



Variations in Soil C, N, P Stocks and Stoichiometry With Soil Depth and Forest Types in Qilian Mountains of Northwest China

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Forests ecosystem plays a significant role in supplying multiple services given the unique properties of forest soils, in which the elements of C, N, and P are essential to support soil fertility and site productivity. However, soil properties at different soil depths between plantation forests (PF) and natural forests (NF) have not been well quantified. Therefore, the current study was carried out in the Qilian Mountains of northwest China to determine the difference between PF and NF in the soil properties, both physical (e.g., bulk density, BD) and chemical (e.g., pH value, the contents, stocks, and stoichiometry of soil organic carbon (SOC), total N (TN), and total P (TP)). Research analyzed soil samples at different depths (0–20, 20–40, 40–60, 60–80, and 80–100 cm). The results showed that the soils' pH values and BD were significantly higher ($p \leq 0.05$) in PF than in NF and increased with soil depth. The contents of SOC, TN, and TP decreased considerably with soil depth and then stabilized at the soil depth of 80–100 cm. The NF showed significantly higher ($p \leq 0.05$) SOC, TN, and TP contents than PF, confirming that the soil quality of PF had not fully recovered yet. The stocks of SOC and TN quickly decreased with soil depth up to 40–60 cm and stabilized gradually. Additionally, the soil stoichiometry of C:P and N:P decreased significantly with rising soil depth, while the C:N ratio remained unchanged. The N:P and C:P ratios were lower in PF than in NF, while the C:N ratio was higher in PF than in NF. In conclusion, the results show that the soils of NF present significantly higher stocks of SOC and TN but lower (or nearly equal) TP stocks than PF (under the same age group and tree species composition). These results imply that maintaining NF and avoiding their replacement by PF can help keep higher soil quality and related ecosystem services.

Keywords: natural forests, plantation forests, stoichiometry, element stocks, Qilian Mountain

INTRODUCTION

In global ecosystems, forest soil is a vital constituent as the primary source of plant nutrition. Carbon (C), nitrogen (N), and phosphorus (P) are the soil's main nutritional and structural elements and the major limiting factors for global ecosystem health (Reed et al., 2015; Rahman et al., 2018). The stocks of total nitrogen (TN), total phosphorus (TP), soil organic carbon (SOC), and C:N:P stoichiometry are indicators of soil fertility and plant nutrient conditions (Sterner and Elser, 2002; Batjes, 2014; Ali et al., 2022). Researchers use stoichiometry frequently to associate plants with soil nutrients in various forest types (Moe et al., 2005; Liu et al., 2017; Yang et al., 2018). These nutrients continuously circulate among the soil depths through biogeochemical cycling, which confirms the even flow of energy and sustains the stability of ecosystems (Lü et al., 2017). However, some factors such as soil type, soil depths, forest types, forest conversion, and possibly forest species composition (Louman et al., 2010; Tadesse et al., 2014) can result in changes in the SOC, TN, and TP contents, stocks, and stoichiometry (Lin et al., 2018; Hu et al., 2019). Therefore, many studies showed a significant difference in the impact of the forest conversion between natural forest (NF) to plantation forest (PF) on the quality and quantity of SOC, TN, and TP (Guo et al., 2016; Lin et al., 2018; Ngaba et al., 2019). However, such studies were not carried out evenly among regions and are scarce in the dryland regions of the Qilian Mountains of northwest China, where plantation and natural forests exist in the same climatic zone.

In the last few decades, PF has sharply increased worldwide to meet the growing demand for domestic and industrial timber (Berthrong et al., 2009; Ahmad et al., 2018), slow down the increase of CO₂ concentration in the atmosphere (Jackson et al., 2005; van Dijk and Keenan, 2007; Ahmad et al., 2021), protect soil against nutrient losses, and supply hydrological and many other ecosystem services. However, PF can alter the C, N, and P contents, stocks, and stoichiometry of forest soils due to changes in the species composition and many different stand structure parameters compared with surrounding or original natural forests (Wall and Hytönen, 2005; Freier et al., 2010; Ahmad et al., 2019), and the interferences of silviculture activities (Yang et al., 2005; Zheng et al., 2008). Such studies have reported significant effects of PF on physicochemical soil properties (Jackson et al., 2005; Berthrong et al., 2009; Laganriere et al., 2010). However, the research results are inconsistent, such as studies comparing non-forested lands to afforested lands from previous agricultural systems converted to plantations (Paul et al., 2002; Berthrong et al., 2009; Laganriere et al., 2010). Natural forests provide vital natural resources, goods, and services (Wang et al., 2020). It is of great value in soil-water conservation, adding C, N, and P to maintain and improve soil quality and fertility (Behera and Sahani, 2003; Ashagrie et al., 2005; Yang et al., 2005; Zheng et al., 2008). The NF can sustain the nutrient cycles of forest soils,

especially SOC, TN, TP, and physicochemical soil properties such as BD and pH values (Han et al., 2019; Ngaba et al., 2019). Hence, questions have arisen about whether the PF can similarly provide beneficial soil properties after plantations (Gogoi et al., 2021).

NF is being converted into PF, especially in monoculture tree plantations worldwide, including in China (Chen et al., 2005). This transformation creates many problems and ultimately affects the physicochemical soil properties such as soil BD and pH value, the nutrient contents, stocks, and stoichiometry of SOC, TN, and TP (Yang et al., 2019; Sun et al., 2021; Yang et al., 2021). Furthermore, many studies demonstrated a considerable influence on soil properties, for example, when the broadleaved NF were converted to monoculture PF in subtropical China (Behera and Sahani, 2003; Chen et al., 2005; Lemma et al., 2006; Nsabimana et al., 2008). However, these results were not entirely reliable due to the interferences from the difference in age groups, tree species compositions (Yang et al., 2009; Wang et al., 2011), or climatic and site conditions. Hence, such studies recorded variations in soil properties after NF were transformed to PF but never reported the differences in soil properties between NF and PF with the same tree species composition (such as *Picea crassifolia* and *Sabina przewalskii* in the Qilian Mountains of northwest China) and age groups under the same topographic and climatic conditions. Therefore, the current study was carried out to assess variations and compare the physicochemical soils properties of PF and NF in the Qilian Mountains at soil depths within 0–100 cm.

MATERIALS AND METHODS

Study Area

This study was conducted in the Qilian Mountains (Qifeng, Sidalong, and Xishui Forest Farms), Sunan Yugur Autonomous County (38°49'18.7"N 99°36'09.8"E), Zhangyi city, Gansu Province, northwest China (Figure 1). The elevation ranges from 2,450 to 3,300 m. The climate is arid and semi-arid, with mean annual precipitation of 410–540 mm, which increases with rising elevation (Wang et al., 2003). Most precipitation (86%) falls from May to September (Zhang et al., 2011). The mean annual air temperature varies from –0.3 to 8.1°C and decreases with rising elevation (Wang et al., 2009). The annual accumulated frost-free period is 127 days. About 60% of the daily photoperiodic is full sunshine, and the yearly pan evaporation is 1,785 mm (Yuan and Hou, 2015). The primary soil parent materials are slope deposits and residuals from limestone, shale, and conglomerate. The degree of downwards minerals transition was mostly indistinct/vague and obvious. The compactness was usually moderate, slightly loose, while less soils were compact and firmly loose. The soil structure was frequently massive or bulky and granular. The soil texture was commonly loam, sandy loam, and clay loam, while soil moisture was mostly moist/damp, but some soils were dry in the PF and NF.

