

Article

Effects of Sanqi Cultivation on Soil Fertility and Heavy Metal Content in the Sanqi–Pine Agroforestry System

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Abstract

The Sanqi–pine agroforestry (SPA) system is considered a sustainable agroforestry model. However, empirical studies that clearly elucidate the impact of Sanqi cultivation on soil fertility and the heavy metal content within the SPA system are still lacking. This study established monoculture *Pinus armandii* (MPA) and SPA systems to conduct a comparative analysis of dynamic changes in soil physicochemical properties and the heavy metal content of Sanqi and pine over one year (with semi-monthly sampling), followed by a comprehensive evaluation of soil fertility and heavy metal pollution. Following the land use conversion from MPA to SPA, there was a notable increase in soil moisture (SM), total nitrogen (TN), and nitrate nitrogen (NO_3^- -N) levels within Sanqi soil. Conversely, total potassium (TK), ammonium nitrogen (NH_4^+ -N), plumbum (Pb), and chromium (Cr) levels experienced a significant reduction. In the case of pine soil, soil moisture (SM), pH levels, and ammonium nitrogen (NH_4^+ -N) content exhibited an increase. However, soil organic carbon (SOC), total phosphorus (TP), total potassium (TK), zinc (Zn), manganese (Mn), plumbum (Pb), and chromium (Cr) contents all significantly decreased. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) demonstrated that Sanqi cultivation not only significantly enhanced soil fertility for Sanqi rather than pine but also reduced the heavy metal content in the soil of both Sanqi and pine within the SPA system. Furthermore, the Nemerow pollution index for both Sanqi and pine soils has decreased, transitioning the pollution status from relatively safe to safe. This suggests that the introduction of Sanqi promotes the sustainable development of the SPA system.

Keywords: Sanqi–pine agroforestry system; soil heavy metals; soil fertility; entropy weight method; TOPSIS; Nemerow pollution index



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1. Introduction

Soil serves as the foundation for the health and sustainable development of agroforestry systems [1]. However, heavy metals, as toxic substances, are characterized by their

strong bioaccumulation potential and persistent environmental presence, posing substantial risks to both ecological systems and human health [2,3]. On one hand, geochemical and geological/mineral factors are crucial in shaping soil properties, nutrient availability, as well as the concentrations and migration of heavy metals, which collectively determine the chemical composition and physical structure of soil, thereby exerting significant impacts on plant growth and ecosystem health [4]. On the other hand, factors such as plant introduction [5], soil niche [6], and seasonal dynamics [7] can significantly influence soil fertility and heavy metal content by regulating both biotic and abiotic factors. The level of soil fertility and the extent of heavy metal contamination are critical for the healthy development of agroforestry systems [8]. Hence, a systematic assessment of soil fertility is crucial for providing a scientific basis for species configuration in agroforestry systems [9,10]. Additionally, a comprehensive analysis of the content and pollution status of heavy metals in agroforestry systems is significant for ensuring the sustainable development of these systems. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) primarily used for descriptive and comparative analysis, is a multi-criteria decision-making method based on the positive and negative ideal solution [11]. Previous studies have revealed that determining the weights of various indicators through the entropy weight method and constructing an evaluation system combined with the TOPSIS model demonstrates objectivity and accuracy [12]. Heavy metal contamination in agroforestry systems originates from a mix of natural sources, such as the weathering of metal-bearing rocks, volcanic eruptions [2], and atmospheric deposition [13], as well as anthropogenic sources including industrial emissions, agricultural practices, and transportation [14–16]. In the assessment of soil heavy metal pollution, the Nemerow method effectively reflects the overall pollution status through a comprehensive index, which is particularly crucial for evaluations under complex geological conditions [17]. This approach not only circumvents the one-sidedness of single-factor evaluation but also overcomes the dilution effect of simple averaging methods [17].

Agroforestry ecosystems combine the cultivation techniques of trees and crops, representing a sustainable development strategy that profoundly affects soil fertility and the concentration of heavy metals [18]. It is also significantly influenced by the species of plants, the ecological niches of the soil, and the fluctuations of the seasons [5–7]. Studies have shown that introducing plants can significantly enhance the soil fertility of both native trees and the introduced plants [19]. For instance, the *Camellia sinensis*–*Juglans regia*/*Glycine max* agroforestry system notably increased the soil pH, ammonium nitrogen, nitrate nitrogen, and organic matter content in *C. sinensis* soil [20,21]. Similarly, the *Saccharum officinarum*–*G. max* agroforestry system also significantly improved the organic carbon and nitrate nitrogen content in *G. max* soil [22]. However, the effects of introducing plants on the heavy metal content in both in situ trees and the soil of the introduced plants are inconsistent [5]. For example, agroforestry systems such as *Sedum plumbizincicola*–*Triticum aestivum*/*Phyllostachys praecox*/*Phyllostachys edulis* [23–25] and *Citrus reticulata*–*C. sinensis* [26] can effectively reduce the heavy metal content in soil. The Mn and Zn content in *C. sinensis* soil were increased in the *C. sinensis*–*C. reticulata* system, whereas the Cu, Zn, and Cd content in *Sedum plumbizincicola* soil showed an increasing trend in the *Phyllostachys edulis*–*Sedum plumbizincicola* system [24,26]. This is attributed to differences in the introduction or in situ plant species [5,27,28], variations in soil properties [29], and alterations in enzyme activity [30]. Moreover, alterations within specific ecological niches can exert an influence on soil fertility and the content of heavy metals. For example, within the *Capsicum annuum*–*Zea mays* intercropping system, a notable increase in available potassium, total nitrogen, and organic matter content was observed in the rhizosphere rather than non-rhizosphere soil of *Capsicum annuum* [31]. Conversely, in the *Tamarix*

ramosissima/*Phyllostachys praecox*–*Sedum plumbizincicola* system, the concentrations of Zn, Cu, Pb, and Cd in the rhizosphere soil of *Phyllostachys praecox* and *Tamarix ramosissima* were significantly reduced, as opposed to the non-rhizosphere soil [6,25]. These variations may be intricately linked to root exudation [32], plant absorption capabilities [33], transpiration intensity [34], and processes of heavy metal chelation [35].

