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# Post-Fire Changes in Canopy Solute Leaching in *Pinus densiflora* Forests

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**Abstract:** Fires can burn canopy fuel and replace leafy crowns with charred branches and trunks, thereby affecting hydrological flow and water chemistry. However, little is known about the effects of fire on throughfall volumes and chemical fluxes in temperate forests. Therefore, we aimed to monitor the volume and chemistry of throughfall in pine trees (*Pinus densiflora*) damaged by the 2022 Gangneung-Donghae Forest fire in the Republic of Korea. Immediately after the forest fire, funnel-type measurements were performed to collect the throughfall beneath five trees at foliage necrosis and crown consumption sites. The amount of water that penetrated in a specified period was continually measured and analyzed in terms of the water quality components. Crown consumption resulted in the passage of more water due to the removal of the tree canopy; however, the ratio of throughfall to total rainfall remained constant as the rainfall amount increased. The throughfall volume was not significantly different owing to the fire damage. The solute concentrations of Ca and TOC at the crown consumption site were higher than those at the foliage necrosis site after the fire; however, no significant difference was observed three months after the fire. In this study, the changes in the amount and water quality of throughfall due to fire were examined over a relatively short period, providing fundamental data for nutrient cycling management of wildfire-damaged soil.

**Keywords:** *Pinus densiflora* forests; throughfall; total organic carbon; calcium; foliage necrosis; crown consumption

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## 1. Introduction

In forests, part of the incident rainfall is intercepted by foliage and branches, whereas the rest is routed to the forest floor via throughfall and stemflow pathways. Rainfall partitioning can influence water balance and biogeochemical cycles in forest watersheds [1]. Distinguished from stemflow, throughfall refers to raindrops that pass through the canopy to reach the ground or are temporarily retained by the aboveground vegetative surface and subsequently drip from the canopy [1]. Throughfall may vary in quantity and chemical composition as a function of tree species, seasonality, meteorological conditions, and canopy structure [2,3].

Raindrops can contact the tree canopy before falling to the forest floor, resulting in the release of exogenous and endogenous soluble elements onto tree branches and leaves. Canopy leaching of nutrients and metals has a substantial impact on soil and water [2]. They can enrich dissolved organic carbon, potassium, calcium, magnesium, sodium, and chlorine [3–5], but may be depleted in ammonium and nitrate [5]. The extent to which the canopy affects the composition of throughfall chemistry depends on the wash-off of dry deposition and canopy exchange processes [6].

The throughfall process is linked to the structure of the forest canopy and varies ecologically across species and genotypes. Leaf shape and configuration affect leaf storage ability. Deciduous trees with flat leaves produce much larger throughfall volumes than coniferous trees with clumped needles. In addition to canopy traits, the vertical distribution of leaves is an important factor that controls rainfall partitioning. The reduction in canopy density due to disturbance or harvesting will likely decrease canopy retention storage but increase the net precipitation that reaches the forest floor. The solute concentration in throughfall is related to the amount of foliage, branches, and epiphytes [7].

Fire-induced injuries to tree crowns and forest canopies affect the rainfall partitioning and hydrological cycles [8]. Low-to-medium heat can damage the tree crowns. After a fire, scorched leaves turn red and eventually fall to the ground. Some species senesce within weeks, while others last months or longer [9]. When exposed to high-to-extreme thermal environments, fire flames directly consume live foliage and buds, small live branches, and small trees, causing tissue death. Crown consumption is the most immediately apparent condition with branches and leaves being either completely consumed or visibly charred.

Fire causes spatial and temporal changes in throughfall amounts and dissolved solutes. In areas affected by fires, the amount of rainfall intercepted by vegetation decreased because of the canopy loss, while rain reaching the ground surface increased [10–12]. When fires occur, macronutrients such as calcium, phosphorus, potassium, and magnesium are leached from leaves and stems and released into the soil [13–15]. The redistribution of nutrient compounds is determined by carbon and nitrogen structures and quantities, fire intensity, topography, meteorology, and other factors [16,17].

