

# CHARACTERIZING THE DYNAMICS OF SOIL PHYSICO-CHEMICAL PROPERTIES WITHIN DIFFERENT FOREST TYPES EXPOSED TO DIFFERENT FIRE DISTURBANCES

XU, S. Z.<sup>1</sup> – ZHANG, L.<sup>2</sup> – LI, H. G.<sup>3</sup> – LIU, F. L.<sup>1\*</sup> – LONG, S. S.<sup>1\*</sup>

<sup>1</sup>*College of Forestry, Central South University of Forestry & Technology, Changsha 410004, Hunan, China*

<sup>2</sup>*Central South Academy of Inventory and Planning of NFGA, Changsha 410014, Hunan, China*

<sup>3</sup>*Hunan Vocational Institute of Safety Technology, Changsha 410151, Hunan, China*

*\*Corresponding authors*

*e-mail: shisheng@csuft.edu.cn; liuf1680@126.com; phone: +86-731-8562-3450; fax: +86-159-7417-0413*

(Received 16<sup>th</sup> Oct 2025; accepted 30<sup>th</sup> Jan 2026)

**Abstract.** Fire disturbances, a critical factor in forest ecosystems, significantly impact soil properties, yet the interaction between fire intensity and forest type remains underexplored, particularly in secondary mixed forests. This study investigated the effects of four fire intensities (control, low, moderate, and high) on the physio-chemical properties of four distinct forest stand types in Southern China. Key soil attributes measured included bulk density (BD), soil water repellency (SWR), soil organic matter (SOM), pH, total nitrogen (TN), total phosphorus (TP), and total potassium (TK). Results indicated that increasing fire intensity led to higher BD, SWR, pH, and TK, while SOM and TP decreased; TN levels showed minimal change. Low-intensity fires caused negligible alterations compared to the control. However, moderate and high-intensity fires induced significant changes, with high-intensity fires having a profound effect on BD, SWR, pH, and SOM. Notably, post-disturbance, TN and TP levels varied significantly among forest types at the same fire intensity. Furthermore, the soil properties of pure forests were markedly different from those of mixed forests. These findings underscore the combined influence of fire intensity and forest stand type on soil characteristics, providing crucial insights for post-fire vegetation restoration and sustainable forest management.

**Keywords:** *soil properties, fire intensity, forest stand types, ANOVA, Southern China*

## Introduction

Fire disturbance is usually a main factor that leads to forest destruction and regeneration. Fire can be divided into wildfire and prescribed fire. Both wildfire and prescribed fire affect soil ecosystem functions by changing the physical and chemical properties of soils, such as bulk density (BD), soil water repellency (SWR), soil organic matter (SOM), pH, total nitrogen (TN), total phosphorus (TP) and total potassium (TK) (Pellegrini et al., 2025; Francos et al., 2024). Recent studies further underscore that climate change is influencing the intensity and frequency of fires, which are altering historical fire regimes and thereby introducing new uncertainties in predicting long-term soil responses (Abatzoglou et al., 2021). Substantial research has been conducted to reveal the effects of fire disturbances on soil properties but the studies have focused mainly on pure forests, and there have been no reports that deal with secondary mixed forests in southern China, such as Hunan.

Fire has been widely studied mainly because of its important role in influencing flora composition, promoting tree regeneration (Matthews, 2016; Al-Khayri et al., 2025),

increasing wood yield (Hewitt et al., 2023), and regulating human ecological environment (Caldararo, 2002). On the one hand, fire disturbance affects the planting rate and reconstruction rate of tree seedlings and forest succession track after fire. On the other hand, it also impacts the biogeochemical processes of elements. Both wildfire and prescribed burn result in short- and long-term changes in the properties of forest soils such as the supply of nutrients (e.g., calcium, TK, and magnesium) that are essential to the long-term sustainability of forest productivity. The immediate physical effects of fire on boreal forest ecosystems include a significant increase in soil temperature and reduction of water infiltration rate into soils (Brantley et al., 2024; Arzubov et al., 2025). Emerging research emphasizes the critical role of post-fire hydrological changes, such as altered infiltration and erosion patterns, in mediating the long-term recovery of soil nutrient cycles (Kominoski et al., 2022) It is of great significance to study the changes of soil physio-chemical properties after forest fires to prevent the degradation of ecosystem functions, properly manage forest resources, and realize their sustainable development.

There have been many reports that studied effects of fire disturbances on soil properties within different stands. The existing studies consistently demonstrate that different levels of fire intensity result in variable impacts on soil physio-chemical properties. In general, high intensity fire produces the greatest effect on the soil properties (Kennard and Gholz, 2001; Knicker, 2007). The change of soil pH after fire depends on not only the degree of fire disturbance, but also the time node (Certini, 2005; Moghaddas and Stephens, 2007; Ballard, 2000; Fisher and Binkley, 2000). Most studies found that soil pH was not affected by fire disturbances in the same stands, but there were significant differences of pH values among different stands. Soil BD was not affected by fire and stand type (Arunrat et al., 2023). High temperature would reduce SOM content (Certini, 2005; Kutiel and Naveh, 1987). There was no significant difference of SOM between different stands before fire, but the differences might become significantly different after fire. In terms of soil TP and TK, it is controversial whether fire disturbance has an effect on their content. It is generally believed that there is no significant difference of TP and TK between plantations, but the content of TK in planted forests is generally lower than that in natural forests. Most studies revealed that after fire, the TN content decreased with the increase of fire intensity (Gordillo-Rivero et al., 2014; Wright et al., 2021). Fire also increased SWR, but greatly depending on the depth of soil layer and vegetation type (Letey, 2001; Robichaud and Hungerford, 2000).

Overall, however, there is still a lack of studies in investigating the influence of fire disturbance on soil properties among different stand types. The existing studies focus mainly on artificial coniferous or broad-leaved pure forests with simple tree species composition, and there have been no reports dealing with the effects of fire disturbances on soil physio-chemical properties within mixed forests, especially in the secondary mixed forest located in Southern China. Thus, there is a strong need to conduct such a study.

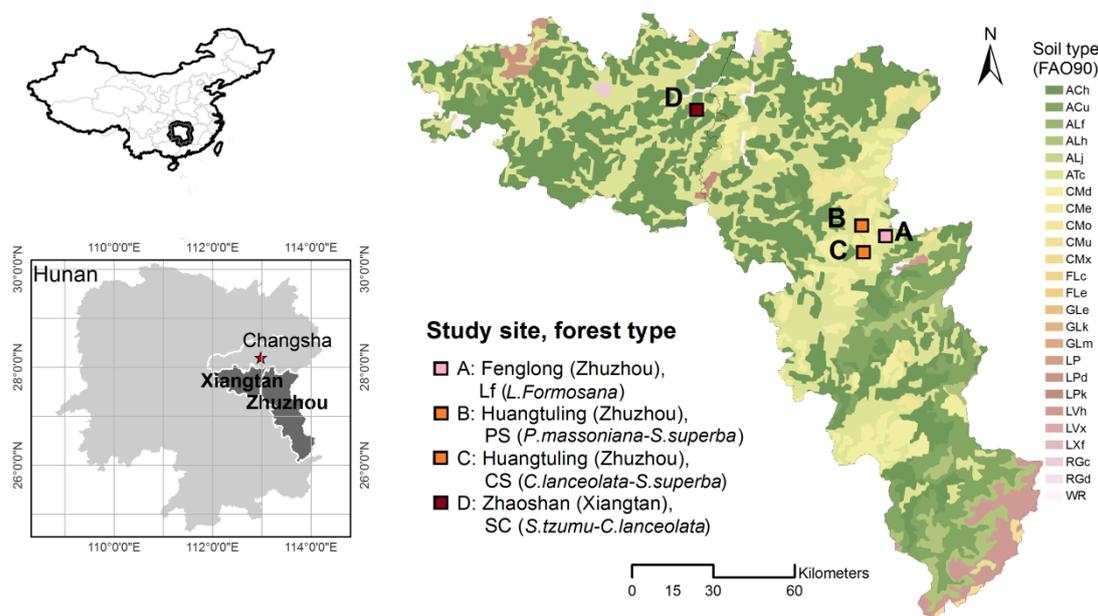
Through an experiment, this study aimed to simultaneously study the effects of fire disturbances on seven soil physio-chemical properties including BD, pH, SOM, TN, TP, TK, and water drop penetration time (WDPT) within the secondary mixed forests located in Hunan of Southern China, with different tree species compositions. Four levels including control, low, moderate and high fire intensity were taken into account. Varied gradient of fire intensity was applied across a pure and three mixed forest stands to characterize the impacts of the fire disturbance intensities on the soil properties and to assess the different susceptibilities of various stands to fire-induced perturbations. It was

expected that the findings from this study could provide the valuable insights into guiding vegetation restoration and the deliberate natural regeneration of fire-affected landscapes in southern China, especially in Hunan. Moreover, these insights could facilitate the judicious utilization of forest soil resources and contribute to enhanced forest productivity through controlled fire practices.