Sanqi (*Panax notoginseng*), a precious traditional Chinese medicinal herb, primarily grows in Yunnan and Guangxi Provinces of China [36]. Research has shown that Sanqi has significant pharmacological effects, including the enhancement of immunity, reduction in inflammation, lowering of blood pressure, and inhibition of tumor growth [37–39]. However, to meet the increasing market demand, some farmers have adopted strategies such as expanding cultivation areas and relying heavily on pesticides and chemical fertilizers to boost yield. This practice not only exacerbates the problem of continuous cropping obstacles but also adversely affects the quality of Sanqi. As a local medicinal herb in Yunnan Province, Sanqi contributes to over 50 percent of the total output value of the province's traditional Chinese medicine industry. The cultivation of Sanqi from the forest understorey aligns with China's Non-agricultural use of cultivated land, addressing the industrial challenge of Sanqi's lack of available cultivation land. Recent studies have demonstrated that Sanqi cultivated from the *P. armandii* forest has been proven to effectively alleviate continuous cropping obstacles [40], improve quality [41], enhance nitrogen fixation capacity [42], and significantly reduce contamination risks [43]. Furthermore, Sanqi can transfer beneficial microorganisms to pine trees and mitigate carbon limitation issues within the microbial communities of pine soil [44,45]. In addition, during the organic cultivation of Sanqi, the avoidance of chemical fertilizers and pesticides may subject its growth and quality to the influence of soil fertility and heavy metal content. Simultaneously, the root system activity of *P. armandii* and the decomposition of its litter also exert significant impacts on the dynamics of soil fertility and heavy metals. Therefore, an in-depth investigation into the effects of Sanqi cultivation on soil fertility and heavy metal content in the SPA system will not only help optimize species allocation in agroforestry systems but also provide theoretical support for formulating scientific and rational soil management strategies. This study established monoculture *P. armandii* (MPA) and SPA systems to comparatively analyze the dynamic changes in soil physicochemical properties and heavy metal content of Sanqi and *P. armandii* over one year (with biweekly sampling). A comprehensive evaluation was further conducted on soil fertility and heavy metal pollution. The following hypotheses were proposed: (I) Sanqi cultivation significantly enhances soil fertility for Sanqi rather than pine, with an increase of over 50%, and (II) reduces the heavy metal content in the soil of both Sanqi and *P. armandii* within the SPA system by 18% and 39%, respectively. This research revealed the impact of Sanqi cultivation on the relationship between soil fertility and heavy metal content, providing a scientific basis for the health and sustainable development of the SPA system.

2. Materials and Methods

2.1. Research Location

This study was conducted in Dadishui Village, Xundian County, Kunming City (103°12'45" E, 25°28'18" N), which belongs to the subtropical plateau monsoon climate zone and exhibits distinct monsoon climate characteristics [42]. Winters and springs are relatively dry with scarce rainfall, while summers and autumns are humid and rainy. The average annual precipitation reaches 1900 mm, and the mean annual temperature is 14.5 °C. In the SPA system, the forest slope ranges between 5° and 15°, with an elevation of approximately 2199 m. The soil type is red earth, and the forest is predominantly composed

of *P. armandii* trees planted over 30 years ago, with a canopy density of about 0.7–0.9, an average diameter at breast height of 18 cm, and an average tree height of 9.5 m.

Before commencing the cultivation of Sanqi, the undergrowth was meticulously cleared of weeds, small shrubs, and decomposing leaves. Following this, the area underwent thorough deep plowing, executed two to three times with a compact rotary tiller, penetrating to a depth of 20 to 30 cm. Subsequently, the soil in the undergrowth was expertly fashioned into raised beds, which followed the natural contour lines of the terrain. These beds formed plots with dimensions of 10 to 20 m in length, 1 to 1.5 m in width, and a height ranging from 0.30 to 0.40 m. Following the method proposed by Jia et al. [44], in January 2020, we transplanted one-year-old Sanqi seedlings at a spacing of 10–15 cm × 10–15 cm per plant, with a transplanting depth of 3–5 cm, and immediately covered them with a 3–5 cm thick layer of pine needles post-transplantation. Routine management measures primarily involved the prohibition of pesticide and chemical fertilizer use, manual rodent control, and the installation of a drip irrigation system to regularly supplement water during the dry season.

2.2. Experimental Design and Soil Sampling

We utilized a randomized block design to conduct two experiments to examine the effects of land use conversion from the MPA to the SPA system on the soils of Sanqi and *P. armandii*, respectively (Figure 1). The five treatments and their abbreviation were as follows:

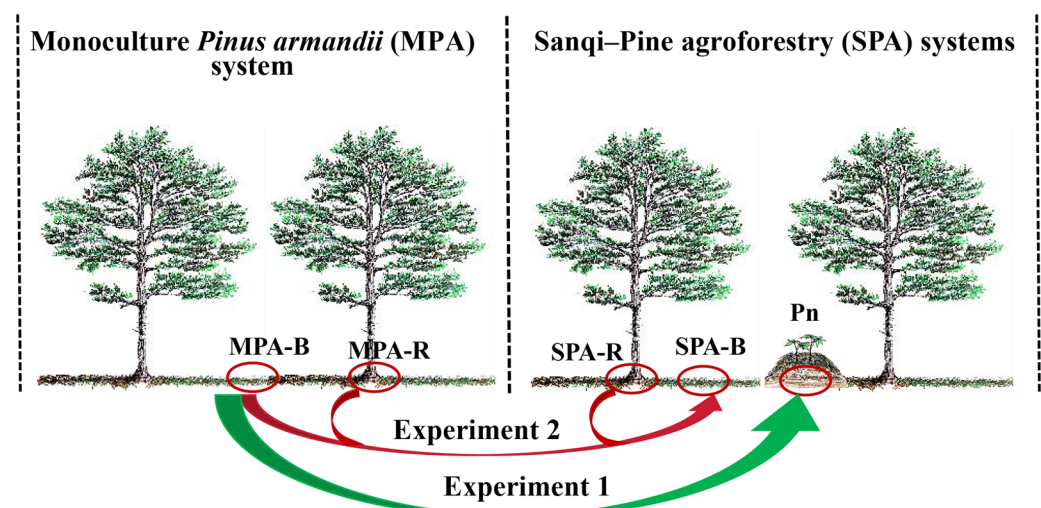


Figure 1. Design of experiment in the MPA and SPA systems. The green and red arrows denote the Experiment 1 and Experiment 2, respectively.

Experiment 1: To investigate the impact of the transition from the MPA system to the SPA system on soil fertility and heavy metal content in Sanqi, we established two treatment groups: one was the bulk soil of the MPA system (MPA-B), and the other was the soil cultivated with Sanqi in the SPA system (Pn).

Experiment 2: To clarify the effects of Sanqi cultivation on soil fertility and heavy metal content in *P. armandii* soils, we designed four treatment groups. These included the bulk soil of the MPA system (MPA-B), the rhizosphere soil of the MPA system (MPA-R), the bulk soil of the SPA system (SPA-B), and the rhizosphere soil of the SPA system (SPA-R).

Given the presence of repeated treatments in Experiments 1 and 2, this study included a total of 5 different treatments. For each treatment, 3 replicate plots (each measuring 10 m × 10 m) were established, resulting in a total of 15 plots. The monitoring period spanned a full year (from 10 September 2020, to 20 August 2021). During this period, we

collected a total of 360 soil samples, calculated as follows: 5 (treatments) $\times$ 3 (plot replicates per treatment) $\times$ 12 (months) $\times$ 2 (sampling/semi-month). Soil samples were collected using the five-point sampling method and thoroughly mixed to form a single composite sample [42]. The soil adhering to the root surface (0–2 mm) of *P. armandii* was considered as rhizosphere soil [46]. Simultaneously, soil samples were collected approximately 20 cm away from the roots of *P. armandii* to serve as bulk soil. The collected soil samples were rapidly transported back to the laboratory using dry ice. After sieving through a 2 mm mesh screen, the samples were divided into two groups and stored at 4 °C and room temperature, respectively, for subsequent analysis.

