Medium-Term Effects of Different Wildfire Severities on Soil Properties: a Case Study of Hengduan Mountains, southwestern China

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Abstract. A forest fire can affect most soil properties, lead to severe erosion responses, and sometimes even catastrophic consequence: post-fire debris flows. Five years after a forest fire occurred on June 1st, 2014, in the Ren’eyong basin located in the central part of the Hengduan Mountains, the burned area was still being affected by the post-fire debris flows and flash floods. Therefore, assessing the extent of soil properties recovery is very important for predicting the development impact of wildfire-induced geological hazards. We tested the selected soil properties: soil moisture content (SMC), dry density, total soil porosity, soil organic matter content (SOM), saturated hydraulic conductivity, soil sorptivity (S), and soil water repellency (SWR) by in situ and laboratory experiments at two depths: 0~2 cm and 2~5 cm beneath the soil surface in the low severity (LS) fire, medium severity (MS) fire, high severity (HS) fire areas, and adjacent unburned areas (as a control, C), respectively. The water drop penetration time (WDPT) test results showed that the SWR disappeared. The ANOVA analysis results indicated that, for the topsoil (0~2 cm), most of the selected soil properties had a significant variance except for the S; only SMC and SOM showed a significant change for the deeper soil. The LS fire had negligible effects on these soil parameters at both depths. However, for the topsoil, the MS and HS fire effects were significant for most of these soil properties. The MANOVA analysis and paired t-test results indicated that the fire severity effects on the soil properties were significant, and the variance of fire severity effects was not constant at both depths. The Principal Component Analysis (PCA) further confirmed that the HS and MS fires had significant impacts on the soil properties, and the effects of the LS fire were negligible. These results demonstrated that the medium-term effects of the high and moderate severity wildfires on the selected soil properties of the topsoil were significant. The partially recovered soil properties forebode an intense slope erosion or even a further catastrophic consequence.
1. Introduction

The Hengduan Mountains are considered a high-risk wildfire area due to the seasonal climates, general warming, and drying trends\textsuperscript{[1]}. Wildfires can affect most of the soil properties and lead to a substantial loss of the vegetation and forest floor, resulting in a significant alteration of soil hydrology, severe erosion responses, and sometimes a more catastrophic consequence such as secondary geological hazards: flash floods or post-fire debris\textsuperscript{[2, 3]}. Therefore, assessing the extent to which the soil properties have recovered is very important for predicting the development trend of the secondary geological hazards induced by wildfire. Previous works\textsuperscript{[2, 4]} confirmed that the dynamic change of the wildfire-related soil erosion responses is mainly controlled by the recovery process of the soil properties, which strictly hinges on fire severity and the time series after the fire. The effects of fire on soil properties are generally negligible below 5 cm\textsuperscript{[5]}.

The fire severity is defined as the burning degree of the forest floor and vegetation\textsuperscript{[6]}. A given wildfire often creates many burned patches with a wide range of fire severity\textsuperscript{[7]}, the most critical factor affecting soil properties\textsuperscript{[8]}. In the short term, wildfire often increases soil water repellence and a decrease in saturated hydraulic conductivity\textsuperscript{[9]}. It can also cause the soil bulk density to increase due to the collapse of the soil aggregates and decrease of the soil organic matter (SOM) and soil moisture content (SMC)\textsuperscript{[3, 9]}. However, the medium-term effects of the fire on the soil properties are very complex. The effects of fire are reversible, and these fire-induced changes on soil properties will disappear with time\textsuperscript{[10, 11]}. However, a unified understanding of the precise recovery time of a given soil parameter is still deficient. For example, Pereira et al.\textsuperscript{[12]} reported that the SWR disappeared nine months after a fire, while the fire-induced SWR layer was still observed by Huffman et al.\textsuperscript{[13]} 22 months after a fire.