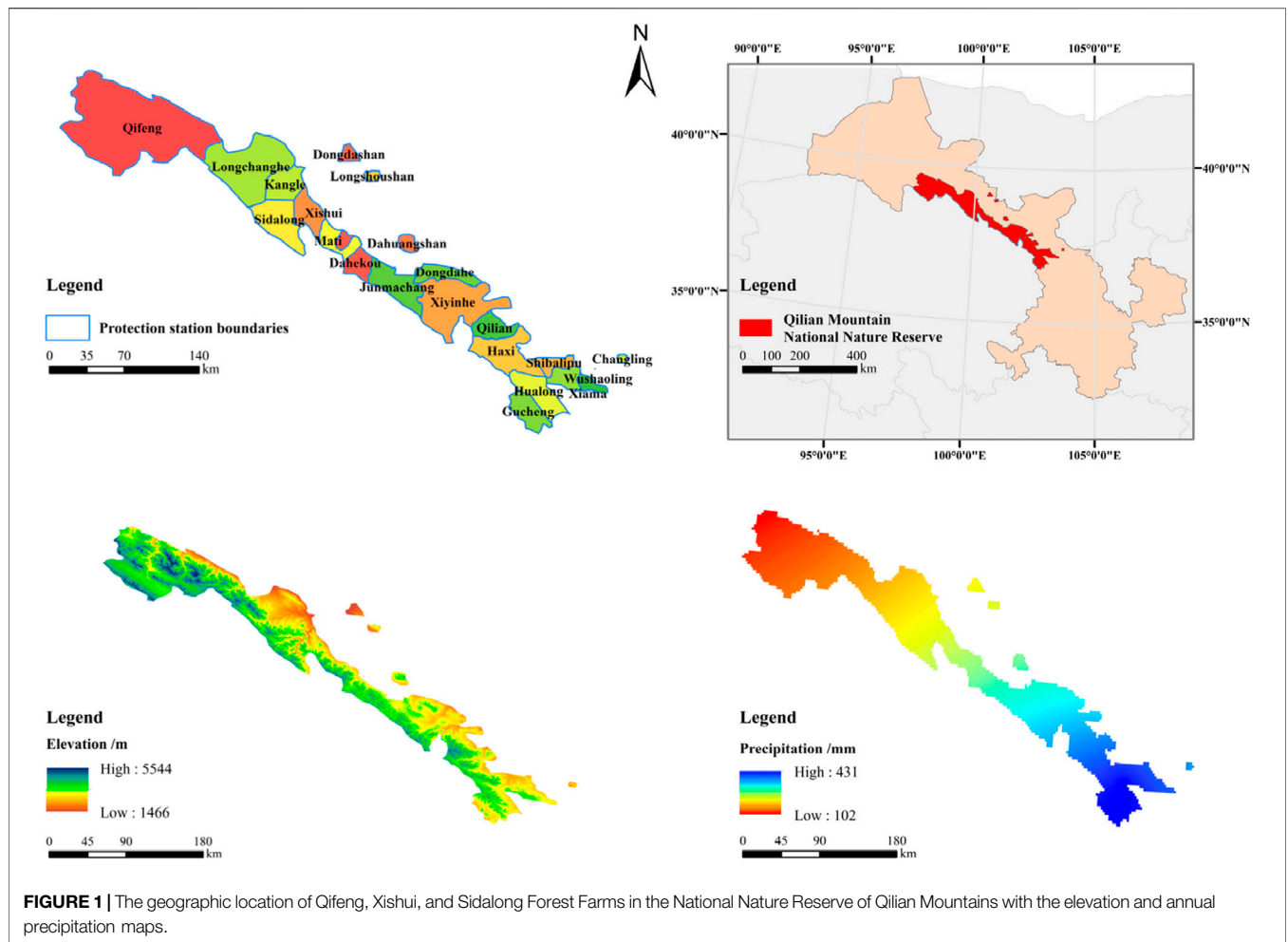


FIGURE 1 | The geographic location of Qifeng, Xishui, and Sidalong Forest Farms in the National Nature Reserve of Qilian Mountains with the elevation and annual precipitation maps.

TABLE 1 | The basic plant community properties of the PF and NF in the forest farms of Qilian Mountains.

Stand structures	PF			NF		
	Mean ± SD	Min.	Max.	Mean ± SD	Min.	Max.
Tree density (individuals ha ⁻¹)	1,163 ± 527	475	2,425	1,332 ± 517	270	2,500
Average tree height (m)	5.81 ± 1.54	2.80	8.60	7.82 ± 3.73	3.10	17.3
Average diameter at breast height (cm)	16.7 ± 11.4	3.67	53.1	24.7 ± 12.9	4.89	53.1
Average dominant tree height (m)	8.77 ± 3.04	1.10	14.4	12.5 ± 4.14	5.30	19.4
Average shrub height (cm)	50.6 ± 21.5	25.0	89.0	52.0 ± 22.9	21.0	93.0
Herbaceous average coverage (%)	0.30 ± 0.28	0.07	0.95	0.28 ± 0.17	0.11	0.900
Herbaceous average height (cm)	11.2 ± 4.27	6.00	22.0	16.1 ± 26.8	6.00	138
Canopy density (%)	42 ± 12.86	20.0	69.0	39.1 ± 17.1	20.0	70.0

Most of the forests belong to the natural forests of Qinghai spruce (*Picea crassifolia*), which grow on the shady and semi-shady slopes within the elevation range of 1,750–3,550 m (but concentrated within 2,200–3,200 m), and also the natural forests of Qilian juniper (*Sabina przewalskii*), which grow on the dry and sunny slopes within the elevation range of 2,600–4,000 m (Rong

et al., 2019). At the same time, the adjacent PF was also dominated by Qinghai spruce and Qilian junipers. Both PF and NF belong to the middle-aged groups. There are rich ground mosses on the floor of spruce forests due to their unique habitat. The dominant shrubs and herbs species were *Berberis diaphana*, *Caragana jubata*, *Salix sylvestris*, *Sabina*

procumbens, *Dasiphora fruticosa*, *Carex oshimensis*, *Potentilla fruticosa*, *Polygonum viviparum*, and *Agropyron cristatum* under both forest types. The average tree density of the surveyed plots was 1,163 and 1,332 trees ha⁻¹ for PF and NF, respectively. The average tree height was 5.8 and 7.82 m, and tree DBH was 16.7 and 24.7 cm for PF and NF, respectively. Similarly, the average height of dominant trees was 8.77 and 12.5 m, and the canopy density was 42% and 39% for PF and NF, respectively (Table 1).

Plot Setting and Soil Sampling

For both PF and NF, 46 sample plots were selected to investigate the physicochemical soil properties. The plot size was 20 m × 20 m, and a pit of 1 m² was dug out at the forest floor and replicated three times for each soil profile. Each soil profile was classified into O, A, AB, B, BC, C, and other horizons, and a total of 230 soil samples (115 of each forest type) were collected. For physical analysis (soil bulk density, BD), the soil samples were collected at each soil depth using stainless-steel augers and oven-dried at 104°C for 48 h. The soil samples for chemical analysis were collected from the soil profiles using a multi-point mixed-method at the soil depths of 0–20, 20–40, 40–60, 60–80, and 80–100 cm. The litter, leaves, roots, insects, and larger residues were separated and removed. All soil samples were screened through a 2-mm sieve mesh. The soil samples were air-dried under the ceiling fan and stored at room temperature to determine physicochemical soil parameters. The stored soil samples were then analyzed with standard methods to determine the pH value, soil organic carbon (SOC), total N (TN), and total P (TP) contents and transformed into stocks (SOCs, TNs, TPs) and soil stoichiometry (C:N:P ratios) under the soil depth (SD) and forest types (FT).