2.3. Determination of Soil Properties

Soil moisture (SM) was calculated by measuring the ratio of the wet weight of the soil to its dry weight [44]. A pH meter (Model AB23 PH-F, Beijing, China) was used to determine the soil pH value [47]. The potassium dichromate oxidation method was employed to measure the soil organic carbon (SOC) [48]. A continuous flow analyzer (Seal Auto Analyzer AA3, Berlin, Germany) was utilized for precise quantitative analysis of total nitrogen (TN), total phosphorus (TP), ammonium nitrogen ($\text{NH}_4^+\text{-N}$), and nitrate nitrogen ($\text{NO}_3^-\text{-N}$) [49]. After digestion with $\text{HF-HCl-HNO}_3\text{-HClO}_4$, the content of elements such as total potassium (TK), zinc (Zn), copper (Cu), manganese (Mn), lead (Pb), chromium (Cr), and cadmium (Cd) was determined by flame atomic absorption spectrometry AA-6300 (Shimadzu, Kyoto, Japan) [43].

2.4. TOPSIS Analysis of Soil Fertility and Heavy Metals

We selected SM, pH value, TN, TP, TK, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, and SOC to evaluate soil fertility and chose Zn, Cu, Mn, Pb, Cr, and Cd to comprehensively assess heavy metal pollution levels. First, standardize the physicochemical properties and heavy metal content of the soil, and then determine the weights of each indicator based on the entropy weight method. Subsequently, calculate the relative closeness of soil fertility and heavy metal content using the improved Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method [50]. The specific methods are as follows:

① Entropy method weighting analysis.

(a) Data standardization:

$$\text{Positive indicators : } u_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (1)$$

$$\text{Negative indicators : } u_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (2)$$

where u_{ij} is the value of indicator j in the i sample ($i = 1, 2, n; j = 1, 2, n$), and $\max(x_{ij})$ and $\min(x_{ij})$ are the maximum and minimum values, of indicator x_{ij} , respectively, and u_{ij} is the normalized x_{ij} .

(b) Calculate the weight of the i sample data under the j indicator for that indicator a_{ij} :

$$a_{ij} = \frac{u_{ij}}{\sum_{i=1}^n u_{ij}} \quad (3)$$

(c) Taking E_j as the entropy value of the j indicator:

$$E_j = -k \sum_{i=1}^n a_{ij} \ln(a_{ij}), k = 1 / \ln(n) > 0, E_j \geq 0 \quad (4)$$

(d) Weighting of the Indicator W_j :

$$W_j = \frac{1 - E_j}{\sum_{j=1}^m D_j} \quad j = 1, 2, 3, \dots, m \quad (5)$$

② Comprehensive analysis by improved TOPSIS method.

(a) Normalize the original matrix $R = (r_{ij})_{m \times n}$ to obtain a normalized decision matrix $Z = \{Z_{ji}\}$:

$$Z_{ji} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^m r_{ij}^2}} \quad i = 1, m; j = 1, n \quad (6)$$

(b) Obtain the weighted decision evaluation matrix $X = (x_{ij})$:

$$x_{ij} = W_j \times Z_{ji}, \quad i = 1, m; j = 1, n \quad (7)$$

(c) Determine the positive and negative ideal solutions for each indicator:

The positive ideal solution:

$$x^1_j = \begin{cases} \max\{x_{ij}\} \\ \min\{x_{ij}\} \end{cases}, j = 1, n \quad (8)$$

The negative ideal solution:

$$x^2_j = \begin{cases} \min\{x_{ij}\} \\ \max\{x_{ij}\} \end{cases}, j = 1, n \quad (9)$$

(d) Distances to positive and negative ideal solutions were calculated for each indicator.

The distance from x_j to the positive ideal solution is:

$$d^1_j = \sqrt{\sum_{i=1}^m (x_{ij} - x^1_j)^2} \quad i = 1, m \quad (10)$$

The distance from x_j to the negative ideal solution is:

$$d^2_j = \sqrt{\sum_{i=1}^m (x_{ij} - x^2_j)^2} \quad i = 1, m \quad (11)$$

(e) Calculation of relative proximity:

$$C_i = d^2_j / (d^2_j + d^1_j), \quad i = 1, m \quad (12)$$

C_i represents the relative proximity, and its value range is [0, 1]. The larger the value of C_i for soil fertility and heavy metals, the higher the content of soil fertility and soil heavy metals.

2.5. Evaluation of the Contaminated Levels of Heavy Metals

According to the “Soil Environmental Quality Risk Control Standard for Agricultural Land” (GB15618-2018) [51], the risk screening values for heavy metals in soil environmental quality are shown in Table 1. Upon the application of Equations (1) and (2), it is possible to ascertain the pollution levels of individual heavy metals and a combination of six heavy metals, respectively [52]. For comprehensive evaluation criteria, reference should be made to Table 2.

Table 1. Risk screening values for heavy metals in soil environmental quality.

Heavy Metals	Risk Screening Value (mg/kg)
Zn	200
Cu	50
Mn	626
Pb	90
Cr	150
Cd	0.3
pH	$5.5 < \text{pH} \leq 6.5$

Table 2. Classification criteria of the Nemerow pollution index.

Pollution Class	P_i	Pollution Degree	P_{com}	Pollution Degree
I	$P_i \leq 1.0$	Safety	$P_{Com} \leq 0.7$	Clean (safety)
II	$1.0 < P_i \leq 2.0$	Slight pollution	$0.7 < P_{Com} \leq 1.0$	Clean (threshold)
III	$2.0 < P_i \leq 3.0$	Moderate pollution	$1.0 < P_{Com} \leq 2.0$	Slight pollution
IV	$3.0 < P_i$	Strong pollution	$2.0 < P_{Com} \leq 3.0$	Moderate pollution
V			$P_{Com} > 3.0$	Strong pollution

$$P_i = C_i / S_i \quad (13)$$

$$P_{Com} = \left\{ \left(P_{max}^2 + P_{ave}^2 \right) / 2 \right\}^{1/2} \quad (14)$$

C_i represents the content of heavy metal (i), S_i is the risk screening value for soil heavy metals, P_{Com} denotes the Nemerow pollution index, and P_{ave} and P_{max} indicate the average and maximum values of P_i , respectively.

2.6. Sensitivity Analysis

Sensitivity analysis can not only reveal the relative contribution of various parameters to the assessment results but also serves as an important method to verify the rationality of the selected indicators [53]. A higher sensitivity index for different parameters indicates a greater influence of those parameters on the assessment results.

$$S_i = \frac{\left| \left(\frac{V_i}{N} - \frac{v_i}{n} \right) \right|}{V_i} \times 100\%$$

where S_i represents the sensitivity of i th assessing unit, V_i and v_i are the values of i th assessing unit and i th input index after removal, N and n are the number of parameters.