## Materials and methods

### Study sites

The field experiment and sampling were conducted in the native forests of Fenglong (113°4'- 113°43'E, 26°43'- 27°6'N) and Huangtuling (113°49'- 113°51'E, 27°6'- 27°34'N) in Zhuzhou City, and Zhaoshan (112°59'- 113°4'E, 27°54'-28°0'N) in Xiangtan City, Hunan Province, southern China (Fig. 1). Both Fenglong and Huangtuling were located in Zhuzhou city, with similar geographical locations and climate conditions. The climate is characterized by subtropical monsoon with warm wet summers and cold dry winters. Temperature varies from -11.9°C to 40°C with annual average of 17.8°C. Mean annual precipitation is 1411 mm with the interval of 1400 ± 550 mm, depending on the west Pacific Sea surface temperature. Zhaoshan is located in Xiangtan with the climate of subtropical monsoon too. The annual average temperature is about 17.5°C, ranging from -8.5°C to 39.3°C. The mean annual precipitation is 1450 mm (Xu et al., 2016).



**Figure 1.** The Study areas located in Hunan Province, humid subtropical southern China. Soil type: Soil Unit Symbol, FAO 90 (Harmonized World Soil Database, 2008)

The soil characteristics of three study sites were similar (Table 1; Fig. 1), with Yellowish Red earth soil (Chinese Soil Taxonomy, corresponding to the Haplic Alisols and Haplic Acrisols after the FAO/UNESCO Taxonomy). The soil had similar nutrient concentrations (Table 1). The yellowish red earth soil (5YR 7/3, 4/6, Munsell color code) was composed of about 25.36~29.03% clay, 20.71~29.12% silt, and 41.85~54.1% sand

in topsoil. The gravel content was 3.35~5.75%. The soil depth was 60~100 cm. Bulk density of the topsoil was 1.37~1.42 g·cm<sup>-3</sup>. The organic carbon of the soil was 0.94~4.53%. The pH of the topsoil was 4.84~6.63. However, the subsoil was composed of 30.74~37.19% clay, 19.11~26.88% silt, 3.30~7.74% gravel, and 41.79~45.56% sand. The bulk density and organic Carbon were 1.33~1.36 g·cm<sup>-3</sup> and 0.43~1.26%, respectively. The pH of the subsoil was 4.90~6.71.

**Table 1.** The soil properties of the study areas in Zhuzhou and Xiangtan, Hunan Province, humid subtropical China\*

Category	Attribute	Topsoil	Subsoil
Main soil type	Soil Unit Symbol (FAO 90)	Alh and Ach	
	Soil Groups in Chinese Soil Taxonomy FAO/UNESCO Taxonomy	Yellow earths and Red earths Haplic Alisols and Haplic Acrisols	
Soil properties	Reference Soil Depth (cm)	60~100	
	Gravel Content (%)	3.35~5.75	3.30~7.74
	Sand Fraction (%)	41.85~54.1	41.79~45.56
	Silt Fraction (%)	20.71~29.12	19.11~26.88
	Clay Fraction (%)	25.36~29.03	30.74~37.19
	Reference Bulk Density (kg dm <sup>-3</sup> )	1.37~1.42	1.33~1.36
	Organic Carbon (% weight)	0.94~4.53	0.43~1.26
	PH (H <sub>2</sub> O)	4.84~6.63	4.90~6.71

The data set is provided by Cold and Arid Regions Sciences Data Center at Lanzhou (<http://westdc.westgis.ac.cn>)

Fenglong and Huangtuling were selected because they were strongly affected by deforestation due to slash-and-burn cultivation, with a large area (about 1.0122 10<sup>5</sup> ha) of the forested lands, thus allowing the experiment conducted within three different forest stands including the mixed pine and evergreen broadleaved forest, and the mixed conifer and evergreen broadleaved forest in Huangtuling, and the pure deciduous forest in Fenglong. Zhaoshan was chosen as another experimental site mainly because of its similar climate and soil characteristics with the primary vegetation and secondary vegetation seriously disturbed by human activities. The total area of the region was 6.8 10<sup>3</sup> ha, including 3.434 10<sup>3</sup> ha of forested land with a percentage forest cover of 52.96%, thus allowing the experiment conducted within the mixed deciduous and coniferous forest.

### Plot establishment and fire treatments

Four stand types of forests were selected from the three sites (Table 2): (1) the pure deciduous forest (*L. formosana*) in the site of Fenglong, named *Lf* herein after; (2) the mixed pine and evergreen broadleaved forest in the site of Huangtuling (*P. massoniana-S. superba*), named *PS*; (3) the mixed conifer and evergreen broadleaved forest in the site of Huangtuling (*C. lanceolata-S. superba*), named *CS*; and (4) the mixed deciduous and coniferous forest in the site of Zhaoshan (*S. tzumu-C. lanceolata*), named *SC*. The *Lf* had a density of 1300 plants per hectare with the stand age of 17 years. The diameter at breast height (DBH) and mean tree height were 14 cm and 10.3 m, respectively. The dominant tree species included *Liquidambar formosana* and *Pinus massoniana*.

**Table 2.** The statistical parameters of forest stands in the study sites

Variables*	Stands and sites			
	Lf	PS	CS	SC
Forest types	L. formosana	P. massoniana-S. superba	C. lanceolata-S. superba	S. tzumu-C. lanceolata
Location	Fenglong (Zhuzhou)	Huangtuling (Zhuzhou)	Huangtuling (Zhuzhou)	Zhaoshan (Xiangtan)
Density (trees/ha)	1300	2000	1400	1600
Stand age (yr)	17	9	6	6
DBH (cm)	14	9.2	9.7	12
H (m)	10.3	5.4	6.1	6.6
Dominant species	<i>Liquidambar formosana</i> , <i>Pinus massoniana</i>	<i>Pinus massoniana</i> , <i>Schima superba</i> , <i>Liriodendron chinense</i> , <i>Taxus chinensis</i>	<i>Cunninghamia lauceolata</i> , <i>Schima superba</i> , <i>Liriodendron chinense</i> , <i>Taxus chinensis</i>	<i>Sassafras tzumu</i> , <i>Cunninghamia lanceolata</i> , <i>Pinus massoniana</i> , <i>Pinus elliottii</i>

DBH = diameter at breast height; H = mean tree height

The density of *PS* was 2000 plants per hectare with a stand age of 9 years, a mean DBH of 9.2 cm and a mean tree height of 5.4 m. The tree species consisted of *Pinus massoniana*, *Schima superba*, *Liriodendron chinense*, and *Taxus chinensis*. The stand density and age of *CS* were 1400 plants per hectare and 6 years, respectively. The mean DBH was 9.7 cm, and the mean height was 6.1 m. The forest was formed mainly by *Cunninghamia lauceolata*, *Schima superba*, *Liriodendron chinense*, and *Taxus chinensis*. The stand *SC* was 6 years old and had a density of 1600 plants per hectare. The mean DBH and mean height were 12 cm and 6.6 m, respectively. The stand was dominated by tree species *Sassafras tzumu*, *Cunninghamia lanceolata*, *Pinus massoniana*, and *Pinus elliottii*.

In order to examine the effects of fire disturbances on the physical and chemical properties of the soil within the selected four forest stands, four intensity levels of prescribed fire were chosen and described in detail in *Table 3*, including control (not affected by fire), low, moderate, and high intensity. In the experiment, the same fire intensities were applied to the selected forest stands (*Lf*, *PS*, *CS*, and *SC*). Within each of the four selected forest stands, four 20 m × 20 m sample plots (*Fig. 2a* as an example) were established corresponding to the four fire intensity levels: unburned, low, moderate, and high intensity fire (*Fig. 2b–d* as examples). The specific operations were similar to those in the study of Si et al. (2009). Each of the four fire intensity levels was repeated three times within each of the four forest stand types, which led to a total of 48 plots (*Table 4*). All the fire treatments were done on December 23, 2014. We simulated the fires in December mainly because (1) December is the fire season in the study region (Hunan Province of Southern China); and (2) a wildfire recently occurred there. Meanwhile, for the controlled experiment, we selected adjacent unburned stands that had comparable forest types. The stand ages of the plots were different across the stand types but the same within each of the four stand types and thus the age factor that affects the soil properties could be ignored.