Soil Chemical Analysis

The soil organic carbon content was determined by the K₂Cr₂O₇-H₂SO₄ digestion method (Walkley, 1947). The content of total soil P was measured by dissolved nitric acid (NH₃), perchloric acid digestion (HClO₄), and hydrofluoric acid (HF) using an automated discontinuous analyzer. The content of total soil N was measured with a fully automatic Kjeldahl analyzer (dissolved by H₂SO₄ along with a catalyst). The soil pH value was measured with a pH-meter at 1:5 soil water suspension (Mclean, 1982).

Data Calculation and Statistical Analysis

The SOC stock at each soil depth was calculated as follows (Hu et al., 2018):

$$\text{SOCs} (\text{Mg ha}^{-1}) = \text{SOC contents} (\text{g kg}^{-1}) \cdot \text{BD} (\text{g cm}^{-3}) \cdot \text{ST} (\text{cm}) / 10 \quad (1)$$

Similarly, the soil stocks of total N and P (TNs and TPs) were calculated using the above equation. Here, ST denotes the soil layer thickness (cm).

The data analysis was performed using one-way ANOVA (Analysis of Variance) to determine the impacts of FT and

SD, respectively, on the physicochemical soil properties. Two-factor ANOVAs were conducted to investigate the impact of SD, FT, and their interactions on soil properties. The Tukey HSD all-pairwise comparison (least significant difference) test at $p < 0.05$ was used to compare the means. Origin Lab-2019 was used to evaluate the correlation between physicochemical soil parameters and perform the PCA (principal component analysis) for each forest type.

RESULTS

Variation of BD and Soil pH Value with Soil Depth and Forest Types

The soil BD and pH values differed among soil depth and forest types significantly ($p \leq 0.05$), showing an increase with rising soil depth for both forest types (Figure 2A). The mean BD of PF and NF increased from the lowest values of 0.833 and 0.813 at the topsoil depth (0–20 cm) to the highest values of 1.37 and 1.10 g cm⁻³ at the deepest soil depth (80–100 cm). Similarly, the pH values increased from 8.16 and 7.80 at the topsoil depth for PF and NF to 8.41 and 8.23 at the deepest soil depth (Figure 2B). The BD at all soil depths of PF was higher than those of NF, and this difference increased with rising soil depth, from 0.02 g cm⁻³ at the topsoil depth (0–20 cm) to 0.27 g cm⁻³ (based on the data pair) at the soil depth of 80–100 cm (Figure 2A).

Similarly, the soil pH values at all soil depths of PF were higher than those of NF, but this difference decreased with rising soil depth, from 0.36 at the topsoil depth to 0.18 (based on the data pair) at the deepest soil depth (Figure 2B). The mean soil BD of 0–100 cm soil depth was 1.03 g cm⁻³ for PF, higher than the corresponding value of 0.97 g cm⁻³ for NF. Similarly, the mean soil pH value of 8.30 for 0–100 cm soil depth for PF was higher than the pH value of 8.10 for NF (Table 2).

Variation in SOC, TN, and TP Contents With Soil Depth and Forest Types

The contents of SOC, TN, and TP differed among soil depths (SD) and forest types (FT) significantly ($p \leq 0.05$), showing a decrease with rising soil depth for both PF and NF. The SOC and TN contents at all soil depths of PF were lower than those of NF (Figures 2C, D). The difference in SOC content decreased from 12.7 g kg⁻¹ (based on the data pair of 49.9 and 62.6 g kg⁻¹) at the topsoil depth to 12.3 g kg⁻¹ (based on the data pair of 19.1 and 31.4 g kg⁻¹) at the deepest soil depth (Figure 2C). The mean SOC content of 0–100 cm soil depth for NF (44.3 g kg⁻¹) was significantly ($p \leq 0.05$) higher than that of PF (32.0 g kg⁻¹) (Table 2). The difference in TN content decreased from 1.05 g kg⁻¹ (based on the data pair of 3.53 and 4.58 g kg⁻¹) at the topsoil depth to 1.00 g kg⁻¹ (based on the data pair of 1.18 and 2.18 g kg⁻¹) at the deepest soil depth (Figure 2D). The mean TN content of 0–100 cm soil depth for NF (3.07 g kg⁻¹) was significantly higher ($p \leq 0.05$) than that of PF (2.15 g kg⁻¹) (Table 2).

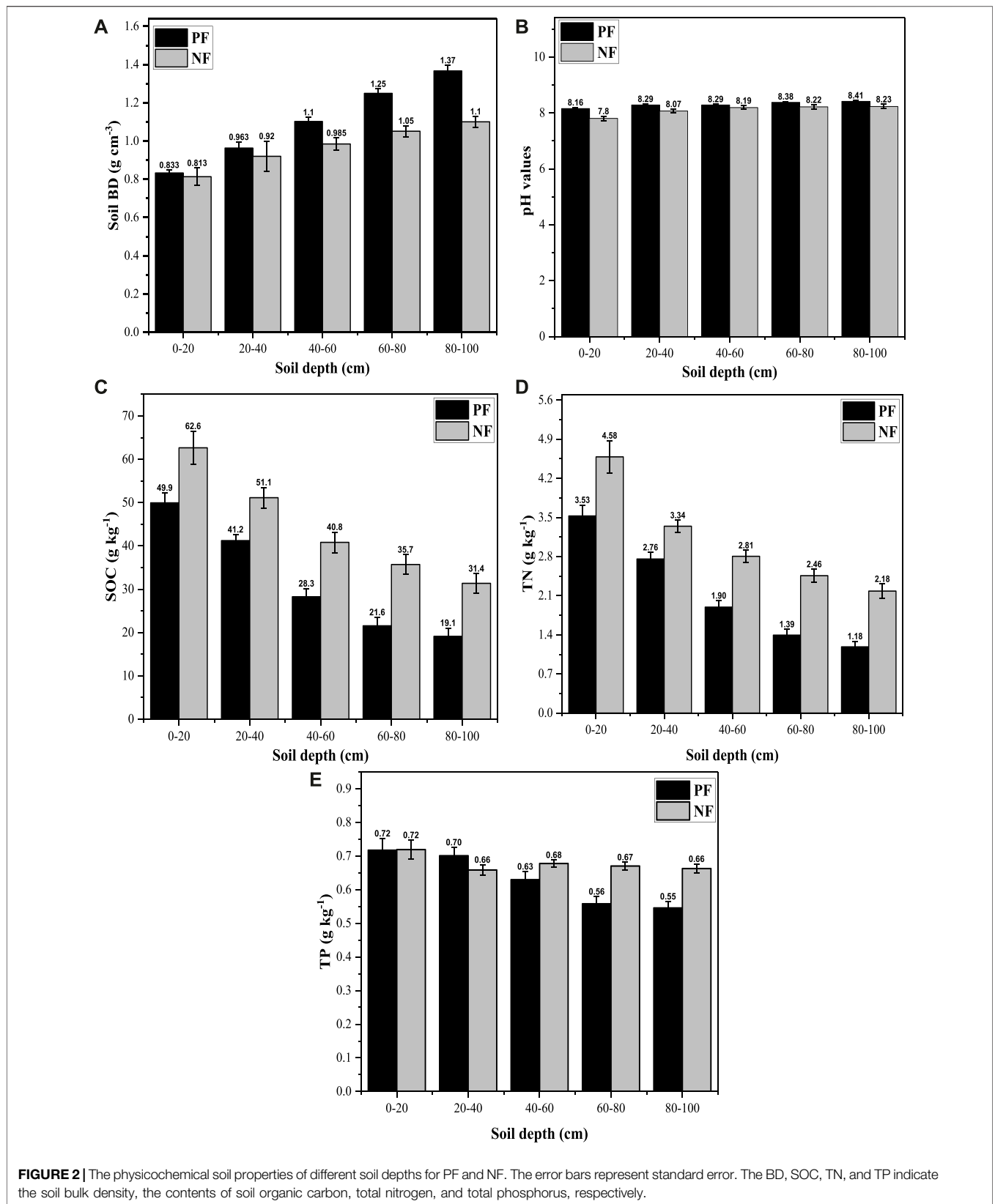


FIGURE 2 | The physicochemical soil properties of different soil depths for PF and NF. The error bars represent standard error. The BD, SOC, TN, and TP indicate the soil bulk density, the contents of soil organic carbon, total nitrogen, and total phosphorus, respectively.