2.7. Statistical Analysis

The Shapiro–Wilk test and Levene’s test were employed to evaluate the normality and homogeneity of variance of the dataset, respectively. Consequently, SPSS 19.0 software (SPSS, Inc., Chicago, IL, USA) was used to conduct a repeated measures analysis of variance (RMANOVA) to evaluate the physicochemical properties, heavy metal content, and their relative proximity in soils under different treatments. Post hoc comparisons were conducted using Tukey’s HSD test, and confidence intervals were estimated using frequentist approaches. The corrplot and readxl packages in R language (Version 1.6.2) were utilized to generate correlation heatmaps between soil physicochemical properties and heavy metals. During the correlation analysis, to effectively minimize the likelihood of false positive findings, the data underwent correction for false discovery rate (FDR).

3. Results

3.1. Variation Characteristics of Edaphic Factors and Evaluation of Soil Fertility in MPA and SPA Systems

The annual dynamic changes in soil factors exhibited certain differences (Figure 2A). Analysis of annual average values showed that after land use conversion from MPA to SPA, the contents of SM, TN, and NO_3^- -N in Sanqi soil increased significantly, while TK and NH_4^+ -N contents decreased significantly. No significant differences were observed in pH value, SOC, and TP contents (Figure 2B, Table S1). Moreover, the cultivation of Sanqi significantly increased the SM, pH, and NH_4^+ -N content in the soil of *P. armandii*, whereas the SM content and pH value in bulk soil were higher than those in rhizosphere soil. In contrast, the contents of TN, TP, TK, and SOC decreased in the soil of *P. armandii*, with no significant difference observed between rhizosphere and bulk soils (Figure 2B). Additionally, there was no significant difference in NO_3^- -N content between the MPA and SPA systems.

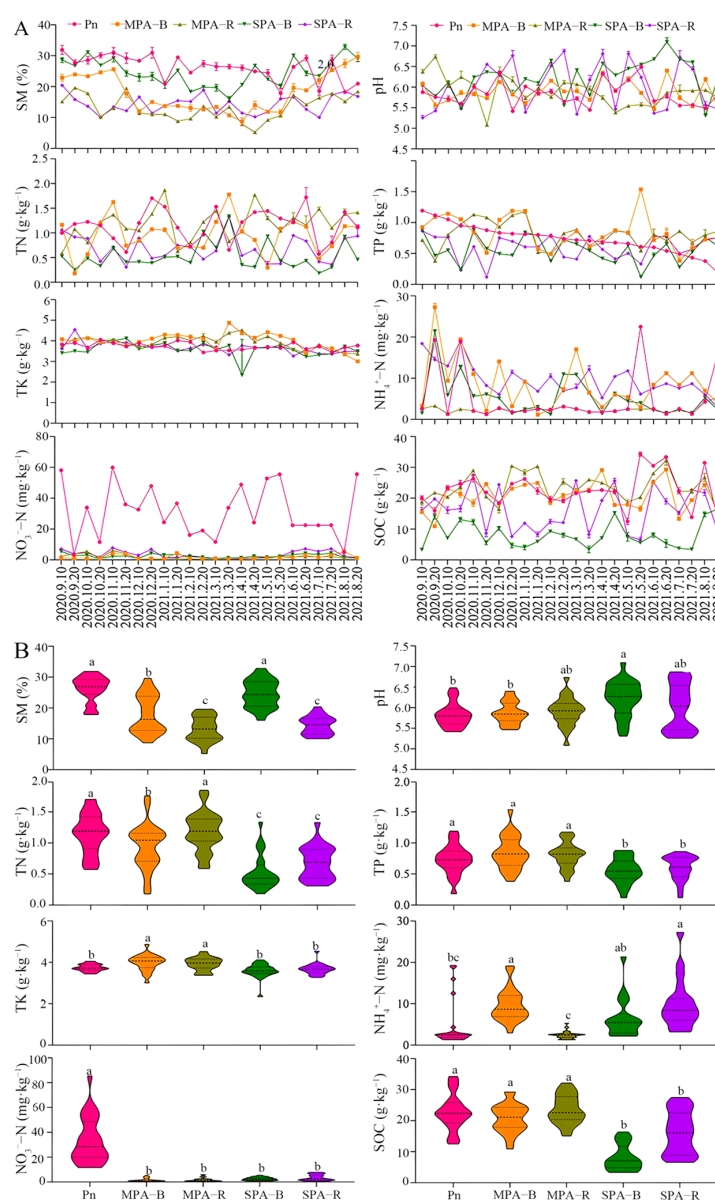


Figure 2. Dynamic variations in soil physicochemical properties over one year (A) and annual average values (B). Different lowercase letters indicate significant differences between treatments.

Utilizing the entropy weight method and an enhanced TOPSIS technique, we conducted a thorough assessment of soil fertility within both MPA and SPA. The annual variation range of relative proximity across various treatments was observed to be between 0.056 and 0.924 (Figure 3A). The cultivation of Sanqi significantly increased the relative proximity of soil fertility ($p < 0.05$). Annual data revealed that in the MPA system, the relative proximity of bulk soil fertility for *P. armandii* is significantly higher than that of rhizosphere soil, whereas in the SPA system, no significant difference is observed between the relative proximity of bulk and rhizosphere soil fertility for *P. armandii* (Figure 3B, Table S2). The two-factor analysis of variance indicated that the treatment significantly affected soil fertility ($p < 0.001$), while the interaction between time and treatment did not show significant effects (Table S3).

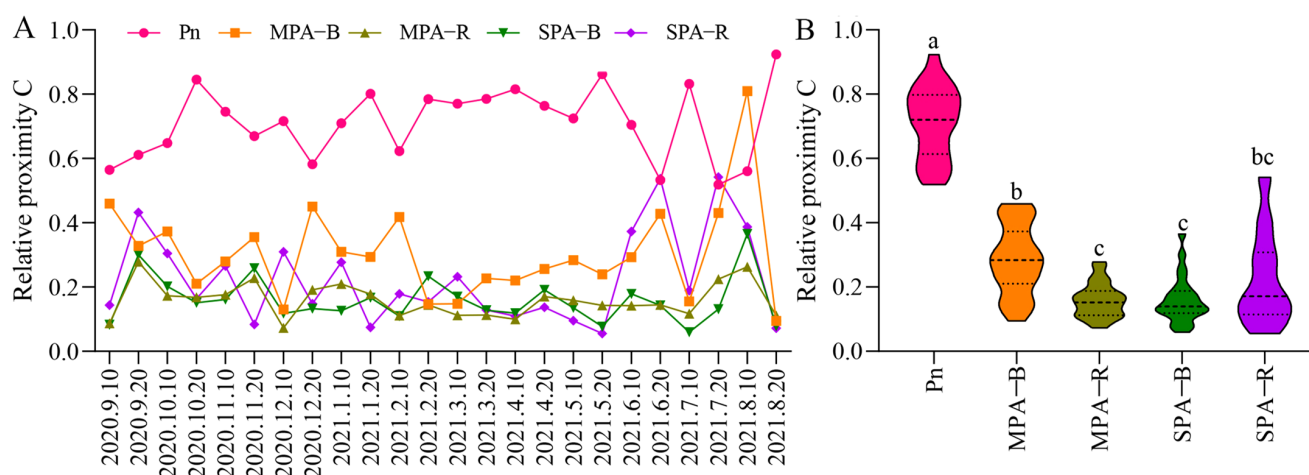


Figure 3. Changes in relative proximity C over one year (A) and annual average values (B). Different lowercase letters indicate significant differences at $p < 0.05$ level.