**Table 3.** The summary of the prescribed burns for the four forest stand types used to examine the effects of fire intensity levels on the soil properties (Ryan, 2002)

Characteristics	Fire levels			
	Control	Low	Moderate	High
Fire intensity levels	No fire	Low-intensity prescribed fire	Moderate-intensity prescribed fire	High-intensity prescribed fire
Class burn	Unburned	Light surface burn	Light surface burn	Crown fire
The general type of fires	/	Surface fire	Surface fire	Deep burning or crown fire
Flame height	/	<1.5 m	1.5-3.0 m	>3.0 m
Severity	Plant parts green and unaltered, no direct effect from heat	Canopy trees with green needles although stems scorched	Canopy trees with green needles although stems scorched	Canopy trees killed and needles consumed
Fire intensity levels	/	Surface litter, mosses, and herbs charred or consumed	Surface litter, mosses, and herbs charred or consumed	Surface litter of all sizes and soil organic layer largely consumed
Class burn severity	/	Soil organic layer largely intact and charring limited to a few mm depth	Soil organic layer largely intact and charring limited to a few mm depth	White ash deposition and charred organic matter to several cm depth

**Table 4.** The field operations in the prescribed fire experiments (four forest types × four fire intensity treatments)

Fire levels	Stand types			
	Lf	PS	CS	SC
Control	Control (C-Lf)	Control (C-PS)	Control (C-CS)	Control (C-SC)
Low	Low (L-Lf)	Low (L-PS)	Low (L-CS)	Low (L-SC)
Moderate	Moderate (M-Lf)	Moderate (M-PS)	Moderate (M-CS)	Moderate (M-SC)
High	High (H-Lf)	High (H-PS)	High (H-CS)	High (H-SC)

### Soil sampling

The soil was sampled (Fig. 2e as an example) within each unburned (control) and burned plot (low, moderate, and high intensity fire) of four selected forest stands (Lf, PS, CS, and SC). Four soil samples at the soil layers of 0-5 cm, 5-10 cm, 10-15 cm and > 15 cm, including ash and litters, were taken using a stainless soil cutting ring sampler (72 mm × 52 mm) within each sampled plot, labeled and homogenized in the lab. For the unburned treatment, we collected the soil samples at the time after the fire event (December 23, 2014). For the burned plots, we collected the soil samples at intervals of 3 days (December 26, 2014), 3 months (January 24, 2015), 6 months (June 27, 2015) as the time elapsed since the fire event (December 23, 2014). In this study, these time nodes were set to eliminate the effect of fire time on the experimental results.



**Figure 2.** Photo examples of the experiment: (a) one stand and plot design before fire; (b–d) Stands firing; (e) Soil samples taken; and (f) measurement process of SWR using WDPT

### **Laboratory analysis**

In the lab, the soil samples were separated into three parts for different analyses:

#### **(1) BD and SWR**

All the samples were dried for 2 days at a temperature of 105°C, then shattered and sieved through a 2 mm sieve. The soil BD ( $\text{g}\cdot\text{cm}^{-3}$ ) was determined by obtaining a known volume of soil, drying it to remove the water and weighing the dry mass. SWR (s) was measured by WDPT (s) method (Fig. 2f as an example) (Vihnanek and Ballard, 1988). The soil of each sample was exposed to a controlled laboratory atmosphere (20°C, 50% relative humidity) for 24 h to eliminate the potential effects of any variation in preceding atmospheric humidity on SWR (Doerr et al., 1998). According to Buczko et al. (2002), the penetration times were classified in intervals and in classes (wetable or non-water repellent soil (<5 s), and slightly (5–60 s), strongly (60–600 s), severely (600–3600 s) and extremely (>3600 s).

## (2) SOM and pH

The soil samples were analyzed for percent SOM (% SOM) by rapid dichromate oxidation of organic carbon. The soil pH was determined on a soil water suspension (1:2.5 suspension) by pH meter.

## (3) TN, TP and TK

The soil samples were dried for 24 h at 60°C and then passed through a 2 mm sieve. The soil samples were used to analyze for TN, TP and TK. The soil TN (%) was determined by Kjeldahl digestion (Baer et al., 2004) and distillation procedure as described in soil laboratory staff. The soil TP ( $\text{g} \cdot \text{kg}^{-1}$ ) was determined in the soil by Lutz method (Lutz, 1956). Soil TK ( $\text{g} \cdot \text{kg}^{-1}$ ) was extracted by neutral normal ammonium acetate method (MacDonald and Huffman, 2004) and was determined by the flame photometer (Evans Electro Selenium Ltd; Holsted Essex, England).

## Statistical analysis

In this study, the statistics of seven soil properties including BD, SWR, pH, SOM, TN, TP, and TK were first characterized based on four forest stand types (*Lf*, *PS*, *CS*, and *SC*) and four fire disturbance levels (control, low, moderate, and high intensity fire). The comparisons of the soil properties were then made under different fire disturbances given a same forest stand, and across different forest stands given a same fire intensity level, respectively. The comparisons and analyses were conducted using SPSS11.5 software (IBM SPSS Statistics v21.0, IBM Corp., Armonk, NY, USA), including descriptive statistics (mean, standard deviation, standard error of Mean), box plot, one way ANOVA and Fisher LSD test at the significant level of less than 0.05 (MeanDiff, SEM, t Value, Sig, LCL, UCL). We used the one-way-ANOVA because of the following reasons. The longest interval of time for collection of the soil samples after the fires was only 6 months, indicating a short term. Given a plot, moreover, only three different time samples were collected and given a time, the soil samples were collected from all the plots with different fire intensity levels and the stand types. In this study, these time nodes were set to eliminate the effect of fire time on the experimental results. Using control plots as pre-fire disturbance parameters, this study focused only on the short-term impacts of the fire disturbances on the soil physio-chemical properties. The more important is that the interactions between the sample collection time and the forest stand type were not statistically significant for all seven soil properties ( $p < 0.05$ ) and the interactions between the sample collection time and fire intensity were not statistically significant for five of seven soil properties ( $p < 0.05$ ). Thus, the time factor was not taken into account for statistical analysis. In addition, the interactions between the stand type and the fire intensity were not significant for six of seven soil properties. Therefore, we conducted a one-way analysis of variance (ANOVA).

## Results

### Bulk density and soil water repellency

Given a fire intensity level, there were differences of BD ( $\text{g} \cdot \text{cm}^{-3}$ ) and SWR ( $\text{Log}_{10}\text{WDPT}$ , s) values among four stands (*Lf*, *PS*, *CS*, and *SC*) but the differences were not statistically significant at the significant level of  $p < 0.05$  except the significant

difference of BD between CS and other forests (Lf, PS, and SC) after the fire disturbances (Table 5). Given a stand type, the significance of the differences of BD and SWR among different fire intensities varied depending on the intensity levels (control, low, moderate, high intensity fire). The BD and SWR increased with the increase of fire intensity in the same stand. The effects of the fire disturbances on BD and SWR were more obvious under the high intensity fire.

**Table 5.** The mean values with standard deviations of the soil characteristics within each of four forest types

Properties**	Fire levels	Site***							
		Lf		PS		CS		SC	
		N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD
Bulk density (g·cm <sup>-3</sup> )	Control	4	1.27 ± 0.02 AB	4	1.24 ± 0.02 A	4	1.17 ± 0.11 A	4	1.26 ± 0.02 AB
	Low	60	1.26 ± 0.03 A	60	1.24 ± 0.02 A	60	1.17 ± 0.10 A	60	1.25 ± 0.03 A
	Moderate	60	1.28 ± 0.02 B	60	1.26 ± 0.02 B	60	1.21 ± 0.07 B	60	1.27 ± 0.02 B
	High	60	1.30 ± 0.03 B	60	1.28 ± 0.03 B	60	1.25 ± 0.06 C	60	1.28 ± 0.03 B
SWR (Log <sub>10</sub> WDPT, S)	Control	4	0.23 ± 0.29 A	4	0.64 ± 0.20 AB	4	0.44 ± 0.19 A	4	0.54 ± 0.28 A
	Low	60	0.69 ± 0.54 AB	60	0.91 ± 0.47 A	60	0.83 ± 0.51 A	60	0.88 ± 0.51 A
	Moderate	60	0.87 ± 0.61 BC	60	1.03 ± 0.54 AB	60	1.04 ± 0.52 B	60	1.02 ± 0.58 AB
	High	60	1 ± 0.61 C	60	1.16 ± 0.55 B	60	1.15 ± 0.55 B	60	1.14 ± 0.58 B
pH	Control	4	4.54 ± 0.13 A	4	4.27 ± 0.13 A	4	4.29 ± 0.11 A	4	4.21 ± 0.13 A
	Low	60	4.61 ± 0.15 A	60	4.37 ± 0.14 A	60	4.40 ± 0.11 A	60	4.34 ± 0.17 A
	Moderate	60	4.7 ± 0.22 A	60	4.53 ± 0.26 A	60	4.56 ± 0.19 B	60	4.49 ± 0.27 B
	High	60	4.98 ± 0.49 B	60	4.80 ± 0.47 B	60	4.94 ± 0.54 C	60	4.65 ± 0.36 C
SOM (%)	Control	4	3.39 ± 0.90 A	4	1.53 ± 0.66 A	4	2.09 ± 1.06 A	4	1.44 ± 1.06 A
	Low	60	3.08 ± 0.36 A	60	1.4 ± 0.38 A	60	1.83 ± 0.53 A	60	1.29 ± 0.70 A
	Moderate	60	2.87 ± 0.34 AB	60	1.31 ± 0.35 A	60	1.68 ± 0.42 A	60	1.20 ± 0.59 AB
	High	60	2.53 ± 0.48 B	60	1.13 ± 0.32 B	60	1.47 ± 0.30 B	60	1.04 ± 0.50 B
TN (%)	Control	4	0.2 ± 0.06 AB	4	0.12 ± 0.03 AB	4	0.25 ± 0.04 ABC	4	0.09 ± 0.03 A
	Low	60	0.21 ± 0.06 A	60	0.12 ± 0.03 A	60	0.26 ± 0.05 A	60	0.09 ± 0.03 A
	Moderate	60	0.19 ± 0.04 B	60	0.11 ± 0.02 B	60	0.24 ± 0.03 B	60	0.08 ± 0.03 A
	High	60	0.18 ± 0.05 B	60	0.1 ± 0.02 B	60	0.22 ± 0.04 C	60	0.09 ± 0.08 A
TP (g kg <sup>-1</sup> )	Control	4	0.26 ± 0.03 ABC	4	0.22 ± 0.04 ABC	4	0.32 ± 0.04 ABC	4	0.10 ± 0.01 A
	Low	60	0.26 ± 0.02 A	60	0.22 ± 0.03 A	60	0.32 ± 0.04ab A	60	0.09 ± 0.02 A
	Moderate	60	0.25 ± 0.02 B	60	0.21 ± 0.03 B	60	0.31 ± 0.03ac B	60	0.09 ± 0.01 A
	High	60	0.23 ± 0.03 C	60	0.19 ± 0.04 C	60	0.29 ± 0.04b C	60	0.09 ± 0.02 A
TK (g kg <sup>-1</sup> )	Control	4	7.33 ± 0.92 A	4	6.39 ± 0.95 A	4	6.34 ± 0.47 A	4	7.11 ± 1.1 A
	Low	60	7.32 ± 0.76 A	60	6.36 ± 0.77 A	60	6.33 ± 0.38 A	60	7.05 ± 0.92 A
	Moderate	60	7.39 ± 0.74 A	60	6.41 ± 0.76 A	60	6.39 ± 0.43 A	60	7.14 ± 0.92 A
	High	60	7.45 ± 0.81 A	60	6.44 ± 0.83 A	60	6.42 ± 0.53 A	60	7.19 ± 1.01 A