TABLE 2 | The mean physicochemical soil properties of 0–100 cm soil depth for PF and NF.

Soil properties	PF	NF
BD (g cm ⁻³)	1.03 ± 0.24 ^a	0.97 ± 0.23 ^b
pH values	8.30 ± 0.22 ^a	8.10 ± 0.48 ^b
SOC content (g kg ⁻¹)	32.0 ± 16.7 ^b	44.3 ± 19.6 ^a
TN content (g kg ⁻¹)	2.15 ± 1.17 ^b	3.07 ± 1.25 ^a
TP content (g kg ⁻¹)	0.63 ± 0.17 ^b	0.67 ± 0.10 ^a
SOC stock (Mg ha ⁻¹)	64.3 ± 28.6 ^b	80.6 ± 29.6 ^a
TN stock (Mg ha ⁻¹)	4.32 ± 1.87 ^b	5.72 ± 2.09 ^a
TP stock (Mg ha ⁻¹)	1.35 ± 0.32 ^a	1.33 ± 0.40 ^a
C:N ratio	16.7 ± 10.6 ^a	14.5 ± 3.78 ^b
C:P ratio	51.5 ± 29.5 ^b	66.1 ± 28.9 ^a
N:P ratio	4.38 ± 3.33 ^b	5.85 ± 4.09 ^a

The values are means ± standard deviations (SD). The different letters within each row indicate a significant ($p \leq 0.05$) difference between forest types. The BD, SOC, TN, and TP indicate the soil bulk density, the contents of soil organic carbon, total nitrogen, and total phosphorus, respectively.

The mean TP contents of PF and NF generally decreased from the highest values of 0.72 in both PF and NF at the topsoil depth to the lowest values of 0.55 and 0.66 at the deepest soil depth (Figure 2E). However, the variation pattern of TP content along soil depth differed from the continuously decreasing pattern of SOC and TN. For NF, the TP content declined non-significantly and leveled-off within the soil depth of 0–100 cm. For PF, the TP content decreased insignificantly within 0–40 cm and obviously within the depth of 60–100 cm; however, a significant difference existed only between 0–20 cm and 80–100 cm. The mean TP content of 0–100 cm for NF (0.67 g kg⁻¹) was significantly higher than those of PF (0.63 g kg⁻¹) (Table 2). At each soil depth, the percent contribution of overall average contents of SOC, TN, and TP was presented in Figure 4, showing a decrease in soil depth for PF and NF.

Variation in SOC, TN, and TP Stocks with Soil Depth and Forest Type

For both PF and NF, stocks of SOC and TN decreased significantly ($p \leq 0.05$) in each soil depth, while that of TP increased (Figures 3A–C; Table 5). The highest SOC stocks, 82.6 and 96.8 Mg ha⁻¹ for PF and NF, were at the topsoil depth (0–20 cm), and the lowest values, 48.4 and 66.7 Mg ha⁻¹, were at the deepest soil depth (80–100 cm). Similarly, the maximum TN stocks of 5.83 and 7.19 Mg ha⁻¹ for PF and NF were at the topsoil depth, while the lowest values of 3.02 and 4.73 Mg ha⁻¹ were at the deepest soil depth. The TP stock was highest (1.47 Mg ha⁻¹) for both PF and NF at the deepest soil depth, while the lowest values (1.19 Mg ha⁻¹) for both PF and NF were at the topsoil depth. The SOC and TN stocks of NF were higher than PF at all soil depths. The SOC and TN stock differences between PF and NF increased with soil depth, from 14.2 and 1.36 Mg ha⁻¹ in the topsoil depth to 18.3 and 1.71 Mg ha⁻¹ (based on the data pair) at the deepest soil depth (Figures 3A, B). The average SOC stocks, 64.3 Mg ha⁻¹ and 80.6 Mg ha⁻¹ for PF and NF at soil depth (0–100 cm), showed that NF was

significantly higher ($p \leq 0.05$) (Table 2). Similarly, the average TN stocks, 4.32 Mg ha⁻¹ and 5.72 Mg ha⁻¹ for PF and NF at soil depth (0–100 cm), showed NF was significantly higher ($p \leq 0.05$), while no significant difference existed for the TP stocks 1.35 Mg ha⁻¹ and 1.33 Mg ha⁻¹ for PF and NF at soil depth (0–100 cm) (Table 2). The percent contribution of SOC and TN stocks of each soil depth to their total stocks over 0–100 cm soil depth decreased with rising soil depth for both PF and NF, but increased in the case of TP stock (Figures 4B, E).

Variation in C:N:P Stoichiometry with Soil Depth and Forest Type

The soil C:P and N:P ratios of PF and NF decreased significantly ($p \leq 0.05$) with soil depth. The C:P ratios decreased from 73.3 and 89.5 for PF and NF at topsoil depth to 34.7 and 47.7 at the deepest soil depth. The N:P ratios decreased from 5.05 and 6.45 for PF and NF at the topsoil depth to 2.13 and 3.34 at the deepest soil depth (Figures 3E, F). The C:N ratios were similar among all soil depths for both PF and NF, although the variation range for PF was bigger than that for NF (Figure 3D).

The C:P and N:P ratios for NF were significantly higher than those for PF at all soil depths. The differences in C:P and N:P ratios decreased with rising soil depth, from 16.2 to 13.0 for C:P ratios and from 1.40 to 1.21 for N:P ratios, respectively (based on the data pairs in Figures 3E, F). The difference in the C:N ratio between PF and NF increased and then decreased with rising soil depth but was non-significant at all soil depths (Figure 3D). The average C:N ratios were 16.7 and 14.5 for PF and NF at soil depth (0–100 cm), where PF was significantly higher, while the C:P and N:P ratios for PF (51.5 and 4.38) were significantly lower than those for NF (66.1 and 5.85) (Table 2). The percent contributions of each soil depth to the overall stoichiometry of C:P and N:P of soil depth 0–100 cm were calculated for PF (Figure 4C) and NF (Figure 4F), showing decreasing percent contribution of each soil property with rising soil depth for both PF and NF, while the C:N ratios in PF showed an increase up to 40–60 cm and thereafter decreased, and were rather similar in NF.

The Effects of Soil Depth and Forest Type on Physicochemical Soil Properties

The soil depth and forest type intimately affected the physicochemical soil properties, while their interaction showed non-significant effects except for BD and TP content (Table 3). The soil BD, pH value, and the contents of SOC and TN were highly significantly correlated with both FT and SD. The TP content was positively associated with SD ($p \leq 0.001$) and significantly correlated with FT ($p \leq 0.05$). The stocks of SOC and TN were highly significantly correlated with both FT and SD ($p \leq 0.001$), but the TP stock was only positively associated with SD ($p \leq 0.001$) and non-significantly correlated with FT. The C:N ratio was somewhat significantly correlated with FT ($p \leq 0.05$) but insignificantly correlated with SD. The C:P and N:P ratios were highly correlated ($p \leq 0.001$) with FT and SD. Overall, most physicochemical soil properties were highly affected by SD and FT (except TP stock and C:N ratio).