3.2. Analysis of Soils Heavy Metal Variation Characteristics and Pollution in MPA and SPA System

The annual dynamic changes in heavy metals in soil are shown in Figure 4A. When the land use transitioned from pure forest to Sanqi, the Pb and Cr contents in Sanqi soil decreased significantly, while the changes in Zn, Cu, Mn, and Cd contents were not significant (Figure 4B). Meanwhile, the contents of Zn, Mn, Pb, and Cr in *P. armandii* soil also decreased significantly, while the changes in Cu and Cd contents were not obvious. Furthermore, in both MPA and SPA systems, except for Mn, no significant differences were observed in the contents of other heavy metals between rhizosphere and non-rhizosphere soils of *P. armandii* (Figure 4B, Table S4).

Utilizing the entropy weight method and an enhanced TOPSIS technique, we conducted a thorough evaluation of the concentrations of six heavy metals. This study revealed that the annual variation range of relative proximity for heavy metals in soils subjected to different treatments was between 0.026 and 0.962 (Figure 5A). As the land use pattern transitioned from pure forest to Sanqi, the relative proximity of heavy metals in both Sanqi and pine soils exhibited a significant decrease, with no significant difference noted between the non-rhizosphere and rhizosphere soils of pine trees (Figure 5B, Table S5). As indicated in Table S6, the treatment, time, and their interaction significantly affect soil heavy metal content.

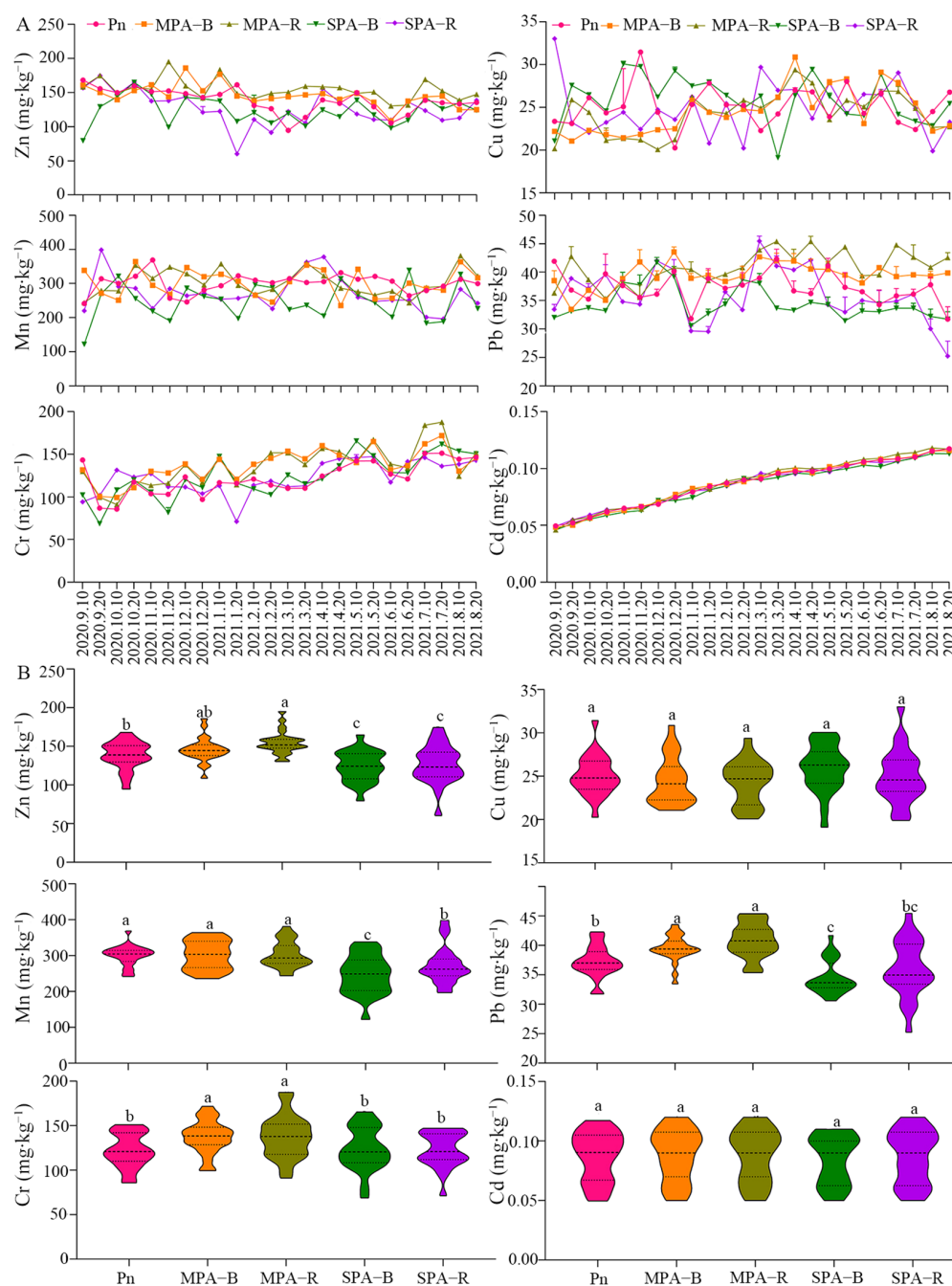


Figure 4. Dynamic variations in soil heavy metals one year (A) and annual average values (B). Different lowercase letters indicate significant differences at $p < 0.05$ level.

The pollution level of heavy metals in the soil was assessed using the Nemerow pollution index (Tables 3 and S7). The Nemerow pollution index values for the different treatments ranged from 0.784 to 0.971, all falling below 1.0, indicating that the soil was in a relatively clean (threshold) degree. The Nemerow pollution index for heavy metals in both Sanqi and pine soils shows a significant decrease after Sanqi cultivation, indicating that the pollution level of the soils has improved from the clean (threshold) to clean (safe). Furthermore, the non-rhizosphere rather than rhizosphere soil of the pine exhibited lower pollution levels.