Throughfall volume and leachates are highly variable and may change as a function of plant species, fire intensity, canopy structure, and interception storage [13,18]. Many studies have analyzed the impact of fires on throughfall pathways and chemical fluxes [15,19]. Chorover et al. [20] found that the concentrations of bivalent cations, such as $Ca^{2+}$ and $Mg^{2+}$ in soil solutions, remained elevated over longer periods of time after a fire compared to those of highly mobile monovalent cations, such as $K^+$, $NH_4{}^+$, and $Na^+$ because of their higher affinity for adsorptive retention on ion exchange sites. Moreover, because organic carbon is also included in ash and charred remains, many studies have indirectly analyzed the impact of wildfires on nutrient cycling by examining changes in calcium and organic carbon concentrations [21–24].

Rainfall partitioning in forests is a function of rainfall amount and intensity, burn severity, and canopy cover and is the most difficult, time-consuming, and expensive quantification in the field [25]. Therefore, the quantification has been principally derived from meteorological and other data used in water balance analysis; however, a small uncertainty in the measurements may produce relatively large errors in a straightforward estimation [26]. Various rainfall interception models have been developed to predict throughfall by empirically or physically addressing the interception process. These models provide insights into the interception processes; however, parameter variability and simplification of natural phenomena are still drawbacks to their use [27]. Alternatively, throughfall can be directly measured by placing collecting containers or trays beneath the target canopy [28]. This measures throughfall more thoroughly than the models, assuming that all rainfall occurs both vertically and uniformly.

Rainfall partitioning has gained increasing attention worldwide in recent years, with special emphasis on canopy traits. However, little is known about the effects of fire on throughfall volumes and chemical fluxes in temperate forests. Therefore, the objectives of this study were to demonstrate the effects of fire on the volumetric partitioning of rainfall and examine the differences in solute concentrations leached according to crown damage. We conducted a field experiment in fire-affected forests to examine the responses of hydrological and geochemical processes to fire disturbance.

## 2. Materials and Methods

### 2.1. Study Site

This study was conducted in a pine forest in Donghae, situated in the eastern coastal region of the Republic of Korea (south Korea). The forest was severely damaged by the

2022 Gangneung-Donghae Forest fire (Figure 1), which burned 4190 ha of forest in Donghae and neighboring Gangneung areas from 3 to 8 March 2022. The forest climate is characterized by the Asian monsoon, with hot, wet summers and cold, dry winters. According to the meteorological data obtained from the nearest Donghae meteorological station of the Korea Meteorological Administration, annual average values for air temperature and precipitation are 12.8 °C and 1266.3 mm, respectively [29]. The area is mostly covered by mature (30–40-year-old) red pine (*Pinus densiflora*) trees, with elevation ranging between 185.8 and 1262.0 m above sea level.