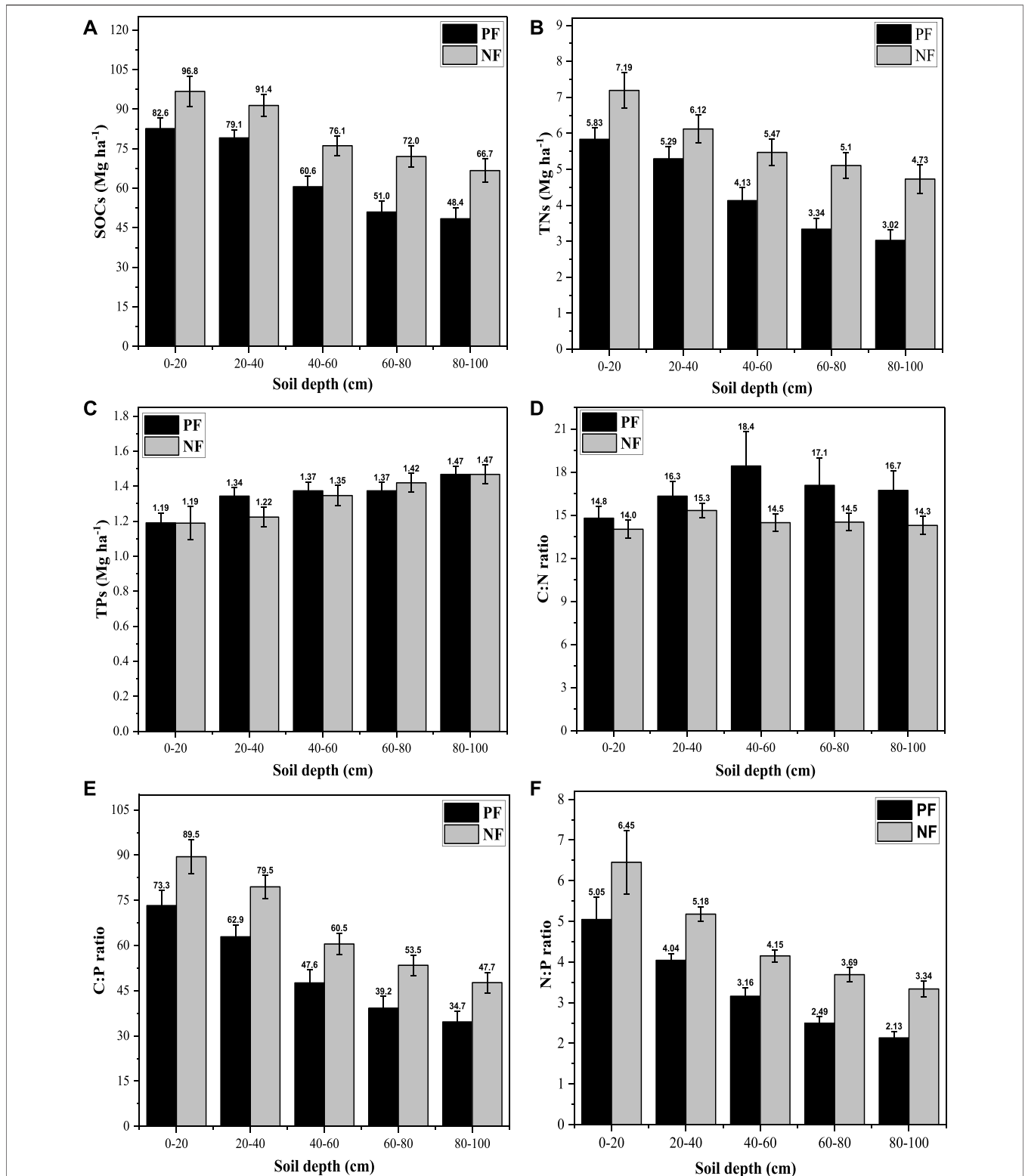


FIGURE 3 | The SOC, TN, and TP stocks and stoichiometry under different soil depths for PF and NF. The error bars indicate standard error. The SOC_s, TN_s, and TP_s indicate soil organic carbon, total nitrogen, and total phosphorus stocks respectively.

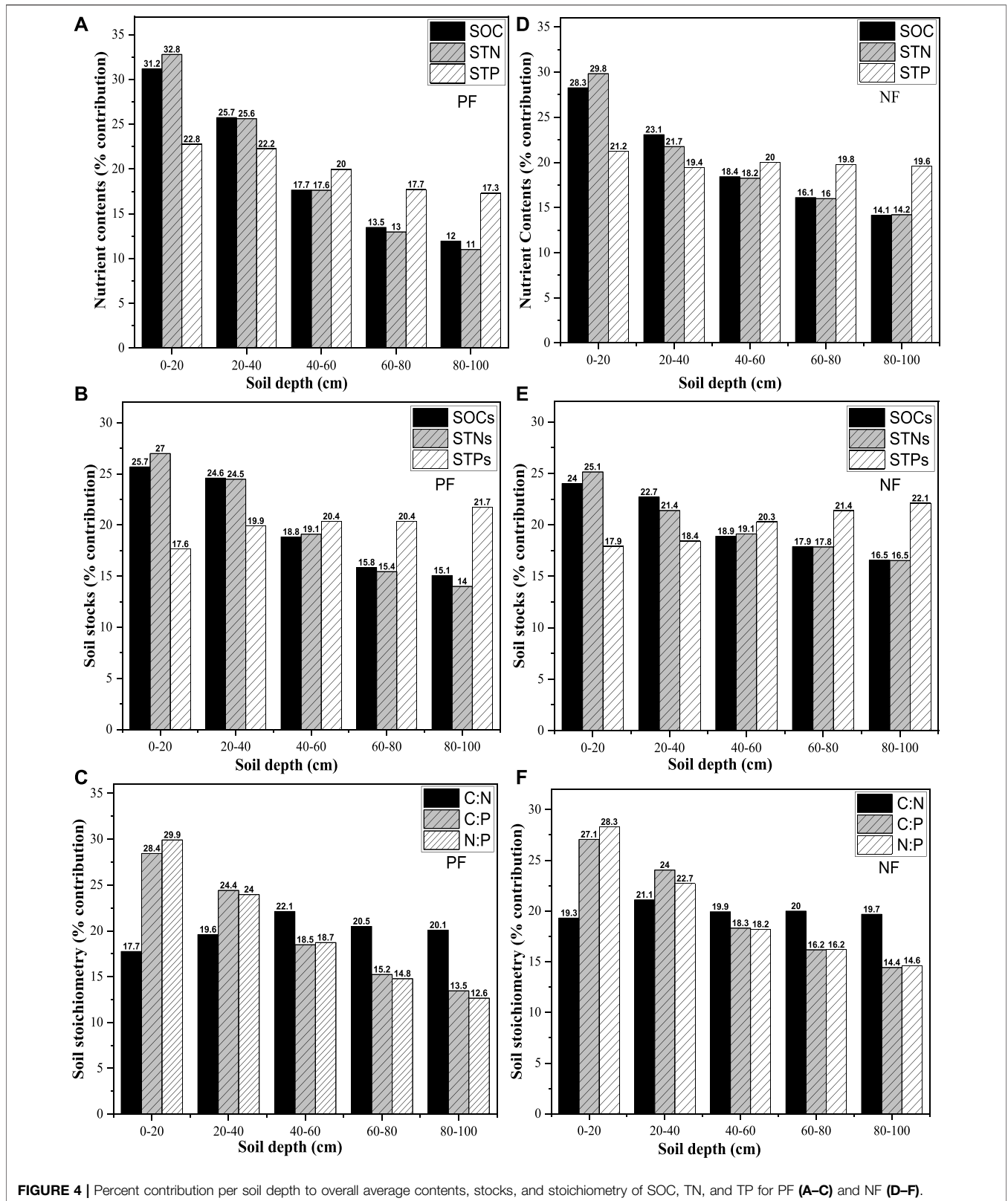


FIGURE 4 | Percent contribution per soil depth to overall average contents, stocks, and stoichiometry of SOC, TN, and TP for PF (A–C) and NF (D–F).