Numerous documents have examined the medium-term effects of fire on soil properties. However, these studies generally focus on the forest ecosystem of the Mediterranean areas\textsuperscript{[14]}, Australia\textsuperscript{[15]}, the Great Xing’an Mountains located in northeastern China\textsuperscript{[16]}, and so on. Insufficient information is available for the medium-term effects of fire severity on the forest soils of the Hengduan Mountains. To address this gap, taking the Ren’eyong basin of the central part of the Hengduan Mountains as an example, we investigated the medium-term fire effects on the selected soil properties: soil moisture content (SMC), dry density (dD), total soil porosity (n), soil organic matter content (SOM), saturated hydraulic conductivity (K), soil sorptivity (S), and soil water repellency (SWR) at 0–5 cm depth by in situ, laboratory experiments, and statistical analyses.

2. Materials and Methods

2.1 Study area and forest fire

The study area (the Ren’eyong basin) is located at the Xiangcheng county (101°13'56" E, 30°10'6" N), the central part of the Hengduan Mountains in southwestern China (Fig. 1). Elevation of the area ranges from 2850 m to 4250 m, and the topography is characterized by deeply cut channels (the Dingqu River and Ren’eyong gully system) and steep slopes with 20°–45° inclination. Natural soils are classified as loamy sand, derived from sandstone, slate, and phyllite. Seasonal climates also characterize the study site, and the mean total rainfall of the rainy season is 372.32 mm, accounting for more than 80% of the annual precipitation. The mean annual temperature is 10.7 °C\textsuperscript{[17]}. On June 1\textsuperscript{st}, 2014, a devastating wildfire swept the study area and burned approximately 6.9 km\textsuperscript{2}. During each rainy season of the first five years after the wildfire, the burned area was repetitively disturbed by
post-fire debris flows (Fig. 1c) and flash floods. According to the criteria suggested by Parsons et al.\cite{18}, we classified the fire severity into four grades: unburned (as a control, C), low severity (LS), moderate severity (MS), and high severity (HS). In addition, we computed the delta normalized burn ratio (dNBR) by processing the Landsat-OLI satellite images and finally obtained the fire severity map combining the field investigations\cite{19} (Fig. 1c).

\textbf{Fig 1.} Maps of a) the location of the Hengduan Mountains in China; b) the terrain of the Hengduan Mountains and the location of the study site; c) the fire severity of the study site (the Ren’eyong basin).

\subsection{2.2 Soil hydraulic tests and laboratory analysis}
We conducted a field survey in September 2018, the fifth rainy season after the fire. The water drop penetration time (WDPT) test was used to measure the soil water repellency (SWR)\cite{20}. Ten test points were selected randomly at each of the four sample sites with different fire severity, respectively. A terraced 10 cm deep hole was dug at each test point, and then the tests were performed with a depth interval of 1 cm by recording the residence time of water drops deposited on the soil surface. Using the criteria suggested by Robichaud et al.\cite{21}, the intensity of the SWR was classified as wettable (WDPT<5 s), and hydrophobic (WDPT≥5 s). Six test points were randomly selected at each sample site with different fire severity to determine the soil hydraulic properties by the Mini-Disk Infiltrometer (MDI, Decagon Devices, Inc. Pullman, W.A.)\cite{22}. Soil hydraulic parameters were evaluated based on the Philip infiltration formula\cite{9}.

\begin{align*}
I &= C_1 \sqrt{t} + C_2 t \\
S &= C_1 \\
K &= \frac{C_2}{A}
\end{align*}

Where, \(I\) is the cumulative infiltration amount/cm; \(t\) is the infiltration duration/s; \(C_1\) is the soil sorptivity (\(S\)) determined by intercepting the data of the first 300 seconds in water infiltration; \(K\) is
the saturated hydraulic conductivity calculated by \( C_s \) in a steady infiltration; and \( A \) is the parameter of van Genuchten model (3.89 in this research).

2.3 Soil sampling and laboratory analysis

Next to each points where the MDI tests were performed, we collected soil samples at two depth ranges: 0–2 cm and 2–5 cm (two replicates per depth interval) using the cutting-ring method\(^9\). The SMC was measured using the oven method, the dD was evaluated using the SMC and the bulk density, and the n was calculated by the soil particle density and the bulk density\(^9\). The SOM content was measured via the loss on ignition method using a muffle furnace (5 h, 550 °C)\(^23\).