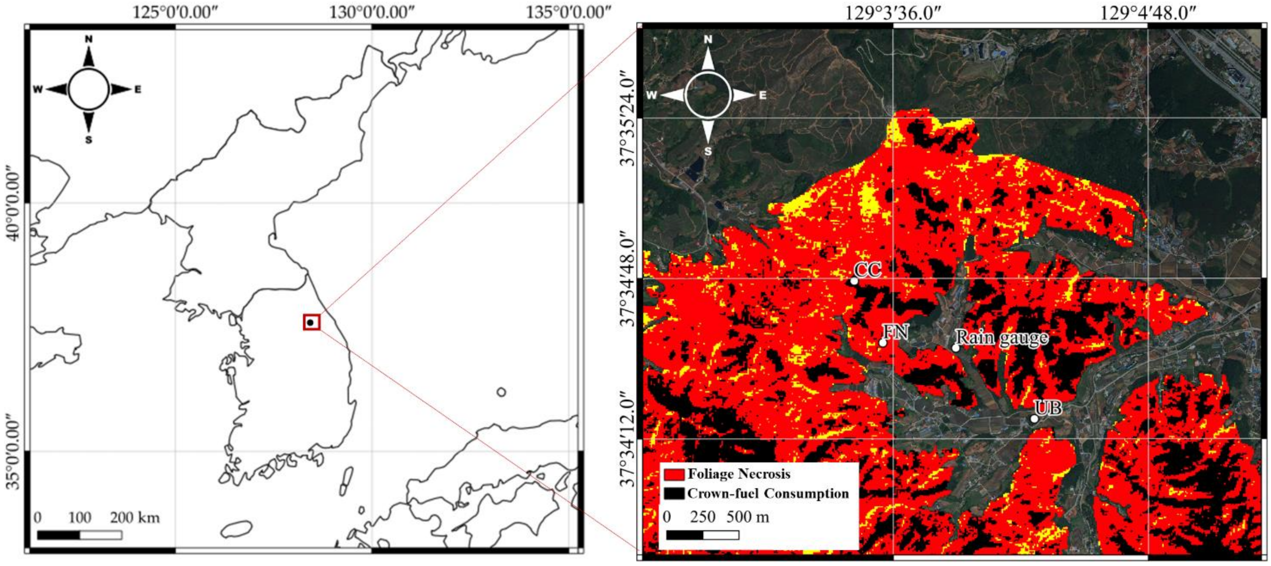


**Figure 1.** Locations of study site, the Republic of Korea.

Heat during fire can affect the physiology of trees. The degree to which a tree is damaged by fire depends on the heat flux incident on various parts of the tree. Based on the degree of physiological mortality and crown injury, the National Institute of Forest Science (NiFOS) classifies vegetation burn severity into three categories: surface fuel consumption, foliage necrosis, and crown fuel consumption [30]. Surface fires consume litter, living shrubs, and herbaceous vegetation covering the soil surface, resulting in surface fuel consumption. Low-to-moderate intensity fires often do not directly damage mature trees but may cause fire-induced foliage loss. In this study, foliage necrosis was defined as the killing or injuring of less than 60% of the trees' foliage by fire. High-intensity crown fires completely burn the foliage and branches of trees, and crown fuel consumption can lead to tree mortality. The NiFOS survey showed that in the total burned area, approximately 23.8, 68.8, and 7.4% were crown fuel consumption, foliage necrosis, and surface fuel consumption, respectively.

As shown in Figure 1, two fire-damaged sites within the burn perimeter of the Gangneung–Donghae fire were chosen based on the degree of vegetation damage; crown-fuel consumption (CC; 37°34′47.5″ N, 129°4′28.9″ E); and foliage necrosis (FN; 37°34′33.6″ N, 129°3′33.0″ E). The two sites were situated approximately 0.5 km apart, avoiding variations in micrometeorology and atmospheric deposition. The experiment was also conducted in an unburned area (UB; 37° 34′16.5″ N, 129° 4′15.8″ E) for cross comparison. As the experiments were conducted in two areas affected by the large fire, the unburned control site was 1.5 km away from the burned sites.

## 2.2. Field Measurement Setup

Field measurements were conducted from May to November 2022 on five red pine trees (replicates) at two burned sites and the control site (Figure 2). Throughfall was defined as the average volume of rainfall that reached the ground below the forest canopy.