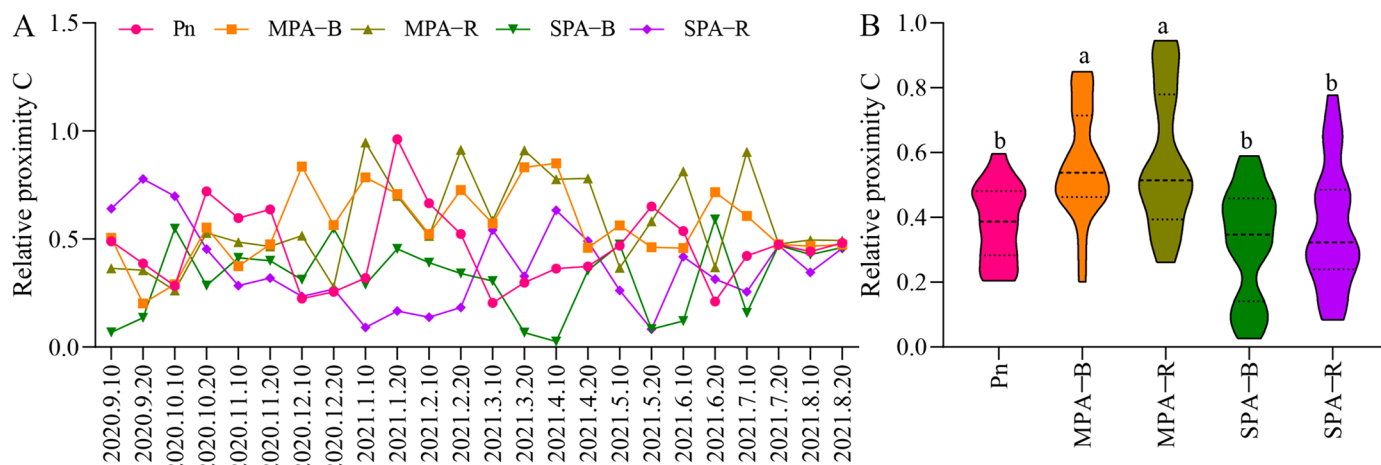


Figure 5. Changes in relative proximity C of heavy metals over one year (A) and annual average values (B). Different lowercase letters indicate significant differences at $p < 0.05$.

Table 3. Nemerow pollution index of heavy metals in the Sanqi and pine soils.

	P_i (Zn)	P_i (Cu)	P_i (Mn)	P_i (Pb)	P_i (Cr)	P_i (Cd)	P_{com}
Pn	0.69 ± 0.004 c	0.50 ± 0.006 b	0.48 ± 0.002 b	0.41 ± 0.013 c	0.81 ± 0.007 b	0.29 ± 0.001 b	0.808 ± 0.008 d
MPA-B	0.73 ± 0.005 b	0.49 ± 0.003 c	0.48 ± 0.002 a	0.43 ± 0.011 b	0.92 ± 0.009 a	0.290 ± 0.001 b	0.901 ± 0.004 b
MPA-R	0.77 ± 0.006 a	0.49 ± 0.004 c	0.48 ± 0.002 a	0.45 ± 0.008 a	0.92 ± 0.009 a	0.29 ± 0.001 a	0.971 ± 0.003 a
SPA-B	0.62 ± 0.009 e	0.52 ± 0.004 a	0.39 ± 0.001 d	0.38 ± 0.010 d	0.83 ± 0.010 b	0.28 ± 0.001 c	0.858 ± 0.012 c
SPA-R	0.64 ± 0.005 d	0.50 ± 0.003 b	0.44 ± 0.001 c	0.40 ± 0.012 cd	0.82 ± 0.008 b	0.290 ± 0.001 b	0.784 ± 0.010 e

Note: Different lowercase letters indicate significant differences at $p < 0.05$ level.

3.3. Sensitivity Analysis in the TOPSIS and Nemerow Index

In this study, a sensitivity analysis was conducted to identify the key factors influencing soil fertility, soil heavy metals, and the Nemerow index. The results indicated that NO_3^- -N exerted the most significant influence on soil fertility, with a sensitivity of up to 14.33% (Figure 6A). Furthermore, the degree of impact of each parameter on soil heavy metals and the Nemerow index followed the order: $\text{Cr} > \text{Cd} > \text{Pb} > \text{Cu} > \text{Zn} > \text{Mn}$ and $\text{Cr} > \text{Cd} > \text{Mn} > \text{Pb} > \text{Cu} > \text{Zn}$, respectively (Figure 6B,C).

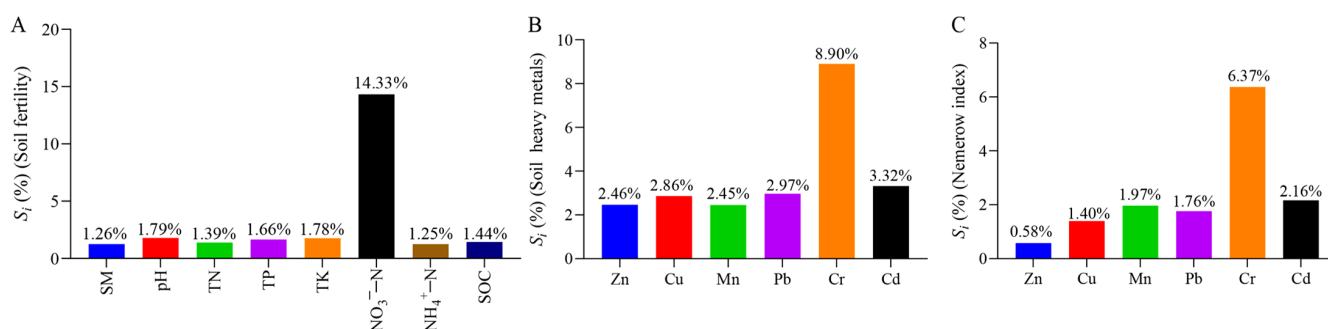


Figure 6. Analysis of average sensitivity for soil fertility (A), soil heavy metals (B), and Nemerow index (C).

3.4. Analysis of the Correlation Between Physicochemical Properties and Heavy Metals in the Soils of Sanqi and *P. armandi*

There was a significant negative correlation between soil fertility and heavy metal content ($p < 0.001$), indicating that higher soil fertility generally corresponds to lower heavy metal levels (Figure 7). For Sanqi soils, Pb exhibited negative correlations with soil SM and NO_3^- -N (Figure 8A). Cr also showed negative correlations with both SM and TP

content. Similarly, Cd displayed a negative correlation with TP content. However, Zn was positively correlated with TK, TP, and $\text{NH}_4^+\text{-N}$ (Figure 8A). Additionally, soil pH was positively correlated with Cu content. For pine soils (Figure 8B), the content of Zn showed a negative correlation with SM and pH but exhibited significant positive correlations with TK, TN, TP, and SOC content ($p < 0.01$). Both Mn and Pb were negatively correlated with SM, while demonstrating significant positive correlations with TK, TN, TP, and SOC content. Cr displayed a positive correlation with TN but showed significant negative correlations with $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$. Cd exhibited negative correlations with TK and $\text{NH}_4^+\text{-N}$, respectively.