The same uppercase letters indicate NO significant differences between the fire treatments given a forest stand, and between the stand types given a fire intensity level

One Way ANOVA, Fisher LSD test; \*\*pH = pH value; TN = total nitrogen; TP = total phosphorus; TK = total potassium; SWR = soil water repellency. \*\*\*Lf = *L. formosana*, PS = *P. massoniana-S. superba*, CS = *C. lanceolata-S. superba*, and SC = *S. tzumu-C. lanceolata*  
P < 0.05

In LF stand, there were no significant differences of BD between the control and other three fire disturbances (Table 5), however, the differences of BD between the low fire intensity and both the moderate and high intensities were significant (p < 0.05). In the

same stands of *PS*, *CS* and *SC*, there were no significant differences of BD between the control and low intensity fire. In *PS* stand, the BD values from the control and low intensity fire were significantly different from those of the moderate and high intensity fires although there was no significant difference of BD between the moderate and high intensity fires. In *CS* stand, there were significant differences of BD between both the control and both the moderate and high intensity fires, and between the low intensity fire and both the moderate and high intensity fires. There was also a significant difference of BD between the moderate and high intensity fires. In *SC* stand, the difference of BD was only significant between the low intensity fire and both the moderate and high intensity fires. The fire disturbances had a greater effect on *CS* than other stands. In the unburned stands, BD of *CS* was significantly lower compared with those in other stands.

SWR showed no significant differences between the unburned and low intensity fire in all four forest stands ( $p < 0.05$ ) (*Table 5*). After the moderate intensity fire, SWR was significantly higher than the unburned in *Lf* and *CS*. However, there were no significant differences between the unburned and moderate intensity fire in *PS* and *SC*. Compared with the unburned forest stands, after the moderate intensity fire SWR increased by 2.8 and 1.4 times in *Lf* and *CS*, respectively. In *Lf*, *CS* and *SC*, the high intensity fire led to significantly higher SWR values compared with those in the control, but there was no significant difference in *PS*. There were significant differences of SWR between the low intensity fire and high intensity fire for all the stands. However, the differences of SWR between the moderate and high intensity fires were not significant for all the stands. In addition, the stand *PS* had a significant higher SWR than the stand *Lf* in the control and low intensity fire stands (*Table 5*).

### ***Soil organic matter and PH***

Both SOM (%) and pH showed differences among the stands (*Lf*, *PS*, *CS*, and *SC*) and different intensity fires (control, low, moderate, and high intensity fire) (*Table 5*). Within each of the stands, with the increase of fire intensity, SOM had a decreased trend, while soil pH showed an increased trend. The significance of the difference varied depending on the stands and intensity fires.

Given each of the stands, there were no significant differences of SOM and pH between the unburned and low intensity fire (*Table 5*). Given a stand, there were also no significant differences of SOM among the control, low and moderate intensity fire, but the SOM values of the high intensity fire were significantly lower than those from the control and low intensity fire in *Lf* and *SC*, and even lower than those from the control, low and moderate intensity fires in *PS* and *CS*. This meant that there were significant differences of SOM between the moderate and high intensity fire in *PS* and *CS* but not in *Lf* and *SC*. Given a fire intensity level, the SOM value in stand *Lf* was significantly higher than those in *PS*, *CS* and *SC* (*Table 5*).

After the moderate intensity fire, the pH showed significantly different from those of the low intensity in both *CS* and *SC* stands but not in both *Lf* and *PS* stands (*Table 5*). Moreover, the high intensity fire led to pH values that were significantly different from those of the control, low and moderate intensity fires in all the forest stands. Under different fire intensities, the highest and lowest value of pH was observed in *Lf* and *SC*, respectively (*Table 5*). Except in the stands of high intensity fire, the pH in *Lf* was significantly higher than that in *PS*, *CS*, and *SC*. After the high intensity fire, soil pH in *Lf* was significantly higher than that in *PS* and *SC*, and pH in *CS* was also significantly higher than that in *SC*.

### **Total nitrogen, total phosphorus and total potassium**

Given each of the four stands, overall, as the fire intensity increased, both TN (%) and TP ( $\text{g}\cdot\text{kg}^{-1}$ ) slightly decreased, while TK ( $\text{g}\cdot\text{kg}^{-1}$ ) slightly increased (Table 5). The results indicated no significant differences of TN between the unburned stands and the stands with low and moderate intensity fires for all the forest types, however, both the moderate and high intensity fires resulted in the TN contents that were significantly different from that of the low intensity fire in *LF*, *PS* and *CS* stands but not in *SC* stand (Table 5). There was significant difference of TN between the moderate and high intensity fires in *CS* stand but not in *Lf*, *PS* and *SC* stands. Moreover, for all the intensity fires, TN values of *CS* and *Lf* stands were significantly higher than those of *PS* and *SC* (Table 5). Given a fire intensity, there were significant differences of TN among the stands except no significant difference between *PS* and *SC* after the high intensity fire.

Within each of the four stands, there were no significant differences of TP between the burned stands and the unburned stands. However, the TP values significantly differed from each other among the different intensity fires in *Lf*, *PS* and *CS* stands but not in *SC* stand (Table 5). Given a fire intensity level, the content of TP was greatest in *CS* stand, then *Lf*, *PS* and *SC*. In the unburned forests, TP showed no significant difference between *Lf* and *PS* (Table 5). However, there were significant differences of TP among the stands after the fire disturbances.

Finally, although given the same stands, there was a slightly increased trend of TK values as the fire intensity increased, the increases were statistically not significant for all the stands (Table 5). The concentrations of TK showed greatest value in the stand *Lf*, then *SC*, *PS* and *CS*. In the unburned stands, there were no significant differences among the stands. However, TK values of *Lf* and *SC* stands were significantly higher than those of *PS* and *CS*.

## **Discussion**

### **Effects of prescribed fire on bulk density and soil water repellency**

We found that BD and SWR ( $\text{Log}_{10}\text{WDPT}$ , s) increased with the increase of fire intensity within the same forest stands. The increases were greatest and significant in the stands with high intensity fire. Compared with BD, SWR was more affected by the fire disturbances. The characteristics had nothing to do with tree species. There was substantial literature that dealt with the effects of different fire intensities on the soil physical variables in forest stands, including increase (Letey, 2001; Glenn and Finley, 2010), and decrease (Johnson, 1992) or little effect (Doerr et al., 1998). Letey (2001) reported that the intensity of water repellency was increased by fire intensity because the temperature destroyed water repellency in grass sites, particularly in the sites of high intensity fire, which is consistent with the conclusion of this study. But, Doerr (1998) reported that low intensity fire did not affect water repellency in *Eucalyptus* and *pine* forests in Portugal, and BD were reduced after wildfires, but there were no significant differences between the burned and unburned sites (Xue et al., 2014), which is different from the conclusion of this study. We found that there were no significant differences in SWR with the different fire intensities in all four forest stands, except for the high intensity fire led to significantly high SWR than the control and low intensity fire. After the fire disturbances, BD showed significant differences only between *CS* and other three forest stands (*Lf*, *PS*, and *SC*). Scotter (1963) found that there were no significant

differences in SWR with the different intensity fires in all kind of forests at Daxing'an Mountain range, which is not in agreement with the results of this study. The main reason was that the conifer mixed forest was the dominating forest in the study (*Ass. Herbage-Larix gmelini* forest, *Ass. Rhododendron dauricum-Pinus sylvestris* var *mongolica* forest, *Larix gmelini-Pobulus davidiana* forest, *slope-Larix gmelini* forest, *Ledum palustre-Larix gmelini* forest).