The throughfall was measured using a conical collector (200 mm in diameter) installed 1 m above the ground immediately after the fire. Six collectors were randomly placed at 120-degree intervals in 1 m and 2 m radii around the target trees (Figure 3). The throughfall collected from the conical collectors was drained into a sealed 2.0 L polyethylene bucket and bottle via 10 mm diameter pure silicone hoses. The crown tops of the collectors were wrapped with glass wool to exclude insects, leaves, and other debris. After each rainfall event, the collected samples were transported to the laboratory in a refrigerated icebox, and both the quantity and quality of the samples were analyzed. The water stored in the six collectors was arithmetically averaged to estimate the throughfall volume of the target trees during discrete rainfall events. Gross rainfall was continuously measured in an open area adjacent to the throughfall monitoring sites. A tipping bucket rain gauge (RG3-M, Onset®, Onset Computer Corporation, Bourne, MA, USA) was used to measure gross rainfall data. A manual rain gauge (Korea Scientific Corporation, Siheung, Republic of Korea) was installed at each study site to estimate the total rainfall volume. The spatial distribution of the gross rainfall was assumed to be homogeneous over the study site.


**Figure 2.** (**a**) Throughfall collectors in unburned (left), foliage necrosis (middle), and crown fuel consumption sites (right), and (**b**) schematic layout of collectors.

Dissolved chemicals in the throughfall and rainfall samples were analyzed at the National Instrumentation Center for Environmental Management (NICEM) at Seoul National University, South Korea. Prior to chemical analysis, the water samples stored in the six collectors for each tree were combined to form one composite sample. To avoid sample contamination, all collectors, hoses, and throughfall containers were washed and rinsed with deionized water after composite sampling. Throughfall samples were immediately stored at 4 °C and subsequently transported to the NICEM for further analysis. Due to the volume constraints of the chemical analysis, water samples that were insufficient or contaminated were excluded from the analysis.

The total organic carbon (TOC) in the throughfall samples was quantified using the high-temperature combustion oxidation method, and the concentration of calcium (Ca) was quantified using inductively coupled plasma-atomic emission spectrometry [31,32].

Canopy traits are the major features that affect rainfall partitioning in forests. Tree attributes, such as crown width, tree height, canopy base height, and diameter at breast height (DBH) were measured for all target trees at the two sites. Crown width was measured using a ruler, and tree height and canopy base height were measured using a HAGA altimeter (Haga Metallwarenfabrik, Nürnberg, Germany). Throughfall has been linked to canopy characteristics, such as basal area and cover [33]. The canopy characteristics of the target trees were derived from fisheye images using a Gap Light Analyzer program [34].