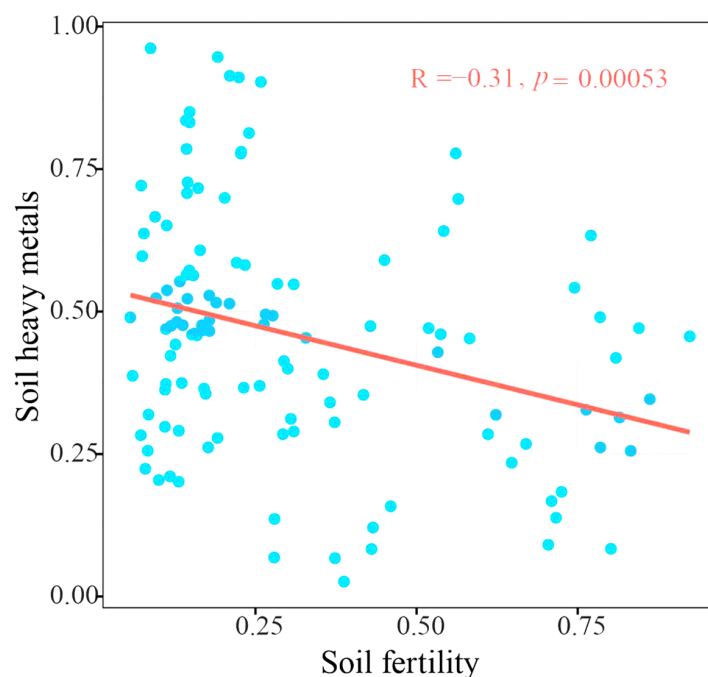


Figure 7. Correlation analysis between the soil fertility and the soil heavy metals. The gray shaded area shows the 95% confidence interval of the fit.

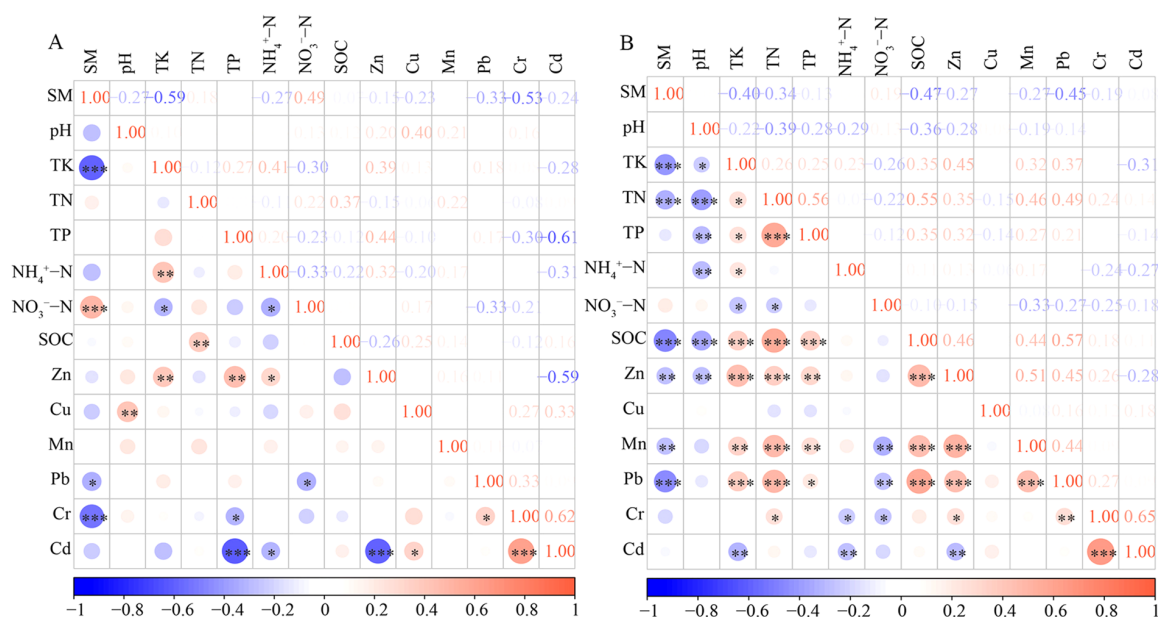


Figure 8. Spearman correlation analysis of soil heavy metals and edaphic factors in the soil of Sanqi (A) and pine (B). ***, **, and * represent $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively.

4. Discussion

4.1. The Land Use from the MPA to the SPA System Enhanced the Soil Fertility for Sanqi Rather than *P. armandi*

Compared to the MPA system, the SPA system significantly increased the SM, TN, and NO_3^- -N content in Sanqi soil, while also enhancing the pH, SM, and NH_4^+ -N levels in *P. armandi* soil (Figure 2). There are variations in the practices of different plants within agroforestry systems, which subsequently result in differences in soil nutrient composition. For instance, the sugarcane–soybean system has been shown to significantly increase NO_3^- -N content in the soil of soybean [22], while the tea–soybean system has assisted in improving the pH and increasing NH_4^+ -N content in the soil of tea [21]. During the cultivation process of Sanqi, reducing direct sunlight exposure [54], regularly replenishing water [55], and applying pine needle litter [56] can effectively minimize soil moisture evaporation, thereby increasing soil water content. Meanwhile, the application of organic fertilizers (such as humic acid) provides soil microorganisms with sufficient carbon sources, effectively enhancing microbial activity, thereby strengthening nitrogen mineralization and significantly increasing inorganic nitrogen content in the soil [45,57]. Additionally, prior to cultivating Sanqi, the application of lime is used to raise soil pH levels to meet the growth requirements of Sanqi and to facilitate the accumulation of its medicinal components [58]. TOPSIS analysis results further revealed that introducing Sanqi into the SPA system could significantly enhance the soil fertility of Sanqi, while the soil fertility of *P. armandi* remained relatively stable (Figure 3). The entropy weight and sensitivity analysis also indicated that NO_3^- -N contributed the most to enhancing soil fertility, accounting for 26.29% and 14.33%, respectively. Previous studies have shown that NO_3^- -N has a direct effect on soil fertility [59]. In addition, cultivation of Sanqi increases the diversity and network complexity of nitrogen-fixing microorganisms [42]. Therefore, we concluded that the addition of organic fertilizer and changes in nitrogen-fixing microorganisms were the main factors that increased NO_3^- -N content.