After the high intensity fire, BD significantly increased compared with that after the low intensity fire at the same forest stands. Some studies suggested that there were no significant differences or significant decreases in BD between burned and unburned. Dyrness et al. (1989) reported that BD with low value existed in burned soil, and there were no significant differences between burned and unburned sites, absolute values of BD declined at burned sites. It was also reported that BD was much higher at cultivated lands than other lands but it significantly decreased after burned. BD reduced in crop residue burned farmlands and charcoal sites too (Cheng et al., 2025). This was in disagreement with the results of this study because their research area was agricultural land. We found that after the fire disturbances, BD increased and had higher values in the secondary broad-leaved forest stand (*Lf*) than in the mixed conifer and broadleaved forests (*PS*, *CS*, and *SC*). Compared with other forests, the fires had more effects on BD in *CS* because compared with those in the unburned stands, their differences of BD after burned became smaller. Given a fire intensity level, the difference of BD among the different stands is related to soil depth and vegetation types. The BD of the first layer of *Betula platyphylla* Suk was lowest in all forests and in the second and third layer soil of *Betula platyphylla* Suk forest, it showed no significant difference compared with other forests (*Pinus tabulaeformis* Carr, *Amygdalus mongolica* (Maxim.) Ricker) (Zhang et al., 2015), implying a different finding from the result of this study. BD was significantly lower in native broadleaved forest than *C. lanceolata* plantation (Wang et al., 2009), which was in disagreement with the results of this study. Zhao et al. (2011) reported that after the low intensity fire, BD values were similar in different forests, including *Ass. Herbage-Larix gmelini* forest, *Ass. Rhododendron dauricum-Pinus sylvestris* var *mongolica* forest, *Larix gmelini-Pobulus davidiana* forest, *slope-Larix gmelini* forest, *Ledum palustre-Larix gmelini* forest. After severe fires, BD values became different compared with those in the unburned sites, but no significant differences, and they were higher in artificial coniferous forests than in natural broad-leaved forests (Zhang et al., 2013). This finding was inconsistent with the results of this study.

The effect of fires on SWR increased as the increased intensity of fire. Compared with the SWR values in the unburned stands, the increases of SWR became significant in all the four stands except *PS* only after the high intensity fire, which indicated that SWR in the stand soils depended on the intensity of fire. Other studies showed that SWR was affected by fire intensity, fire duration, site type, and soil depth (Gordillo-Rivero et al., 2014), the results were similar to those in this study. In the stands with low intensity fire, WDPT was higher than that in the unburned stands, but no significant differences were found. The high intensity fire significantly increased water repellency (Gordillo-Rivero et al., 2014; MacDonald and Huffman, 2004).

In addition to fire intensity, the characteristics of SWR after fire are related to time and soil depth (Qin et al., 2024). The thickness of the water repellent layer depends on fire intensity (Chen et al., 2020). The study showed that in chaparral, fire could cause the intensification and translocation of water repellent substances (DeBano, 2000). The conclusion was consistent with that of this study. Other studies implied that the unheated

control cores had greater WDPT than three burning treatments although the WDPT values of the four soils at their surfaces were not significantly different (Robichaud and Hungerford, 2000). Rice (1993) found that wildfire in plantations caused water repellency to be burned off the surface soil but intensified it in lower soil layers. Moreover, some authors found that a more severe fire at the soil surface could destroy or move the water repellent substances downward during the fire, leaving an extremely wettable surface on top of the water repellent layer (Letey, 2001; Onda et al., 2008). The depth of the wettable surface layer was associated with the severity of fire and deep sandy soils. Jiang et al. (2005) found that moderate intensity fire increased SWR, but high intensity fire either enhanced or destroyed hydrophobicity, as different temperature peaks or heating periods were reached at the soil surface, which led to different results depending on soil types. Glenn and Finley (2010) observed that infiltration rates significantly increased from moderate to high intensity fire. They found that the moderate intensity fire resulted in the largest number of samples that had strong WDPT in comparison to other intensity fires. This was different from the results in this study mainly due to their study being conducted in shrub and grass dominated areas not in forested lands. We found that the forest types had nothing to do with SWR except Lf showing a significant lower SWR than other stands after the high intensity fire. However, others reported that Holm oaks had smaller SWR values compared to pine and eucalyptus forest (Zavala et al., 2014). In addition, Buczko et al. (2002) pointed out that pure stands had lower water repellency than mixed stands. The results were different from the finding of this study due to the different tree species, different site conditions, and different soil depths.

### ***Effects of prescribed fire on soil organic matter and PH***

Substantial research has been conducted in the field of the effects of prescribed fires on SOM and pH but inconsistent findings are often observed. Some studies noted that SOM decreased after fire disturbances (Certini, 2005), while other experiments indicated that SOM increased after fires (Cheng et al., 2025). In this study, SOM in four forest stands consistently decreased as the fire intensity increased but there were no significant differences of SOM between the unburned and low intensity fire, and compared with those in the stands of the unburned and low intensity fire, the SOM values became significantly smaller in all four stands until the high intensity fire. This is in agreement with the finding in the study of Certini (2005), in which SOM significantly decreased after severe wildfire because high temperature led to decomposition of soil organic matter. Kutiel and Naveh (1987) also reported that SOM decreased in burned areas. Moreover, fires could increase effective nutrients in soil. Low intensity prescribed fires usually result in little change in soil carbon, but severe prescribed fires or wildfires can result in a huge loss of soil carbon (Johnson, 1992). On the contrary, it documented an increase in SOM following fire (Cheng et al., 2025). Al-Khayri, 2025). Stromgaard (1992) also showed an increase in SOM during light to moderate fires because of the incorporation of unburned or partially burned slash fragments into soil. In heavy fire areas, SOC was higher than that in unburned, low, and moderate intensity fire sites, in Daxing'an Mountain range (Zhao et al., 2011). Although there was no significant difference in SOC between low and moderate intensity fire, SOC increased with the increased fire intensity (Zhao et al., 2011). In this study, we found that SOM in Lf was significantly higher than that in other three forests for the unburned and burned stands. This is in agreement with the conclusion of the study by Xue et al. (2014), who found that the mass fraction of SOM in the *White Birch* was greatest and smallest in *Pinus sylvestris*

after high intensity fire because litter was decomposed in *White Birch* faster than in *Pinus sylvestris*. On the contrary, other reports suggested that there was no significant difference in SOM of the samples from different forest ecosystems (Baer et al., 2004), which is inconsistent with the result of this study mainly because of the differences in tree species and experimental methods. Zhao et al. (2011) reported that significant difference of SOM existed between different forests after low intensity wildfire, and the main reason is the difference in stand types. In different site conditions, the highest value of organic carbon was observed at charcoal site (Adeyemo et al., 2023). Due to severe burning, the lowest value of organic carbon was recorded at farmland where crop residues were burned for land preparation (Alvarez, 2024).

Although there have been reports in which fire disturbances had a little effect on soil pH (Campbell, 1977), at present, most studies indicated that soil pH increased after burned (Certini, 2005; Ballard, 2000; Qin et al., 2012; Scotter, 1963). Moreover, pH in broadleaved forests was greater than that in coniferous forests (Wang et al., 2009). In this study, we found that pH increased by the increase of the fire intensity, and had a little difference in the low and moderate fire intensity compared with the unburned stands. However, significant differences of pH were found between the unburned and high intensity fire stands, indicating that the high intensity fire had a significant effect on soil pH. Meanwhile, pH in the secondary pure forest (*Lf*) was higher than that in other forests under any fire intensity, and significant differences were found (except the high intensity fire). But, there were no significant differences of pH among other three mixed broadleaved conifer forests (*PS*, *CS*, and *SC*). Scotter (1963) reported that the value of pH in all burned areas increased, when compared with unburned forests. Soil pH also increased after burning of crop residue (Kumar et al., 2025). The increase of pH after burned was because soil organic acid was decomposed, which could increase the content of metal ions (Certini, 2005; Ballard, 2000). However, pH significantly increased only at higher temperature (450-500°C) (Certini, 2005). Soil pH increased after crop residue burned in farmlands and was significantly higher than that in cultivated lands (Kumar et al., 2025).

The pH in native broadleaved forests was significantly higher than that in *C. lanceolata* plantation soil. Zhao et al. (2011) reported that soil pH could not be affected by low intensity fire but increased in moderate and high intensity areas compared with unburned sites because moderate and high intensity fire led to an amount of unionized organic acids in soil and litter burned off, which is in agreement with the results of this study. Zhao et al. (2011) also found that soil pH was higher in broadleaved forest (*Betula platyphylla*) than in other forests but there were no significant differences of pH among coniferous forests after low intensity fire. Qin et al. (2012) showed that pH at *Larix gmelinii* was higher than in *Betula platyphylla* after high-severity fire in Greater Khingan Mountains. However, a result by Campbell et al. (1977) indicated no difference in pH between burned and unburned soils in *Ponderosa* pine in Northern Arizona, because soil pH was not affected by fire. This is in disagreement with the results of Qin et al. (2012), who found that soil pH in *Schima superba* pure forest was lower than in *Pinus massoniana*, because *Schima superba* pure forest led to the increase of acidification. After low intensity fire, there were no significant difference in soil pH between *Cypress* and *Pinus armandii* plantations (Han et al., 2014). Ulery (1993) indicated that pH increased following high-severity prescribed fire because of the release of alkaline ions from production of potassium (K) and sodium (Na) oxides, hydroxides, and carbonates in the ash and also organic acid denaturation with heating. We also found that soil pH significantly increased

after the high intensity fire. However, Xu et al. (2016) demonstrated that pH increased at *Pinus sylvestris*, while decreased in other forests after high intensity fire compared with control plots. Soil pH increased significantly in the soil one-year post-fire and then decreased progressively after four and seven years (Xue et al., 2014), which is in disagreement with the finding of this study, because the research duration and the fire intensity were inconsistent.