2.4 Statistical analysis

The effects of fire severity on soil properties were evaluated using a one-way analysis of variance (ANOVA) method. If the ANOVA test showed an overall significant impact, a Tukey HSD test was performed. Next, a MANOVA analysis was performed to examine the effects of fire severity, soil depth, and their interactions on the soil properties. To further ascertain the significant variance between the two depths (0–2 cm and 2–5 cm), the paired t-test was carried out synchronously. The Pearson correlation analysis was used to explore the relationship among the soil parameters. The datasets at both depths were analyzed by the Principal Component Analysis (PCA) to visually represent the fire severity effects on soil properties. A significance level of 0.05 was adopted for the statistical tests.

3. Results

3.1 Changes in soil hydrological properties

According to the WDPT tests, almost no hydrophobic soil samples were found in the burned or unburned areas, indicating that the fire-induced soil water repellency (SWR) disappeared five years after the fire. Another possibility is that the fire did not cause any SWR. The MDI test results showed that the burned area's soil sorptivity (Table 1, S) is not significantly different from the unburned area at both depths. In terms of the saturated hydraulic conductivity (Table 1, K), the results showed that only the topsoil (0–2 cm) of the HS area had significant variance in contrast to that of the control area. Based on the above results, we can opine that the hydrological properties of the burned soil had recovered to the pre-fire level after a five-year recovery, excluding the K of the topsoil in the HS area. The Pearson correlation analysis results (Fig. 2) showed that the correlation between the S and K was significant at both depths, respectively.

3.2 Changes in soil physical and chemical properties

For the SMC (Table 1), only the mean values of the HS area were significantly lower than those of the control at both depths. The SMC of the LS and MS areas showed negligible differences compared to those of the control at both depths. For the dry density and the total soil porosity (Table 1, dD, n), the two parameters of the topsoil in the HS and MS areas had significant variance compared to the control. However, they showed insignificant differences from the control area at deeper layers (2–5 cm). The SOM content (Table 1) decreased with increasing fire severity at both depths, and the mean values of the HS and MS areas were significantly lower than that of the control.
Table 1. Mean values and standard error of soil moisture content (SMC), soil dry density (dD), soil total soil porosity (n), soil organic matter content (SOM), soil sorptivity (S), and saturated hydraulic conductivity (K), where, C, unburned (as a control); LS, low severity fire; MS, moderate severity fire; HS, high severity fire. The p values are the results of the ANOVA analyses, and the mean values sharing the same lowercase indicate no significant difference at $p < 0.05$ (Tukey test)

| Soil depth | Fire severity | SMC (%) | dD $(g \text{ cm}^{-3})$ | n (%) | SOM (%) | S $(×10^4 \text{ cm s}^{-1})$ | K $(×10^4 \text{ cm s}^{-1})$ |
|------------|---------------|---------|-----------------|-------|---------|----------------|----------------|
| 0~2 cm     | C             | 42.02±1.49ab | 0.94±0.03c | 62.44±1.31a | 14.99±1.45a | 29.00±5.68a | 10.83±1.84a |
|            | LS            | 44.86±2.12a | 1.05±0.05bc | 57.74±2.11ab | 13.32±0.93ab | 19.92±4.20a | 8.16±1.79ab |
|            | MS            | 35.64±2.02b | 1.16±0.03ab | 55.10±1.23bc | 10.22±0.37b | 28.68±5.84a | 12.32±2.20a |
|            | HS            | 21.37±1.25c | 1.30±0.04a  | 51.21±1.54c | 9.68±0.97b  | 12.85±2.96a | 3.81±0.50b  |
|            | p value       | 0.000    | 0.011         | 0.001 | 0.003   | 0.081         | 0.011         |
| 2~5 cm     | C             | 29.88±1.62ab | 1.24±0.05a  | 50.56±2.00a | 11.54±0.53a | 9.60±2.93a  | 7.51±5.27a  |
|            | LS            | 33.89±1.46a | 1.21±0.06a  | 53.45±2.13a | 10.27±0.90a | 18.54±5.29a | 6.17±1.44a  |
|            | MS            | 24.93±2.16b | 1.36±0.06a  | 46.26±2.28a | 7.36±0.15b  | 17.71±3.02a | 6.68±1.41a  |
|            | HS            | 16.72±1.31c | 1.37±0.02a  | 48.73±0.91a | 7.05±0.08b  | 9.86±3.36a  | 4.11±0.99a  |
|            | p value       | 0.000    | 0.856         | 0.087 | 0.000   | 0.207         | 0.856         |

Fig 2. Heat map of the Pearson correlation analysis. “**” indicates $p < 0.01$, “*” indicates $p < 0.05$.