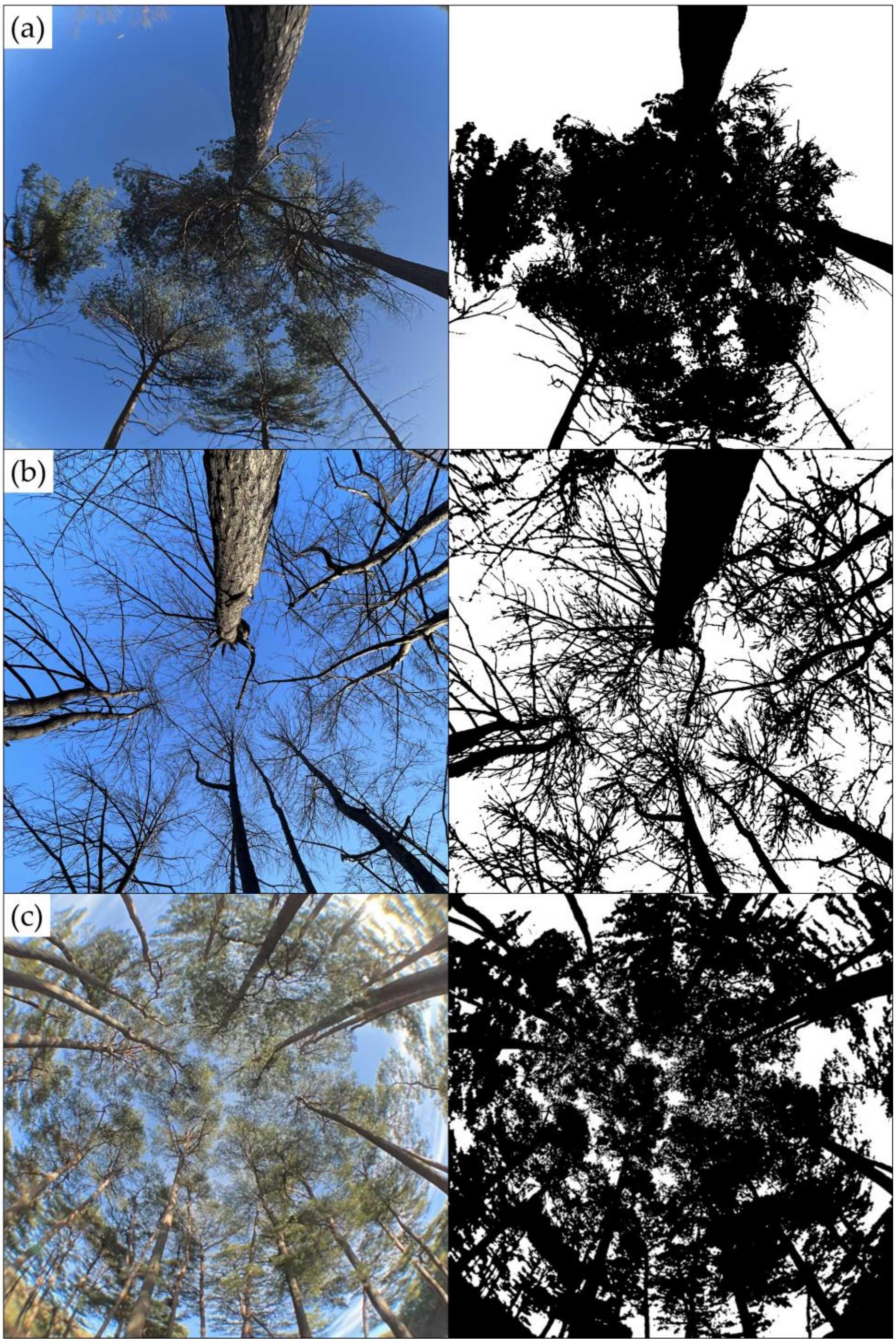


**Figure 3.** The fisheye images for canopy characteristic analysis in (**a**) foliage necrosis, (**b**) crown fuel consumption, and (**c**) unburned sites.

### *2.3. Statistical Analysis*

We checked the homogeneity of variance and normality among the groups for water quantity and quality data for each treatment (two treatments × five replicates). If the data satisfied both conditions, we performed a one-way ANOVA and Tukey's post-hoc test to analyze the effect of each treatment. If the data did not meet one of the conditions of homogeneity of variance or normality, we performed a non-parametric variance analysis (Kruskal–Wallis test) followed by the Bonferroni test to analyze the differences between the groups. The statistical significance level was set at 0.05, and analysis was performed using the R statistical package [35].

# 3. Results

## 3.1. Stand Structure

The morphological traits of the pine trees (n = 5) at the three sites are summarized in Table 1. The average tree height and DBH at the FN site were higher than those at the CC site. This was mainly explained by the difference in stand density: 875 trees and 1275 trees per ha in the FN and CC sites, respectively. Trees at low-density sites generally grow faster than those at high-density sites because of the absence of competition for light and other resources.

**Table 1.** Tree characteristics in the study sites.

| Site | FN | CC | UB |
|---|---|---|---|
| Age class | VI | VI | VI |
| Stand density * (tree/ha) | 875 | 1275 | 425 |
| DBH (cm) | 37.2 ± 1.3 | 27.6 ± 2.6 | 50.8 ± 1.6 |
| Basal * area ($m^2$/ha) | 63.9 ± 14.6 | 40.3 ± 6.7 | 86.3 ± 5.4 |
| Tree height (m) | 17.3 ± 2.2 | 11.7 ± 1.6 | 23.7 ± 3.6 |
| Canopy base height (m) | 9.5 ± 0.9 | 5.2 ± 1.5 | 11.7 ± 3.5 |
| Canopy cover (%) | 65.5 ± 5.8 | 43.0 ± 4.1 | 79.8 ± 4.4 |
| Major axis of the crown (m) | 9.7 ± 1.4 | 6.9 ± 2.3 | 7.3 ± 1.6 |
| Minor axis of the crown (m) | 8.4 ± 1.8 | 6.3 ± 2.0 | 6.5 ± 0.5 |

* Only for *Pinus densiflora*.