TABLE 3 | Effects of SD, FT, and their interaction on soil properties based on two-way ANOVAs.

Variables	Forest types (FT)		Soil depth (SD)		FT x SD	
	F	P	F	P	F	P
Soil bulk density	30.00	0.0000	38.49	0.0000	3.90	0.0044
Soil pH value	18.29	0.0000	6.76	0.0000	0.82	0.5165
SOC content	42.41	0.0000	37.15	0.0000	0.13	0.9713
TN content	65.23	0.0000	56.29	0.0000	0.60	0.6629
TP content	7.59	0.0064	5.96	0.0000	3.23	0.0133
SOC stock	21.59	0.0000	13.39	0.0000	0.19	0.9410
TN stock	36.82	0.0000	17.64	0.0000	0.53	0.7160
TP stock	0.19	0.6609	4.15	0.0029	0.34	0.8500
C:N ratio	4.03	0.0458	0.40	0.8116	0.30	0.8803
C:P ratio	18.97	0.0000	20.51	0.0000	0.05	0.9947
N:P ratio	38.54	0.0000	189.01	0.0000	2.04	0.0897

The significance level was tested at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$.

PCA for Physicochemical Soil Properties under the Soil Depth and Forest Types

The PC1 and PC2 define physicochemical soil parameters for PF and NF (Figures 5A, C). The sum of PC1 and PC2 explains 80.3% and 80.6% variations in physicochemical soil properties of PF and NF. The cumulative contribution rate of PC1 (59.7%) mainly reflects the soil BD, SOC, and TN for PF, while the contribution rate (56.6%) for NF mainly reflects the pH values, SOC, and TN. Similarly, the cumulative contribution rate of PC2 (20.6%) reflects the significant contribution of pH values for PF, while the contribution rate (24.0%) for NF defined the significant variability in soil BD and TP. The score plot for soil depth in each forest type was also developed (Figures 5B, D). The physicochemical soil properties under each soil depth occupied different sections of the diagrams. The soil depths (60–80 and 80–100 cm) were close for PF and NF and were in the analogous ordination space, resulting in the least significant differences. As a result, the correlation coefficient of soil parameters at these depths should be high. The soil properties occupying different positions in the diagram, such as the opposite location, reveal significant variation and quantitative changes between the soil properties. The soil depths (0–20 and 20–40 cm) for PF and NF were also lying closely, indicating minimal differences, though the overall differences for a soil depth of 0–20 cm were higher than those at 20–40.

Correlations among Physicochemical Soil Properties

The Pearson's correlation analysis revealed a strong correlation among the physicochemical soil properties under PF and NF at 0–100 cm soil depth (Figure 6). The SOC was positively correlated with TN, and TP, while negatively correlated with pH ($r = 0.78, 0.41, \text{ and } -0.30$, respectively) under PF (Figure 6A). Similarly, the SOC was positively correlated with TN and slightly correlated with TP, while a negative correlation was observed with pH for NF ($r = 0.83, 0.17, \text{ and}$

-0.66 , respectively) (Figure 6B). The TN was positively correlated with TP ($r = 0.54$), while a negative correlation was found with pH for PF ($r = -0.04$). For NF, the TN was also positively correlated with TP ($r = 0.30$), and a negative correlation has existed with soil pH values ($r = -0.61$). The TP has negatively correlated with soil pH and BD for PF ($r = -0.04, -0.51$), while only negatively correlated with pH for NF ($r = -0.16$). The soil BD was strongly negatively correlated with SOC, and TN for PF and NF, while positively correlated with soil pH values ($r = -0.78, -0.75, -0.64, -0.45, 0.28, \text{ and } 0.30$, respectively).

DISCUSSION

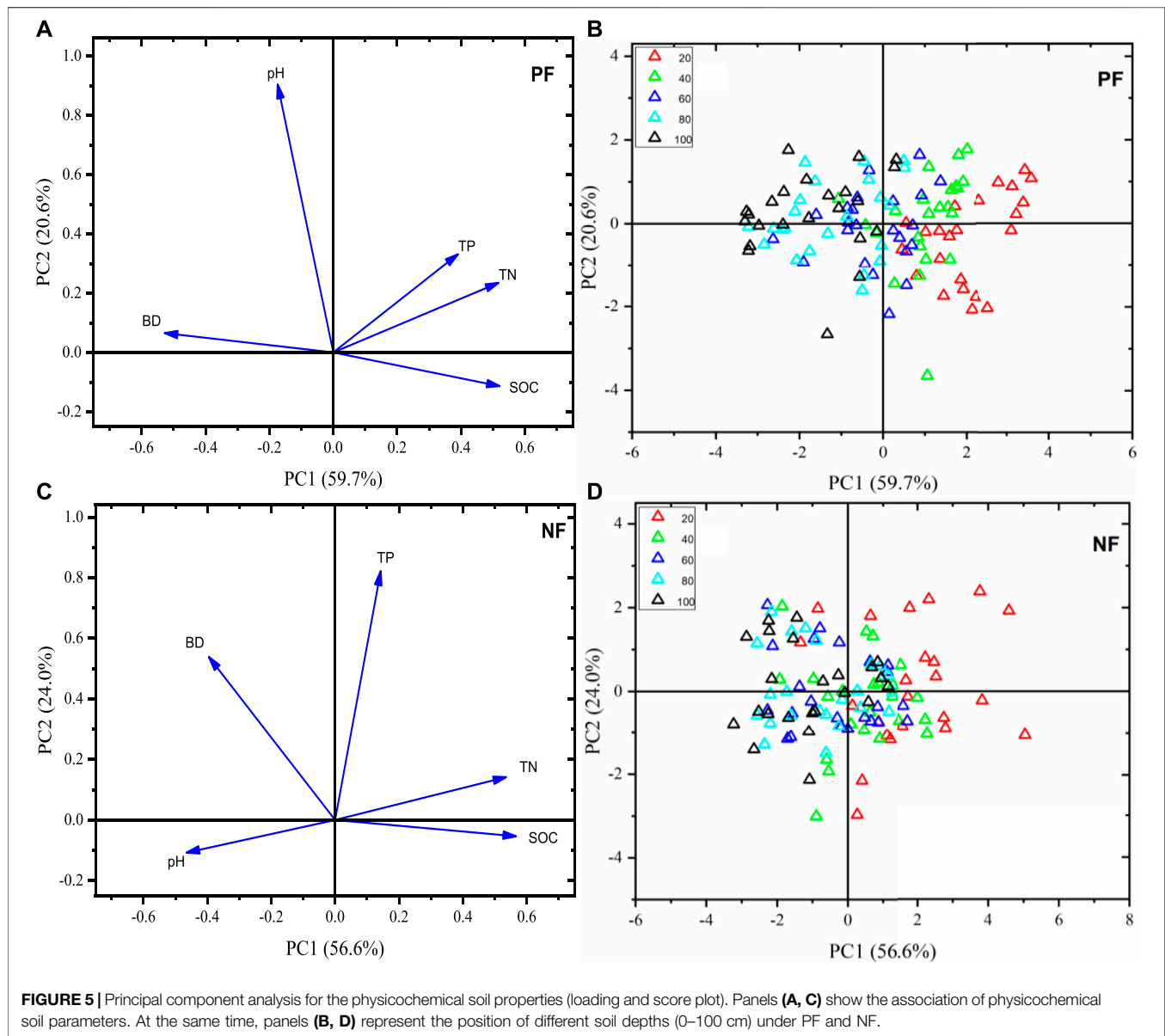
Effects of Soil Depth and Forest Type on Soil BD and pH Value