4.2. Land Use Conversion of the MPA to the SPA System Reduced Heavy Metal Content in the Soil of Sanqi and *P. armandi*

With land use converted from MPA to SPA, a significant decrease in Pb and Cr content was observed in the Sanqi soil. Concurrently, the Zn, Mn, Pb, and Cr content in *P. armandi* soil also exhibited a notable declining trend (Figure 4). Moreover, the relative proximity of heavy metals decreased in both Sanqi and pine soils. These findings align with research results from agroforestry systems such as *Sedum plumbizincicola*–*Triticum aestivum* / *Phyllostachys violascens* / *Phyllostachys edulis*, as well as *Citrus reticulata*–*Camellia sinensis* [23–26]. However, the types of heavy metal content reduction in the SPA system differ from those in other agroforestry systems, which is attributed to factors such as the nutrient requirements of Sanqi, soil tillage, water management, organic fertilizer application, and so on. The intercropping model significantly enhances plants' heavy metal absorption capacity by promoting root secretion of organic acids [60,61]. Prior study has indicated that the chelating properties of organic acids are especially important because they create stable complexes with metals, increasing their mobility and availability for plant uptake [62]. Organic acids, including phenolic and palmitic acids, obtained from the roots of Sanqi plants cultivated in forests rather than on farmland [47], may stabilize and solubilize metal ions in the soil, thereby promoting their transport to plant roots. Moreover, Sanqi cultivation can alter the community structure of bacteria, fungi and nitrogen-fixing bacteria in the soil [42,44], and changes in their community structure or activity could result in lead to changes in metal morphology and bioavailability. Previous studies have indicated that the SPA system improved the heavy metal uptake ability of both Sanqi and

P. armandii [43], while demonstrating no negative impact on either the quality of Sanqi [41] or the growth of *P. armandii* [45]. Furthermore, soil tillage not only leads to a reduction in SOC content, thereby weakening the soil's adsorption capacity for heavy metals [63], but also mixes heavy metals from the surface soil into deeper soil layers [64], effectively reducing the heavy metal content in the soil of the SPA system. Rainfall and water replenishment significantly affect the leaching and scouring processes of surface soil, thereby influencing the migration and concentration of heavy metals [65]. In the SPA system, the use of drip irrigation facilities to supplement water for Sanqi may also contribute to the reduction in heavy metal content in the surface soil. In addition, the application of organic fertilizers can promote the mineralization of soil organic carbon and effectively reduce the bioavailability of heavy metals in the soil [66]. Supplementing organic fertilizers before the cultivation process of Sanqi is also an important measure for reducing heavy metal content in the soil. Additionally, no significant difference was observed between the non-rhizosphere and rhizosphere soils of pine in the SPA and MPA systems following Sanqi cultivation (Figure 5B). Heavy metals in soil exist in various binding forms, such as sulfides, organic matter, carbonates, and oxides of iron and magnesium [67]. During plant growth, variations in the bioavailability of these heavy metals can directly influence their uptake and utilization by plants [68]. Therefore, the total concentration of metals may remain unchanged, while their bioavailability could vary.

4.3. The Relationship Between Soil Fertility and Heavy Metal Content in the Soil of Sanqi and *P. armandii*

The cultivation of Sanqi significantly reduced the heavy metal content in the soil of both the Sanqi and *P. armandii* within the SPA system, correspondingly elevating the pollution level from relatively clean (threshold) degree to clean (safe) degree. Most of the essential nutrient elements required for plant growth and development are derived from the soil, with a close correlation existing between the mineral element content of the soil and Sanqi plants [50]. Non-edible plants that can accumulate heavy metal elements can be effectively utilized for remediation of soil heavy metal pollution, thereby contributing to ecological restoration [69,70]. In contrast, the elemental content of edible plants must be controlled within safe limits to prevent potential health hazards to people through food chain circulation [71,72]. Meanwhile, analysis of the average sensitivity regarding the heavy metal content, the contribution rate of chromium (Cr) reached 6.37% (Figure 6). It is worth noting that there is a significant negative correlation between soil fertility and heavy metal content (Figure 7), while the correlations between different nutrient elements and heavy metals also vary (Figure 8). This indicates that appropriate management measures play a crucially positive role in reducing heavy metal content in soil. Moreover, in the Sanqi soil, the content of Cr showed a negative correlation with the content of SM and TP (Figure 8A). In contrast, in the *P. armandii* soil, Cr exhibited a positive correlation with the content of TN, while showing a significant negative correlation with the content of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ (Figure 8B). The soil in the MPA and SPA systems showed no signs of heavy metal pollution; however, the single-factor pollution index of Cr was relatively high (0.86), potentially being the main contributor to the increased the Nemerow pollution index. Notably, although the current heavy metal content has not yet reached the pollution threshold, long-term accumulation may pose potential threats to the soil ecosystem. Therefore, it is recommended to regularly monitor the changes in heavy metal content in the SPA system and implement corresponding management measures, such as rational application of phosphorus fertilizers and water management, to prevent the occurrence of heavy metal pollution and ensure the healthy growth of Sanqi and *P. armandii* as well as the stability of the soil ecology.

It is important to acknowledge several limitations of our study. Firstly, the sample size and duration in this research were not substantial enough, which may impact the generalizability of our results. Secondly, our study concentrated on a specific SPA system, and the findings may not be directly transferable to other types of agricultural systems or geographical areas. Looking ahead, we suggest conducting long-term monitoring studies to evaluate the temporal changes in heavy metal levels and their potential effects on crop growth and soil ecology. Furthermore, it would be beneficial to investigate more effective management strategies to alleviate heavy metal pollution, such as biochar amendments, water and fertilizer management, soil tillage, and litter coverage, and to assess their efficacy in reducing heavy metal accumulation in Sanqi and enhancing soil health.

5. Conclusions

The conversion of land use from the MPA to the SPA system resulted in an increase in SM, TN, and NO_3^- -N levels in Sanqi soil and a decrease in Pb and Cr content. For pine soil, the levels of SM, pH, and NH_4^+ -N increased, while the contents of Zn, Mn, Pb, and Cr all significantly decreased. Moreover, TOPSIS analysis demonstrated that Sanqi cultivation not only significantly enhanced soil fertility for Sanqi rather than pine but also reduced the heavy metal content in the soil of both Sanqi and *P. armandi* within the SPA system. Furthermore, the Nemerow pollution index for both Sanqi and *P. armandi* soils has decreased, transitioning the pollution status from relatively safe to safe. In addition, the content of Cr showed a negative correlation with the content of SM and TP in the Sanqi soil. Hence, we recommend the appropriate application of phosphate fertilizers and proper water management to prevent heavy metal pollution, ensuring the healthy growth of Sanqi and *P. armandi* as well as the stability of the soil ecosystem. Future research should concentrate on conducting long-term monitoring of the soil fertility and heavy metals within the SPA system, investigating the effects of management practices on the soil fertility and heavy metals, as well as elucidating the mechanisms among soil fertility, heavy metals and microbial community. In summary, our research findings enhance the understanding of the impact of Sanqi cultivation on soil fertility and heavy metals, offering valuable insights for improving the sustainable management of Sanqi and the management practices of other agroforestry systems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy15092123/s1>, Table S1: Annual average values and 95% confidence intervals (CI) for soil physicochemical properties. Table S2: Annual average value and 95% confidence interval (CI) of the relative proximity C of soil fertility. Table S3: The impact of treatment and interaction time, as well as their interactive effects, on the relative proximity C of soil fertility. Table S4: Annual average values and 95% confidence intervals (CI) for heavy metals in soil. Table S5: Annual average value and 95% confidence interval (CI) for the relative proximity C of soil heavy metals. Table S6: The impact of treatment, interaction time, and their interactive effects on the relative proximity C of heavy metals in soil. Table S7: The average value and the 95% confidence interval (CI) of the Nemerow Pollution Index for heavy metals in soil.

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