### ***Effects of prescribed fire on total nitrogen, total phosphorus and total potassium***

There have been reports that showed that the effects of wildfire on soil chemical properties were significantly different between treatment variation, time variation, and treatment-by-time interaction in the Two Way *ANOVA* (Xue et al., 2014). In this study, we found that there were no significant differences of TN between the unburned and burned stands within the same stands. Given a fire intensity level, however, there were significant differences in TN of the samples from the different forest stands except there was no significant difference of TN between *PS* and *SC* after the high intensity fire. Whereas compared with the unburned, TN slightly decreased after the moderate and high intensity fire. In the low intensity fire areas, TN was significantly higher than in the stands with the moderated and high intensity fires except *SC*, which indicated that fire intensity had influence on soil nutrients.

There have been different conclusions about the effects of fire disturbances on soil TN. Some reports showed that fire disturbances had a little effect on soil TN (Moghaddas and Stephens, 2007). This conclusion is similar to the finding in this study because the forest types were analogous (Jeffrey pine, Jeffrey pine-mixed conifer, and mixed white fir forests). Covington and Sackett (1992) reported that soil TN increased after burned. Davidson et al. (2002) also found that  $\text{NH}_4^+\text{-N}$  had an initial increase immediately with fire. Soil organic nitrogen increased as fire intensity increased from low to moderate levels (DeBano and Dunn, 1977; Kutiel and Naveh, 1987; Rice, 1993). Zhao et al. (2011) reported that soil TN increased as the fire intensity increased. Soil TN was significantly higher in high intensity fire than in control, low, and moderate intensity fire areas. In fire-prone forests of *P. massoniana*, wildfires had significant influence on TN, and it increased significantly one year after the wildfire, then decreased progressively and became lower than in the unburned soil (Xue et al., 2014). Kutiel and Naveh (1987) found that in the burned pine forest, TN decreased by 25% compared with the adjacent unburned forest in the upper 2 cm of the “ash-soil”. In fire-prone forests of *P. massoniana*, wildfires had significant influence on TN, and it increased significantly one year after the wildfire, then decreased progressively and became lower than in the unburned soil (Xue et al., 2014). In this study, soil TN in *CS* and *Lf* were significantly higher than in *PS* and *SC* within the unburned and burned areas, which indicated that forest types had great influence on soil TN.

Based on the studies of Jiang et al. (2005) and Xu et al. (2003), in unburned areas, TN in native broadleaved forests was significantly higher than in *C. lanceolata* plantations. Generally, in unburned areas, TN had the greatest values in broadleaved forests, then in coniferous forests and brush and grass lands. This may be related to the amount of litter in different forest types. However, Han et al. (2014) showed that there were no significant differences of TN between *Pinus armandii* and *Cupressus funebris* plantations after low intensity fire, and TN of *Pinus armandii* forest was higher than that of *Cupressus funebris* plantations because fire had more influence on TN of *Pinus armandii* forest. Dyrness et al. (1989) pointed out that after heavily burned, TN values in black spruce were slightly higher than in other forests including *white spruce*, *aspen*, and *birch* forests, but there

were no significant differences between the forests. Meanwhile, soil TN in *Pinus sylvestris* forest was the highest compared with that in other forests because of the lowest content of SOM and the weakest decomposition intensity. After severe burning, the lowest values of TN were recorded at farmland where crop residues burned for land preparation (Arunrat et al., 2023). Prolonged cultivation coupled with residue burning practices severely depleted TN of the cultivated field compared with the uncultivated grassland site. Similarly, great declines of soil TN was found in the grass field that had been undergoing annual burning practice compared with the adjacent virgin forest field (Ademe, 2015).

Similar with TN, after the moderate and high intensity fires, TP slightly decreased compared with the unburned sites but no significant difference was found in all four forests. Given a forest stand, significant difference was found in soil TP among the different fire intensities except SC, indicating that the fires did not have significant influence on TP, but different fire intensities led to different effects on TP relative to control. This is in agreement with the finding of Kutiel and Naveh (1987), who showed that wildfire led to the decrease of TP because the fire released TP from the plant body and litter. Similar conclusion was from the study of Qin et al. (2012), who reported that there were significant differences of TP among different fire intensities.

Most studies found that soil TP increased after burned. Zavala et al. (2014) showed that the extractable TK and TP increased due to the soil heat and ash. Xue et al. (2014) implied that the concentration of TP became significantly high in the burned soils and after one year, there was no significant difference between the burned and unburned soil. However, TP significantly decreased immediately four years after the wildfire and then remained at this level, which is in disagreement with this study due to the difference in tree species (*P. massoniana* forest) and time node (1, 4, and 7 years after the wildfire). Moreover, Rice (1993) found that soil  $\text{PO}_4^{3-}\text{-P}$  in Californian chaparral following fire was correlated with ash depth rather than fire intensity. On each of the four burns, available phosphorus was more abundant than in the adjacent unburned forests (Scotter, 1963). Available phosphorous significantly increased by biomass burning. In Alaska, available phosphorus in upper mineral layers increased after fire (Paudel et al., 2014). Zhao et al. (2011) indicated that after burning, both TP and available phosphorus increased compared with unburned areas.

In this study, it was found that similar to TN, soil TP of CS and Lf was higher than that of PS and SC with the same fire disturbance. In the unburned stands, there was no significant difference of soil TP only between Lf and PS forest. While significant differences were found among the four forests after the fire disturbances. This indicated that soil TP could be affected by forest types. Similar results were obtained in the study of Han et al. (2014), in which soil TP in *Pinus armandii* Franch forest was significantly higher than in *Cupressus funebris* forest. However, Baer et al. (2004) showed that there was no significant difference in soil TP between the grass and forested lands at steep rockyslopes. This may be related to changes in soil substrate, which led to the selective use of nutrients by plants. Xu et al. (2016) suggested that in unburned areas, soil TP at plantation (*Cunninghamia Lanceolata*) was lower than in other three secondary forests (*Pinus massoniana*-*Lithocarpus* mixed forest, *Choerospondias axillaris* deciduous broadleaved forest and *Lithocarpus-Cyclobalanopsis glauca* evergreen broadleaved forest). After high intensity fire, soil TP at larch forest and poplar forest was higher than *Betula platyphylla* forest and *Pinus sylvestris* forest, but no significant difference was found (Pellegrini et al., 2022). Soil TP at *Pinus sylvestris* forest had the lowest value because there was less vegetation under the forest, so TP lose more easily. However, soil

TP in coniferous forests was higher than in broad leaved forest in Greater Khingan Mountains (Qin et al., 2012).

In this study, we found that soil TK slightly increased with the fire intensity, and there was no significant difference in TK among different intensity fires in all four forests. This indicated that soil TK could not be affected by the prescribed fires. However, a certain degree of fire disturbance could effectively promote the development of soil nutrients. This finding is inconsistent with the conclusion of previous studies in which most scholars reported that soil TK increased after forest fire. Granged et al. (2011) showed that the extractable K increased due to the soil heat and ash. Xue et al. (2014) pointed out that TK slightly increased in the soils after post-fire, then decreased progressively in the soils one, four, and seven years post-fire, which is in agreement with the result of this study. Certini (2005) suggested that in a *Quercus rubra*-*Populus grandidentata* forest, available K was significantly higher than unburned a month after wildfire, but increased after three months. Relative to the unburned sites, there was a decrease in soil TK after the moderate and heavy intensity fire. Qin et al. (2012) implied that soil TK decreased as the fire intensity increased, whereas no significant difference was found. Burning stubble also caused a slight reduction in the amount of phosphorus and potassium (Thomas et al., 2000). Kutiel and Naveh (1987) also found that TK decreased with the fire intensity increased, which is not in agreement with the results of this study due to the difference in tree species and fire intensity. In this study, soil TK in the natural broadleaved forest (*Lf*) was higher than in broadleaved mixed plantations (*SC*, *PS*, and *CS*) under the same fire severity. In the control stands, there were no significant differences in soil TK among different forests. After burned (low, moderate, and high intensity fire), soil TK at *Lf* and *SC* was significantly higher than in *PS* and *CS*. Similar result was found in the study of Xue et al. (2014), who reported that TK was generally lower in plantation than in secondary forests (*Pinus massoniana*-*Lithocarpus* mixed forest, *Choerospondias axillaris* deciduous broadleaved forest, and *Lithocarpus-Cyclobalanopsis glauca* evergreen broadleaved forest). Han et al. (2014) found that soil TK in *Pinus armandii* Franch forest was significantly higher than in *Cypress* forest after low intensity fire because the fluidity of potassium was very strong. However, Qin et al. (2012) reported that in coniferous forests and broadleaved forests, soil TK was consistent with each other after high intensity fire, which was in disagreement with the finding of this study.