The soil BD was significantly affected by soil depth and forest type (Figure 2A; Tables 3, 4). The increase of BD with rising soil depth is an integrated result of changing soil texture (Landsberg, 2003; Ali et al., 2019) and decreasing soil organic matter input from the humus layer and tree root litter due to the limited gaseous exchange (Tokunaga, 2006). However, the higher BD in PF than NF might be attributed to the poor growth and associated lower stand biomass, but unlikely due to mechanical compaction on the exposed surface soil by management activities (such as heavy harvest and human trampling) because the forest management for timber production has been prohibited in the natural reservation area for more than 4 decades. Of course, the natural forests were excluded from commercial use in this natural reservation area (Liao et al., 2012).

The increased pH value with soil depth could be associated with less input of humus material (with organic acids) into the deeper soil depths (Table 4). A similar study (Balstrøm et al., 2013) reported that the organic acids present in the topsoil tend to break down before they reach the deeper soil depths, leading to higher pH values in deeper soil depths. The observed lower soil pH value under NF than PF confirmed the results of other studies (Chen et al., 2004). Thus, it may also be explained by the higher SOC content (SOM, correspondingly higher organic acid production) in NF than PF and the much longer time of forest cover and humus decomposition (Chen et al., 2016) in NF than in PF, which ultimately reduced the pH values of soil in a natural forest. Moreover, the better forest stand structure of NF than PF is also an influencing factor (Kafle, 2019).

Effects of Soil Depth and Forest Type on SOC, TN, and TP Contents

Soil depth is an important factor influencing the contents of SOC, TN, and TP (Berger et al., 2002; Olorunfemi et al., 2018). Our study showed a decreasing tendency in SOC, TN, and TP contents (Yang and Liu, 2019); this could be explained by the decreasing inputs of SOM with rising soil depth (Table 4) from both above and below-ground litterfall (Ngaba et al., 2019), especially by the decreasing influence of the humus layer covering the soil surface (Sperfeld



et al., 2017; Zhang et al., 2018; Xu et al., 2019; Yang and Liu, 2019) and the decreasing activities of soil animals and microorganisms (Barreto et al., 2011). With rising soil depth, the soil permeability decreases, and the BD increases, limiting the input of dissolved SOM through leaching (Berger et al., 2002; Clemmensen et al., 2013; Rahman et al., 2022).

The lower contents of SOC, TN, and TP in PF compared with NF (Table 4) could be attributed to the lower accumulation of litterfall and the faster mineralization of SOM due to the more open stand structure, which leads to a higher soil temperature (Liao et al., 2010; Zhang et al., 2016; Wang et al., 2018). Furthermore, the harvesting of biomass and logging residues during site preparations for afforestation, the forest managing measures (e.g., weeding and thinning), and the quicker absorption of nutrients of trees in the fast-growing stage of a plantation may also contribute to the lower contents of SOC, TN,

and TP in the soils of PF than NF (Paul et al., 2002; Jobbágy and Jackson, 2003; Berthrong et al., 2009; Liao et al., 2012).

Effects of Soil Depth and Forest Type on SOC, TN, and TP Stocks and Stoichiometry

The stocks of SOC and TN significantly decreased with soil depth irrespective of the forest types of PF or NF (Wang et al., 2016; Li et al., 2019; Ngaba et al., 2020) except for the TP stocks (Table 5). Our study showed that SOC and TN stocks firstly declined significantly with rising soil depth within the range of 0–60 cm and then stabilized or leveled-off thereafter within the soil depth range of 60–100 cm (Gao et al., 2020). The most important reason might be the highest biological activity in the topsoil, characterized by the highest SOM content and associated nutrient

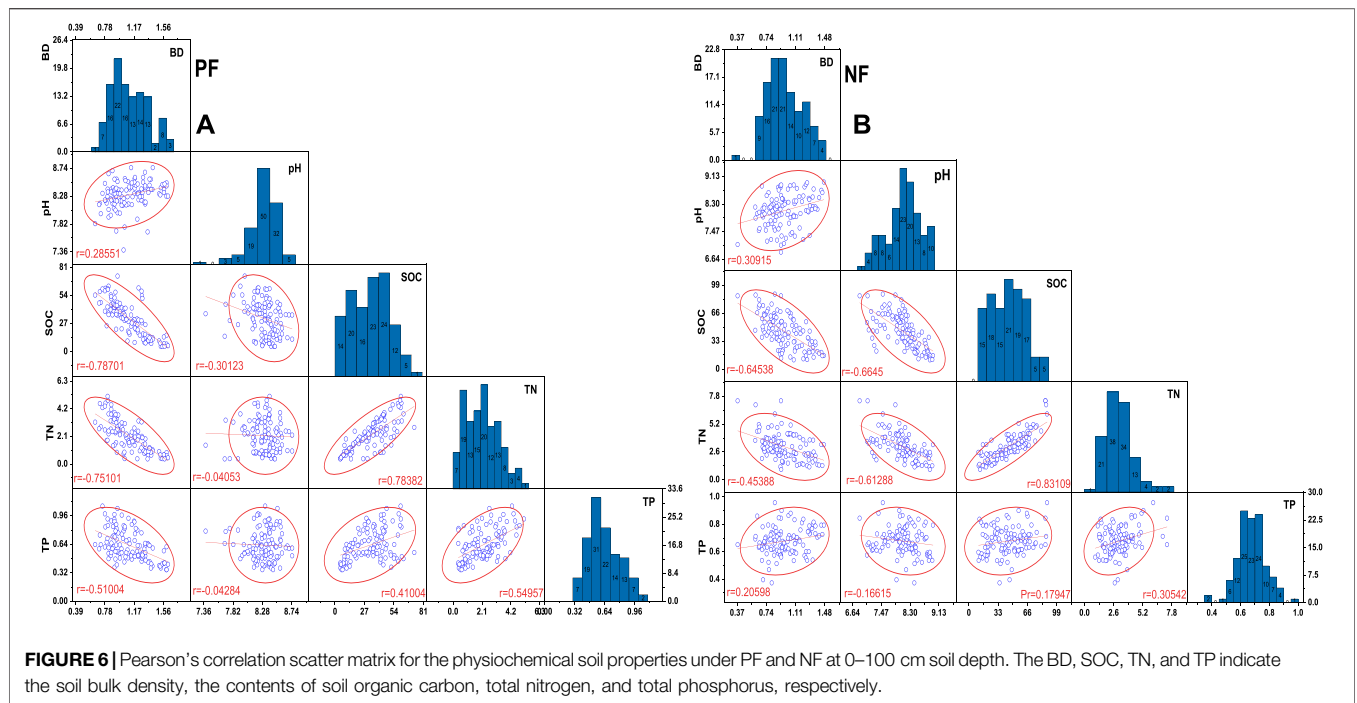


TABLE 4 | The mean physicochemical soil properties in different soil depths from 0 to 100 cm.