Table 2. The results of the MANOVA analysis, which was used to examine the effects of fire severity, soil depth, and their interaction on the selected soil properties

| Effects               | Value | F     | Hypothesis df | Error df | Sig. |
|-----------------------|-------|-------|---------------|----------|------|
| Fire severity         |       |       |               |          |      |
| Pillai’s trace        | 1.79  | 9.10  | 18.00         | 111.00   | <0.001|
| Wilks’ lambda         | 0.00  | 34.90 | 18.00         | 99.98    | <0.001|
| Hotelling’s trace     | 100.57| 188.11| 18.00         | 101.00   | <0.001|
| Roy’s largest root    | 99.24 | 611.96| 6.00          | 37.00    | <0.001|
| Soil depth            |       |       |               |          |      |
| Pillai’s trace        | 0.84  | 30.91 | 6.00          | 35.00    | <0.001|
| Wilks’ lambda         | 0.16  | 30.91 | 6.00          | 35.00    | <0.001|
| Hotelling’s trace     | 5.30  | 30.91 | 6.00          | 35.00    | <0.001|
| Roy’s largest root    | 5.30  | 30.91 | 6.00          | 35.00    | <0.001|
| Fire severity & Soil depth |       |       |               |          |      |
| Pillai’s trace        | 1.26  | 4.46  | 18.00         | 111.00   | <0.001|
| Wilks’ lambda         | 0.03  | 14.10 | 18.00         | 99.48    | <0.001|
| Hotelling’s trace     | 25.42 | 47.54 | 18.00         | 101.00   | <0.001|
| Roy’s largest root    | 25.06 | 154.55| 6.00          | 37.00    | <0.001|

According to the above analyses, we can confirm that the medium-term effects of the LS fire on the selected soil properties were minimal, whether for the topsoil or the deeper soil. However, the medium-term effects of the HS and MS fires were conspicuous, especially for the topsoil. The Pearson
correlation analysis results (Fig. 2) indicate that the correlation among the soil physical and chemical properties was significant at the two depths, respectively. Similarly, the correlation between the two soil hydrological parameters was also significant at both depths. However, the correlation between the soil hydrological parameters and the other selected soil parameters was insignificant.

The MANOVA analysis results (Table 2) indicate that the fire severity, soil depth, and their interaction effects on the selected soil properties were significant. The paired t-test results (Table 3) further show that the effects of soil depth on the SMC, dD, and n were significant for the unburned and LS fire areas. The effects of soil depth on all of the studied soil parameters of the MS fire area were significant. For the HS fire area, only the impact on the SOM and SMC were significant. The MANOVA and paired t-test results further indicated that the effects of fire severity on the soil properties were significant. However, the variance of the fire severity effects was not constant at the two depths. Combining the results of the ANOVA analysis (Table 1), we can also find that the effects of fire severity on the topsoil were more significant than those on the deeper soil.

**Table 3.** The results of the paired t-test, which was used to assess the soil parameters difference between the two depths, the bold fonts represent the significant difference (p < 0.05)

| Parameters | Control | Low severity | Moderate severity | High severity |
|------------|---------|--------------|-------------------|--------------|
|            | t value | p value      | t value           | p value      |
| SMC        | 5.05    | **0.0039**   | 5.75              | **0.0022**   |
| dD         | -11.18  | **0.0001**   | -4.84             | **0.0047**   |
| N          | 11.24   | **0.0001**   | 3.21              | **0.0236**   |
| SOM        | 1.83    | 0.1262       | 2.27              | 0.0726       |
| S          | 2.51    | 0.0538       | 0.44              | 0.6772       |
| K          | 0.53    | 0.6212       | 2.57              | 0.0502       |

**Fig 3.** PCA diagram of areas with different fire severities: unburned (as a control, C), low severity (LS); moderate severity (MS); high severity (HS) at (a) 0~2 cm and (b) 2~5 cm.

