggregate structure, accelerated the decomposition of SOC, and consequently led to an increase in soil bulk density and a decrease in porosity.

In terms of soil nutrients, the results of the present study revealed that the soil organic matter content gradually increased with increasing apple planting duration. In the initial stages of cultivation, the substantial application of organic fertilizers and the relatively high vegetation coverage in orchards effectively contributed to the increase in soil organic matter. As the planting duration increased, the soil microbial activity gradually stabilized, nutrient cycling approached equilibrium, and the soil nutrient content remained relatively stable at a certain level. These trends are consistent with the findings of Hou et al. [49]. Notably, these findings contrast with those of Xu et al. [50], who reported a decline in the organic

matter content of orchard soil for apple trees aged between 8 and 15 years. This discrepancy is attributed primarily to the long-term overreliance on inorganic fertilizers, coupled with a neglect of organic fertilizer application. These findings highlight the importance of balanced fertilization strategies in maintaining optimal soil health and fertility in apple orchards.

The total nitrogen (TN) content in the soil first increased and then decreased with the extension of apple cultivation years. This dynamic change may be closely related to management practices and microbial transformation processes. In the early and middle stages of cultivation, the application of organic fertilizers and nitrogenous fertilizers provided a sufficient nitrogen source for the soil, leading to the accumulation of TN. However, in the later stage (after 22 years in the surface layer), with the increase in apple tree age, the demand for nitrogen increased, and the uptake of nitrogen by roots was enhanced. At the same time, the change in microbial community structure may have affected the nitrogen transformation process. For example, the decrease in soil pH may have inhibited the activity of nitrifying bacteria, reducing the mineralization rate of organic nitrogen, thus leading to a decrease in TN content [19]. Zhang et al. [19] reported that, although the total nitrogen content in orchard soil significantly increased during long-term planting, the growth rates of different organic nitrogen components varied significantly. Specifically, the increase in the proportion of non-acidic nitrogen reduced the mineralization rate of soil organic nitrogen, thereby affecting the supply of soil inorganic nitrogen. As the number of years of apple cultivation increased, the contents of soil phosphorus initially tended to increase, followed by a stabilization phase. These findings are consistent with the research results reported by Zhang et al. [19] and Hou et al. [49]. Huang et al. [51] reported that long-term rice cultivation substantially modified the transformation of surface soil phosphorus and diminished its adsorption capacity. This phenomenon is likely associated with alterations in the soil microbial community structure and a decline in enzyme activity.

With respect to soil acidification, our study revealed that the soil pH gradually decreased as the apple cultivation period increased. This finding aligns with the research conducted by Li et al. [52] in apple orchards situated on the Loess Plateau. The observed acidification can likely be attributed to two primary factors: long-term fertilization practices and the release of exudates from apple roots. The application of acidic fertilizers, combined with the selective uptake of cations by the roots, disrupts the inherent acid–base equilibrium of the soil [53,54]. Soil acidification can significantly influence the bioavailability of specific nutrients and reshape the soil's microbial community structure. These changes, in turn, have the potential to exert profound impacts on crop growth and development, highlighting the need for comprehensive management strategies to mitigate the detrimental effects of soil acidification in apple orchards.

In the context of soil biological properties, the soil microbial biomass gradually tends to increase with increasing apple planting duration. These trends were consistent with the findings of Peruzzi et al. [55]. Moreover, the structure of the soil microbial communities in orchards with varying planting durations has undergone substantial transformations. The root exudates of fruit trees, which change across growth stages, provide diverse carbon sources that distinctly influence the colonization patterns of rhizosphere bacterial communities [56]. The shifts in dominant bacterial species and their relative abundances are intricately linked to changes in soil physicochemical properties, with soil organic matter playing a particularly crucial role [57]. Conversely, Arafat [58] reported that as tea tree planting duration increases, the diversity of microbial communities in the rhizosphere soil of tea trees decreases, likely due to a decrease in the soil organic matter content. These contrasting findings suggest that long-term monoculture does not inevitably lead to a decrease in soil microbial community diversity. Instead, this outcome is highly contingent upon cultivation

management practices, highlighting the importance of adopting appropriate management strategies to maintain or increase soil microbial diversity in agricultural systems.

In terms of spatial distribution, the soil quality indicators exhibited pronounced disparities across the various soil depths. The surface soil layer (0–20 cm) has experienced a notable increase in soil quality, which is attributed primarily to the direct influence of orchard management practices and the intensive activity of plant roots. Consequently, all relevant indicators in this layer outperform those in the deeper soil strata. As the soil depth increases, the rate of change in the physical, chemical, and biological properties of the soil gradually diminishes. This vertical differentiation underscores the critical importance of tailoring fertilization, irrigation, and other management strategies to the distinct characteristics of different soil depths in orchard management. By doing so, we can optimize the utilization of soil resources and fully realize the productive potential of the soil, ensuring sustainable and efficient apple cultivation.

There are significant vertical gradients in microbial composition and nutrient accumulation in the soil profile. The surface soil layer (0–20 cm) showed more significant improvements in soil quality, which is mainly attributed to the direct influence of orchard management practices and the intensive activity of plant roots. All relevant indicators in this layer are better than those in deeper soil layers. With the increase in soil depth, the rate of change in the physical, chemical, and biological properties gradually decreases. This may be because the surface soil is more affected by fertilization, tillage, and root activities. Most of the root systems of apple trees are distributed in the 0–40 cm soil layer, and root exudates are more abundant in the surface soil, promoting the growth and reproduction of microorganisms, thus increasing the accumulation of nutrients. In contrast, the deeper soil is less affected by human activities and root activities, so the changes in microbial communities and nutrient contents are relatively small.

5. Conclusions

Apple cultivation has had a profound effect on the physical, chemical, and biological properties of the soil in the gneiss mountainous regions of the Taihang Mountains. As the number of cultivation years increases, a series of discernible changes occur: the soil bulk density decreases while the porosity increases; the contents of soil organic matter, nitrogen, phosphorus, and other nutrients initially increase and subsequently stabilize; and, conversely, the soil pH value tends to decrease. Additionally, the soil microbial biomass has markedly increased, accompanied by alterations in the microbial community structure. Soil chemical properties serve as the primary drivers of microbial community structure, with temporal and vertical gradients influencing these communities indirectly through their effects on soil chemistry.

Significant vertical differentiation was evident in the soil quality indicators across various spatial depths, with more pronounced improvements observed in the surface soil (0–20 cm) than in the deeper soil depths. This spatiotemporal evolution pattern offers a crucial scientific foundation for the sustainable management of apple orchards in the gneiss mountainous areas of the Taihang Mountains.

A long-term soil health monitoring system should be established to regularly detect soil physicochemical properties (such as pH, organic matter, nitrogen, phosphorus, and potassium) and microbial community structure. Monitoring can be carried out every 5 years, and management measures can be dynamically adjusted according to the monitoring results. Specifically, fertilization strategies should be adjusted rationally, with a particular focus on preventing and controlling soil acidification. Irrigation systems need to be optimized to increase water use efficiency. Moreover, soil cultivation management should be strengthened to improve the soil structure. For example, deep plowing

(30–40 cm) can be carried out in the early stage of cultivation (within 8 years) to reduce soil bulk density; in the later stage, conservation tillage such as no tillage or reduced tillage can be adopted to reduce the destruction of soil aggregates. Cover crops such as legumes (e.g., clover) can be planted in the orchard during the slack season (autumn to spring) to increase soil organic matter input and improve soil fertility.

By adopting these comprehensive measures, soil quality can be effectively maintained and improved, ensuring the long-term and sustainable development of the apple industry in this region.

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