Soil depth (cm)	BD (g cm ⁻³)	pH value	SOC (g kg ⁻¹)	TN (g kg ⁻¹)	TP (g kg ⁻¹)
0–20	0.82 ± 0.16 ^d	7.98 ± 0.34 ^b	56.29 ± 16.33 ^a	3.67 ± 1.30 ^a	0.70 ± 0.15 ^a
20–40	0.94 ± 0.16 ^c	8.18 ± 0.37 ^{ab}	46.19 ± 14.01 ^b	3.05 ± 0.82 ^b	0.68 ± 0.14 ^{ab}
40–60	1.04 ± 0.19 ^b	8.24 ± 0.35 ^a	34.55 ± 15.81 ^c	2.35 ± 0.87 ^c	0.65 ± 0.13 ^{abc}
60–80	1.15 ± 0.20 ^a	8.30 ± 0.37 ^a	28.65 ± 15.86 ^{cd}	1.93 ± 0.92 ^{cd}	0.61 ± 0.13 ^{bc}
80–100	1.23 ± 0.24 ^a	8.32 ± 0.42 ^a	25.26 ± 15.34 ^d	1.68 ± 0.92 ^d	0.60 ± 0.13 ^c
Mean	1.04 ± 0.19	8.20 ± 0.37	38.15 ± 15.47	2.61 ± 0.96	0.65 ± 0.13

The values are means ± standard deviations (SD). The different letters within each column indicate a significant ($p \leq 0.05$) difference among soil depths. The BD, SOC, TN, and TP indicate the soil bulk density, the contents of soil organic carbon, total nitrogen, and total phosphorus, respectively.

TABLE 5 | The mean SOC, TN, and TP stocks in different soil depths of 0–100 cm.

Soil depth (cm)	SOCs (Mg ha ⁻¹)	TNs (Mg ha ⁻¹)	TPs (Mg ha ⁻¹)
0–20	89.37 ± 24.62 ^a	6.49 ± 2.09 ^a	1.19 ± 0.37 ^b
20–40	85.28 ± 25.40 ^a	5.70 ± 1.76 ^{ab}	1.28 ± 0.35 ^{ab}
40–60	68.36 ± 27.16 ^b	4.80 ± 1.85 ^{bc}	1.36 ± 0.36 ^{ab}
60–80	61.51 ± 29.57 ^b	4.22 ± 1.83 ^c	1.40 ± 0.34 ^a
80–100	57.57 ± 30.50 ^b	3.88 ± 1.84 ^c	1.47 ± 0.34 ^a
Total	362.09 ± 27.45	25.09 ± 1.87	6.695 ± 0.35

The values are means ± standard deviations (SD). The different letters within each column indicate a significant ($p \leq 0.05$) difference among soil depths. The SOC, TN, and TP indicate soil organic carbon, nitrogen, and phosphorus stocks.

TABLE 6 | The mean SOC, TN, and TP stoichiometry in different soil depths of 0–100 cm.

Soil depth (cm)	C:N ratio	C:P ratio	N:P ratio
0–20	14.41 ± 3.50 ^a	81.17 ± 26.71 ^a	5.74 ± 3.50 ^a
20–40	15.82 ± 5.47 ^a	71.18 ± 27.42 ^a	4.61 ± 1.32 ^b
40–60	16.45 ± 11.8 ^a	54.06 ± 27.20 ^b	3.65 ± 1.32 ^{bc}
60–80	15.79 ± 9.65 ^a	46.35 ± 25.29 ^b	3.09 ± 1.26 ^c
80–100	15.51 ± 7.18 ^a	41.18 ± 24.17 ^b	2.74 ± 1.33 ^c
Mean	15.45 ± 7.53	63.04 ± 26.16	4.26 ± 1.75

The values are means ± standard deviations. The different letters within each column indicate a significant ($p \leq 0.05$) difference among soil depths under forest types.

accumulation (Ngaba et al., 2020). Higher SOC and TN stocks in NF than PF in this study were comparable with previous studies (Gong et al., 2011; Wang et al., 2018), thought to be due to the more significant inputs of soil nutrients to the mineral soils in NF from their higher accumulated humus and litterfall compared with PF

(Gong et al., 2011; Zhang et al., 2016). The TP stock likely increased with soil depth due to deep phosphorous parent materials or compounds down the soil profile (Xu et al., 2019). The similar stocks of TP (for PF and NF) in this study (Table 2) are in line with other studies (Hu et al., 2018), which indicated that forest conversion increases the

TP stocks in the middle and deep soil depths (20–100 cm). This result is possibly due to the higher P input into the deeper soil depth because of the accelerated humus mineralization and leaching and the reduced P uptake by the young trees in the earlier growth stage of plantations (Xu et al., 2018).

The differences in C:P and N:P ratios among soil depths were significant in this study, as reported in many studies (Liu et al., 2017; Xu et al., 2019; Liu et al., 2021), while it showed a non-significant difference in the C:N ratios among soil depths (**Figure 3D**; **Table 6**). A study in the Loess Plateau of China showed a similar result that the C:N ratios remained unchanged with soil depth (Deng et al., 2013). The C:N ratios of forest soils are negatively associated with the mineralization rate of SOM (Stevenson and Cole, 1999; Hu et al., 2019). Therefore, the lower C:N ratios in NF might be explained by the mineralization stage of SOM in the undisturbed NF. The C:P and N:P ratios could be used as indicators of the saturation or limitation of P and N (Sterner and Elser, 2002) and to assess the structure, health, and function conditions of forests that influence the quality and quantity of litter/humus as well as their mineralization (Wang et al., 2014; Yang et al., 2018). The observed variations of C:N:P ratios with soil depth and forest type in our study are consistent with other investigations (Gong et al., 2011; Zhang et al., 2016; Luo et al., 2019). Based on our results, the soil C:P and N:P ratios for NF were higher than those for PF, but the soil C:N ratios for NF were lower than that of PF, which could be associated with the element content changes, and litter decomposition rate (Yu et al., 2010; Zhang et al., 2016; Wang et al., 2018; Yang et al., 2018). Thus, we concluded that the NF present higher soil C:P and N:P ratios but lower C:N ratios than the PF with the same age group, tree species composition, and similar site conditions.

CONCLUSION

After characterizing the forest soil properties in the Qilian Mountains of northwest China, most physicochemical soil properties (except C:N ratio and TP stocks) differed significantly among soil depth and forest types. The soil BD, pH values, and TP stock increased with rising soil depth, while the contents of SOC, TN, and TP and their stocks and stoichiometry decreased with rising soil depth apart from the C:N ratio, which showed non-significant differences among soil depths. The physicochemical soil properties of NF are much better than those of PF since the NF soils present lower BD, favorable pH value range, higher contents of SOC and TN and TP, and higher SOC and TN

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stocks. Therefore, the physicochemical soil properties in terms of soil fertility in NF are unlikely to be restored in a short period through plantations, indicating that the replacement of NF with PF should be avoided to sustain ecosystem sustainability.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The author MR wrote up, prepared the original manuscript, and performed formal data analysis; YW generated funding acquisition, methodology, and also data availability; KZ supervised, added analysis, and reviewed the article; BA and AsA critically reviewed and edited the manuscript as well as help data computation and analysis; AdA conceptualized the study and data analysis; DM, MA, and ZZ curated data, reviewed the manuscript, visualized as well as incorporate their valuable suggestions regarding draft improvement. The author EB edited the manuscript for extensive revision and corrected English language and grammar related issues. All authors have read and agreed to the current version of the manuscript.

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