Figure 3 shows the first two components (Eigenvalues > 1) of the PCA analyses of both depths. Using the correlation matrices of the soil properties, the components of the PCA were extracted. Component 1 showed 59.4% and 50.0% variations in the soil parameters, for the topsoil and deeper soil, respectively. Component 2 yielded 25.9% and 24.9%. As the ellipses in Fig. 3, the PCA results showed two clusters at the two depths, respectively. The points of the LS are close to those of the C, meaning that the LS fire had negligible effects on the soil properties. However, the MS and HS points are neighboring and keep away from the C points, confirming that the MS and HS fires had significant effects on the soil parameters. In addition, the PCA diagrams of both depths also showed that the S and K stay closely, confirming that the S and K were significantly correlative, as the same trend was observed from results of the Pearson correlation analysis. The SOM, SMC, and n formed another cluster. The dD is almost situated on the reverse extension line of the n, meaning that the soils’s
physical and chemical properties were also closely related, similar to the Pearson correlation analysis results.

4. Discussion and Conclusion
The results indicated that the fire affected the soil properties depending on the fire severity. This agrees with the viewpoints summarized by Zavala et al.[2] and Stavi[3]. Based on the above analyses, we conclude that the high and moderate severity fires had significant medium-term effects on the selected soil properties. But the impact of the low severity fire was insignificant. In addition, the variance of fire severity effects was not constant at the two depths, and the impacts on the topsoil were more substantial in contrast to those on the deeper soil. Low severity fire generally means partial combustion of the organic matter, a lower peak temperature, and a shorter duration of the heat gradient[8]. Hence, it has lesser effects on soils and vegetation, meaning that the low severity fire-induced changes in soil properties can often recover to the pre-fire level in the short term. In contrast, the high severity fire can consume all forest floors resulting in a higher temperature peak and a longer duration of the heat gradient[24]. Therefore, the high severity fire often relates to a significant alteration and a slower recovery of the soil properties. On the other hand, the higher the fire severity, the more severe the erosion response caused[25]. In contrast to the area affected by the high severity fire, the post-fire erosion response of the low severity fire area is mild, which is beneficial for the post-fire revegetation and alleviates soil degradation. The results of this study can elucidate the frequent post-fire debris flows and flash floods that occurred in the Ren’eyong basin during the five years after the fire, and these results also forebode an intense slope erosion or even a further catastrophic consequence.

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Reference
[1] China Forestry Administration National forest fire prevention program (2016-2025) 2016-06
[2] Zavala LM, Celis RDE, Jordán A, 2014 How wildfires affect soil properties A brief review Cuadernos De Investigación Geográfica 40 (2) 311-331
[3] Stavi I 2019 Wildfires in Grasslands and Shrublands: A Review of Impacts on Vegetation Soil Hydrology and Geomorphology Water 11 (5) 1042
[4] Lucas-Borja ME, Plaza-Alvarez PA, Gonzalez-Romero J, Sagra J, Alfaro-Sanchez R, Zema DA 2019 Short-term effects of prescribed burning in Mediterranean pine plantations on surface runoff, soil erosion and water quality of runoff Science of the Total Environment 674 615-622
[5] Alcaniz M, Outeiro L, Francos M, Farguell JU, beda X 2016 Long-term dynamics of soil chemical properties after a prescribed fire in a Mediterranean forest (Montgrí Massif Catalonia Spain) Science of the Total Environment 572 (Dec 1) 1329-1335
[6] Boby LA, Schuur EAG, Mack MC, Verbyla D, Johnstone JF 2010 Quantifying fire severity carbon and nitrogen emissions in Alaska’s boreal forest Ecological Applications 20 (6) 1633–1647
[7] Vega JA, Fontúrbel T, Merino A, Fernández C, Ferreiro A, Jiménez E 2013 Testing the ability of visual indicators of soil burn severity to reflect changes in soil chemical and microbial properties in pine forests and shrubland Plant and Soil 369 (1-2) 73–91
[8] Keeley JE 2009 Fire intensity, fire severity and burn severity: a brief review and suggested usage
International Journal of Wildland Fire 18(1) 116-126