## Conclusions

This study aimed to characterize the dynamic changes and differences of soil physico-chemical attributes within four stands *Lf*, *PS*, *CS* and *SC* following different strengths of fire disturbances. It was found that with the increase of the fire intensity, the soil properties BD, SWR, pH, and TK all showed an increasing trend, while SOM and TP decreased, and TN also decreased but with a slight fluctuation. No significant changes were observed in chemical properties (TN, TP and TK) before and after the prescribed fires. Moreover, the negligible changes were also observed for the other soil properties under the low intensity fire when compared to the control. However, the moderate intensity fire elicited discernible effects, and the high intensity fire exerted a profound and noteworthy influence. After the fire disturbances, TN and TP showed significant differences among the different forest types under the same fire intensity. BD, TP and pH showed significant differences among the different fire intensities within the same forest types. SWR had smallest values in *Lf*, while the soil properties including BD, pH, SOM

and TK generally had significantly greater values in *Lf* than in other forests. The results showed that both the fire intensity and stand type had certain effects on all the soil properties, the effects of the high intensity fire disturbance on BD, SWR, pH and SOM were significant, and TN, TP and SOM had significantly different values among the stands. The values of the soil properties in the pure forest were significantly different from those in the mixed forests.

**Funding.** This study was financially supported by Hunan Provincial Forestry Science and Technology Innovation Program (XLK202435, XLK202501).

## REFERENCES

- [1] Abatzoglou, J. T., Battisti, D. S., Park, W. A., Hansen, W. D., Harvey, B. J., Kolden, C. A. (2021): Projected increases in western US forest fire despite growing fuel constraints. – *Communications Earth & Environment* 2(1). <https://doi.org/10.1038/s43247-021-00299-0>.
- [2] Ademe, Y. A. (2015): Long-term impacts of cultivation and residue burning practices on soil carbon and nitrogen contents in Cambisols of southwestern Ethiopia. – *American Journal of Agriculture and Forestry* 3(3): 65-72. <https://doi.org/10.11648/j.ajaf.20150303.11>.
- [3] Adeyemo, A. J., Ayorinde, A. S., Awodun, M. A., Oyun, M. B. (2023): Nutrients status and soil microbial biomass C and N in charcoal production sites of derived savannah forest of southwestern Nigeria. – *Scientific African* 20: e01684. <https://doi.org/10.1016/j.sciaf.2023.e01684>.
- [4] Al-Khayri, J. M., Khan, T., Ahmad, M., Shehata, W. F. (2025): Ecological impact of forest fires on soil microbial communities and nutrient cycling in temperate and boreal forests. – *Sylwan* 168(12): 916-926. <https://doi.org/10.26202/sylwan.2024058>.
- [5] Alvarez, R. (2024): A quantitative review of the effects of residue removing on soil organic carbon in croplands. – *Soil and Tillage Research* 240: 106098. <https://doi.org/10.1016/j.still.2024.106098>.
- [6] Arunrat, N., Sreenonchai, S., Kongsurakan, P., Iwai, C. B., Yuttitham, M., Hatano, R. (2023): Post-fire recovery of soil organic carbon, soil total nitrogen, soil nutrients, and soil erodibility in rotational shifting cultivation in Northern Thailand. – *Frontiers in Environmental Science* 11. <https://doi.org/10.3389/fenvs.2023.1117427>.
- [7] Arzubov, P. A., Osipov, A. F., Dymov, A. A. (2025): Impact of Fires in Boreal Forests on Carbon Dioxide Emissions from Soil Surfaces (Review). – *Eurasian Soil Science* 58(11). <https://doi.org/10.1134/s1064229325601842>.
- [8] Baer, S. G., Blair, J. M., Collins, S. L., et al. (2004): Plant community responses to resource availability and heterogeneity during restoration. – *Oecologia* 139(2): 617-629. <https://doi.org/10.1007/s00442-004-1541-3>.
- [9] Ballard, T. M. (2000): Impacts of forest management on northern forest soils. – *Forest Ecology and Management* 133(1-2): 37-42. [https://doi.org/10.1016/S0378-1127\(99\)00296-0](https://doi.org/10.1016/S0378-1127(99)00296-0).
- [10] Brantley, S. T., Stuber, O. S., Holder, D. L., Taylor, R. S. (2024): Fire exclusion alters forest evapotranspiration: a comprehensive water budget analysis in longleaf pine woodlands. – *Ecological Monographs* 94(4). <https://doi.org/10.1002/ecm.1623>.
- [11] Buczko, U., Bens, O., Fischer, H., et al. (2002): Water repellency in sandy luvisols under different forest transformation stages in northeast Germany. – *Geoderma* 109(1-2): 1-18. [https://doi.org/10.1016/S0016-7061\(02\)00137-4](https://doi.org/10.1016/S0016-7061(02)00137-4).
- [12] Caldararo, N. (2002): Human ecological intervention and the role of forest fires in human ecology. – *Science of the Total Environment* 292(3): 141-165. [https://doi.org/10.1016/S0048-9697\(01\)01067-1](https://doi.org/10.1016/S0048-9697(01)01067-1).

- [13] Campbell, J. B. (1977): Variation of selected properties across a soil boundary. – *Soil Science Society of America Journal* 41(3): 578-582.  
<https://doi.org/10.2136/sssaj1977.03615995004100030031x>.
- [14] Certini, G. (2005): Effects of fire on properties of forest soils: a review. – *Oecologia* 142(1): 1-10. <https://doi.org/10.1007/s00442-004-1788-8>.
- [15] Cheng, G. C., Lou, J., Zhu, M. N., Zhang, X., Wang, H. M., Tang, Z. H., Wang, W. J. (2025): Fire differentially affects soil properties of forests and grasslands: a global meta-analysis – *Catena* 255. <https://doi.org/10.1016/j.catena.2025.109031>.
- [16] Covington, W. W., Sackett, S. S. (1992): Soil mineral nitrogen changes following prescribed burning in ponderosa pine. – *Forest Ecology and Management* 54(1-4): 175-191. [https://doi.org/10.1016/0378-1127\(92\)90011-W](https://doi.org/10.1016/0378-1127(92)90011-W).
- [17] Davidson, E. A., Savage, K., Verchot, L. V., et al. (2002): Minimizing artifacts and biases in chamber-based measurements of soil respiration. – *Agricultural and Forest Meteorology* 113(1-4): 21-37. [https://doi.org/10.1016/S0168-1923\(02\)00100-4](https://doi.org/10.1016/S0168-1923(02)00100-4).
- [18] DeBano, L. F. (2000): The role of fire and soil heating on water repellency in wildland environments: a review. – *Journal of Hydrology* 231: 195-206.  
[https://doi.org/10.1016/s0022-1694\(00\)00194-3](https://doi.org/10.1016/s0022-1694(00)00194-3).
- [19] DeBano, L. F., Dunn, P. H. (1977): Fire's effect on physical and chemical properties of chaparral soils. – USDA Forest Service General Technical Report Wo-1, Washington, D. C.
- [20] Doerr, S. H., Shakesby, R. A., Walsh, R. P. D. (1998): Spatial variability of soil hydrophobicity in fire-prone eucalyptus and pine forests, Portugal. – *Soil Science* 163(4): 313-324. <https://doi.org/10.1097/00010694-199804000-00006>.
- [21] Dyrness, C. T., Cleve, K. V., Levison, J. D. (1989): The effect of wildfire on soil chemistry in four forest types in interior Alaska. – *Canadian Journal of Forest Research* 19(11): 1389-1396. <https://doi.org/10.1139/x89-213>.
- [22] Fisher, R. F., Binkley, D. (2000): *Ecology and Management of Forest Soils*. – John Wiley, New York.
- [23] Francos, M., Colino-Prieto, F., Sánchez-García, C. (2024): How Mediterranean ecosystem deals with wildfire impact on soil ecosystem services and functions: a review. – *Land* 13(4). <https://doi.org/10.3390/land13040407>.
- [24] Glenn, N. F., Finley, C. D. (2010): Fire and vegetation type effects on soil hydrophobicity and infiltration in the sagebrush-steppe: I. Field analysis. – *Journal of Arid Environments* 74(6): 653-659. <https://doi.org/10.1016/j.jaridenv.2009.11.009>.
- [25] Gordillo-Rivero, Á. J., García-Moreno, J., Jordán, A., et al. (2014): Fire severity and surface rock fragments cause patchy distribution of soil water repellency and infiltration rates after burning. – *Hydrological Processes* 28(24): 5832-5843.  
<https://doi.org/10.1002/hyp.10072>.
- [26] Granged, A. J. P., Zavala, L. M., Jordán, A., et al. (2011): Post-fire evolution of soil properties and vegetation cover in a Mediterranean heathland after experimental burning: a 3-year study. – *Geoderma* 164(1-2): 85-94.  
<https://doi.org/10.1016/j.geoderma.2011.05.017>.
- [27] Han, X., Franssen, H. J. H., Montzka, C., et al. (2014): Soil moisture and soil properties estimation in the Community Land Model with synthetic brightness temperature observations. – *Water Resources Research* 50(7): 6081-6105.  
<https://doi.org/10.1002/2013wr014586>.
- [28] Hewitt, R. E., Day, N. J., DeVan, M. R., Taylor, D. L. (2023): Wildfire impacts on root-associated fungi and predicted plant-soil feedbacks in the boreal forest: research progress and recommendations. – *Functional Ecology* 37(8): 2110-2125.  
<https://doi.org/10.1111/1365-2435.14205>.
- [29] Jiang, W., Zhang, S., Shan, X., et al. (2005): Adsorption of arsenate on soils. Part 2: Modeling the relationship between adsorption capacity and soil physiochemical properties using 16 Chinese soils. – *Environmental Pollution* 138(2): 285-289.