[9] Wang Y, Hu XW, Jin T, Yang Y, Cao XC 2019 Research on the Influence Depth of Soil with Different Burn Severity in the Burned Areas of E’gu Village in Yajiang County Earth Sciences 8 (6) 317-322

[10] Doerr SH, Cerdà A 2005 Fire effects on soil system functioning: new insights and future challenges International Journal of Wildland Fire 14 (4) 339-342

[11] Strydom T, Riddell ES, Rowe T, Govender N, Lorentz SA, le Roux PAL, Wigley-Coetsee C 2019 The effect of experimental fires on soil hydrology and nutrients in an African savanna Geoderma 345 114-122

[12] Pereira P, Ubeda X, Mataix-Solera J, Oliva M, Novara A 2014 Short-term changes in soil Munsell colour value, organic matter content and soil water repellency after a spring grassland fire in Lithuania Solid Earth 5 (1) 209-225

[13] Huffman EL, MacDonald LH, Stednick JD 2001 Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine Colorado Front Range Hydrological Processes 15 (15) 2877-2892

[14] Martinez-Garcia E, Lopez-Serrano FR, Dadi LF, Garcia-Morote FA, Andres-Abellan M, Pumpanen J, Rubio E 2017 Medium-term dynamics of soil respiration in a Mediterranean mountain ecosystem: the effects of burn severity, post-fire burnt-wood, management, and slope-aspect Agricultural and Forest Meteorology 233 195-208

[15] Muñoz-Rojas M, Erickson TE, Martini D, Dixon KW, Merritt DJ 2016 Soil physicochemical and microbiological indicators of short medium and long term post-fire recovery in semi-arid ecosystems Ecological Indicators 63 14-22

[16] Ms XZ, Fan XS, Shu CL, Li CS 2016 Effects of Forest Fire Disturbance in Different Time Series on Soil Properties and Greenhouse Gas Flux in Larix gmelinii Forest of Cold-temperate Zone Ecology and Environmental Sciences 25 (6) 939-946

[17] Hou YT 2019 Study on source characteristics and start-up mechanism of shallow landslide in Reneyong post-fire debris flow Southwest Jiaotong University Chengdu China

[18] Parsons A, Robichaud P, Lewis S, Napper C 2010 Field Guide for Mapping Post-fire Soil Burn Severity USDA Forest Service-General Technical Report RMRS-GTR p 243

[19] Key CH, Benson NC 2005 Landscape Assessment (LA) Sampling and Analysis Methods Firemon: Fire Effects Monitoring and Inventory System Lutes D.C. United States Department of Agriculture.

[20] DeBano LF 1981 Water repellent soils: a state-of-the-art General Technical Report PSW-46 US Department of Agriculture Forest Service Pacific Southwest Forest and Range Experiment Station Berkeley California, U.S.A. p 17

[21] Robichaud PR, Wagenbrenner JW, Pierson FB, Spaeth KE, Ashmun LE, Moffet CA 2016 Infiltration and interrill erosion rates after a wildfire in western Montana USA Catena 142 77-88

[22] Glenn NF, Finley CD 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

[23] Zhu GW, Qin BQ, Gao G, Zhang L 2004 Effects of ignition on the determination of loss on ignition iron and phosphorus in sediments Chinese Journal of Analysis Laboratory 23 (9) 72-76

[24] Francos M, Pereira P, Mataix-Solera J, Arcenegui V, Alcaniz M, Ubeda X 2018 How clear-cutting
affects fire severity and soil properties in a mediterranean ecosystem *Journal of Environmental Management* **206** (JAN15) 625-632

[25] Vega JA, Fernández C, Fonturbel T 2005 Throughfall runoff and soil erosion after prescribed burning in gorse shrubland in Galicia (NW Spain) *Land Degradation & Development* **16** (1) 37-51