- <https://doi.org/10.1016/j.envpol.2005.03.008>.
- [30] Johnson, D. W. (1992): Nitrogen retention in forest soils. – *Journal of Environmental Quality* 21(1): 1-12. <https://doi.org/10.2134/jeq1992.00472425002100010001x>.
- [31] Kennard, D. K., Gholz, H. L. (2001): Effects of high-and low-intensity fires on soil properties and plant growth in a Bolivian dry forest. – *Plant and Soil* 234(2): 119-129. <https://doi.org/10.1023/A:1010507414994>.
- [32] Knicker, H. (2007): How does fire affect the nature and stability of soil organic nitrogen and carbon? A review. – *Biogeochemistry* 85(1): 91-118. <https://doi.org/10.1007/s10533-007-9104-4>.
- [33] Kominoski, J. S., Fernandez, M., Breault, P. (2022): Fire severity and post-fire hydrology drive nutrient cycling and plant community recovery in intermittent wetlands. – *Ecosystems* 25(2): 265-278. <https://doi.org/10.1007/s10021-021-00653-5>.
- [34] Kumar, V., Dev, M., Janaagal, M. et al. (2025): Effect of rice crop residue burning on soil physico-chemical attributes: a study on Indian soil. – *Egyptian Journal of Soil Science* 65(1): 33-44. <https://doi.org/10.21608/ejss.2024.311497.1841>.
- [35] Kutiel, P., Naveh, Z. (1987): The effect of fire on nutrients in a pine forest soil. – *Plant and Soil* 104(2): 269-274. <https://doi.org/10.1007/BF02372539>.
- [36] Letey, J. (2001): Causes and consequences of fire-induced soil water repellency. – *Hydrological Processes* 15(15): 2867-2875. <https://doi.org/10.1002/hyp.378>.
- [37] Lutz, H. J. (1956): *Ecological Effects of Forest Fires in the Interior of Alaska*. – US Government Printing Office, Washington, DC. <https://doi.org/10.3354/ame018001>.
- [38] MacDonald, L. H., Huffman, E. L. (2004): Post-fire soil water repellency: persistence and soil moisture thresholds. – *Soil Science Society of America Journal* 68(5): 1729-1734. <https://doi.org/10.2136/sssaj2004.1729>.
- [39] Matthews, W. (2016): Humans and fire: changing relations in early agricultural and built environments in the Zagros, Iran, Iraq. – *Anthropocene Review* 3(2): 107-139. <https://doi.org/10.1177/2053019616636134>.
- [40] Moghaddas, E. E. Y., Stephens, S. L. (2007): Thinning, burning, and thin-burn fuel treatment effects on soil properties in a Sierra Nevada mixed-conifer forest. – *Forest Ecology and Management* 250(3): 156-166. <https://doi.org/10.1016/j.foreco.2007.05.011>.
- [41] Onda, Y., Dietrich, W. E., Booker, F. (2008): Evolution of overland flow after a severe forest fire, Point Reyes, California. – *Catena* 72(1): 13-20. <https://doi.org/10.1016/j.catena.2007.02.003>.
- [42] Paudel, S., Baer, S. G., Battaglia, L. L. (2014): Arbuscular mycorrhizal fungi (AMF) and success of *Triadica sebifera* invasion in coastal transition ecosystems along the northern Gulf of Mexico. – *Plant and Soil* 378(1): 337-349. <https://doi.org/10.1007/s11104-014-2026-8>.
- [43] Pellegrini, A. F. A., Harden, J., Georgiou, K., et al. (2022): Fire effects on the persistence of soil organic matter and long-term carbon storage. – *Nature Geoscience* 15(1): 5-13. <https://doi.org/10.1038/s41561-021-00867-1>.
- [44] Pellegrini, A., Certini, G., García-Carmona, M., Sánchez-García, C. (2025): A bottom-up perspective on how fire changes ecosystem biogeochemistry via plant-soil interactions. – *Plant and Soil*. <https://doi.org/10.1007/s11104-025-08031-z>.
- [45] Qin, H., Yokoyama, Y., Fan, Q., et al. (2012): Investigation of cesium adsorption on soil and sediment samples from Fukushima Prefecture by sequential extraction and EXAFS technique. – *Geochemical Journal* 46(4): 297-302. <https://doi.org/10.2343/geochemj.2.0214>.
- [46] Qin, X. S., Wang, Y., Hou, D. D. et al. (2024): Assessment of high-severity post-fire soil quality and its recovery in dry/warm valley forestlands in Southwest China through selecting the minimum data set and soil quality index. – *Forests* 15(10). <https://doi.org/10.3390/fl15101727>.

- [47] Rice, S. K. (1993): Vegetation establishment in post-fire *Adenostoma* chaparral in relation to fine-scale pattern in fire intensity and soil nutrients. – *Journal of Vegetation Science* 4(1): 115-124. <https://doi.org/10.2307/3235739>.
- [48] Robichaud, P. R., Hungerford, R. D. (2000): Water repellency by laboratory burning of four northern Rocky Mountain forest soils. – *Journal of Hydrology* 231: 207-219. [https://doi.org/10.1016/S0022-1694\(00\)00195-5](https://doi.org/10.1016/S0022-1694(00)00195-5).
- [49] Scotter, G. W. (1963): Effects of forest fires on soil properties in northern Saskatchewan. – *The Forestry Chronicle* 39(4): 412-421. <https://doi.org/10.5558/tfc39412-4>.
- [50] Thomas, A. D., Walsh, R. P. D., Shakesby, R. A. (2000): Solutes in overland flow following fire in eucalyptus and pine forests, northern Portugal. – *Hydrological Processes* 14(5): 971-985. [https://doi.org/10.1002/\(sici\)1099-1085\(20000415\)14:5<971::aid-hyp4>3.0.co;2-j](https://doi.org/10.1002/(sici)1099-1085(20000415)14:5<971::aid-hyp4>3.0.co;2-j).
- [51] Ulery, A. L., Graham, R. C. (1993): Forest fire effects on soil color and texture. – *Soil Science Society of America Journal* 57(1): 135-140. <https://doi.org/10.2136/sssaj1993.03615995005700010026x>.
- [52] Vihnanek, R. E., Ballard, T. M. (1988): Slashburning effects on stocking, growth, and nutrition of young Douglas-fir plantations in salal-dominated ecosystems of eastern Vancouver Island. – *Canadian Journal of Forest Research* 18(6): 718-722. <https://doi.org/10.1139/x88-110>.
- [53] Wang, Y., Tang, X., Chen, Y., et al. (2009): Adsorption behavior and mechanism of Cd (II) on loess soil from China. – *Journal of Hazardous Materials* 172(1): 30-37. <https://doi.org/10.1016/j.jhazmat.2009.06.121>.
- [54] Wright, J., DeLaMater, D., Simha, A., Ury, E., Ficken, C. (2021): Changes in prescribed fire frequency alter ecosystem carbon dynamics. – *Ecosystems* 24(3): 640-651. <https://doi.org/10.1007/s10021-020-00540-5>.
- [55] Xu, X., Shi, Z., Li, D., et al. (2016): Soil properties control decomposition of soil organic carbon: results from data-assimilation analysis. – *Geoderma* 262(1): 235-242. <https://doi.org/10.1016/j.geoderma.2015.08.038>.
- [56] Xue, L., Li, Q., Chen, H. (2014): Effects of a wildfire on selected physical, chemical and biochemical soil properties in a *Pinus massoniana* forest in South China. – *Forests* 5(12): 2947-2966. <https://doi.org/10.3390/f5122947>.
- [57] Zavala, L. M., García-Moreno, J., Gordillo-Rivero, Á. J., Jordán, A., Mataix-Solera, J. (2014): Natural soil water repellency in different types of Mediterranean woodlands. – *Geoderma* 226-227, 170-178. <https://doi.org/10.1016/j.geoderma.2014.02.009>.
- [58] Zhang, L., Liu, L., Pan, K., et al. (2015): Post-wildfire soil and plant foliar nutrient ratios and soil fungi: bacterial ratios in alpine meadows on the southeastern Qinghai-Tibet Plateau. – *International Journal of Wildland Fire* 24(7): 933-939. <https://doi.org/10.1071/wf14147>.
- [59] Zhang, N., Zhang, H. Q., Lin, H., et al. (2013): Visual simulation of growth process in *Cunninghamia lanceolata* based on competition index. – *Forest Research* 26(6): 692-697. <https://doi.org/10.13275/j.cnki.lykxyj.2013.06.004>.
- [60] Zhao, H. L., Guo, Y. R., Zhou, R. L., et al. (2011): The effects of plantation development on biological soil crust and topsoil properties in a desert in northern China. – *Geoderma* 160(3-4): 367-372. <https://doi.org/10.1016/j.geoderma.2010.10.005>.