The canopy cover for the projected crown area at the CC site was 22.5% lower than that of the FN site (Figure 3). Regardless of tree development, this difference was likely the result of canopy consumption during a fire. According to the heat flux incident on the tree foliage and branches, the canopy was partially or completely consumed. Most of the foliage and small branches were directly scorched by fire flames and consequently consumed at the CC site, whereas the foliage and buds were damaged by heat fluxes at the FN site. The injured foliage did not result in immediate mortality; rather, the trees were able to re-sprout from heat-resistant organs [36]. Necrotic leaves play a hydrological role in controlling the amount of water penetrating through the canopy.

The tree height and canopy base area, as well as DBH, were highest in the UB site, while the stand density of trees in the UB site was lowest among the three sites. The UB site is located near a village and managed properly with heavy and frequent thinning. Therefore, the morphological characteristics of the forest in the UB site were slightly different from those in the FN and CC sites.

## 3.2. Throughfalll

The measured throughfalls at the CC and FN sites are summarized in Table 2. The relative throughfall, which is the ratio of the throughfall amount to gross rainfall, decreased as canopy density increased. This implies an inverse relationship between the canopy density or cover and the amount of throughfall [37]. The amount of throughfall in the CC and FN sites represented 80.4% and 77.0% of gross rainfall, respectively.

Very little data on throughfall have been measured for burned forests. Williams et al. [38] noted that throughfall in the burned forests of the subalpine Rocky Mountains accounted for 86% of gross rainfall in the summer of 2006–2008. Gilliam et al. [39] showed that 80.6% of annual rainfall reached the soil in burned prairies. Fires in pine and oak forests enhanced the throughfall rate from 71.1% to 77.9% of gross rainfall during the growing season of 2019 [25]. Although there is considerable variation between the field measurements, the results of this study are similar to those of previous studies.

**Table 2.** Measured rainfall and rainfall partition in the study sites.

| | Gross Rainfall, GR (mm) | Throughfall, TF (mm) | | | Rainfall Loss (mm) | | | TF/GR (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | n = 7 | CC | FN | UB | CC | FN | UB | CC | FN | UB |
| Mean (±S.E.) | 19.18 (±20.28) | 17.31 (±17.35) | 13.84 (±14.07) | 19.87 (±16.85) | 2.86 (±3.35) | 2.28 (±1.89) | 5.07 (±3.45) | 80.43 (±23.01) | 76.96 (±23.60) | 70.11 (±21.30) |
| Minimum | 1.50 | 0.16 | 0.19 | 0.35 | 0.03 | 0.02 | 0.06 | 10.41 | 12.50 | 8.87 |
| Maximum | 59.60 | 63.66 | 58.19 | 57.10 | 17.93 | 11.85 | 20.99 | 150.34 | 138.27 | 99.78 |

Crown-fuel consumption (CC); foliage necrosis (FN); unburned area (UB); number of measurements (n); and standard error (S.E.).

As illustrated in Figure 4, the throughfall fraction became constant when it exceeded a certain amount of rainfall because it surpassed the retention limit of the crown. Part of the rainfall was retained by the leaves and branches, and the rest penetrated through the canopy. When the leaves and branches became saturated by rainfall, the retention capacity was completely occupied; thus, all incident rainfall reached the forest floor, resulting in the marginal retention of rainfall [40,41]. This is demonstrated by the Aston curve shown in Figure 4.

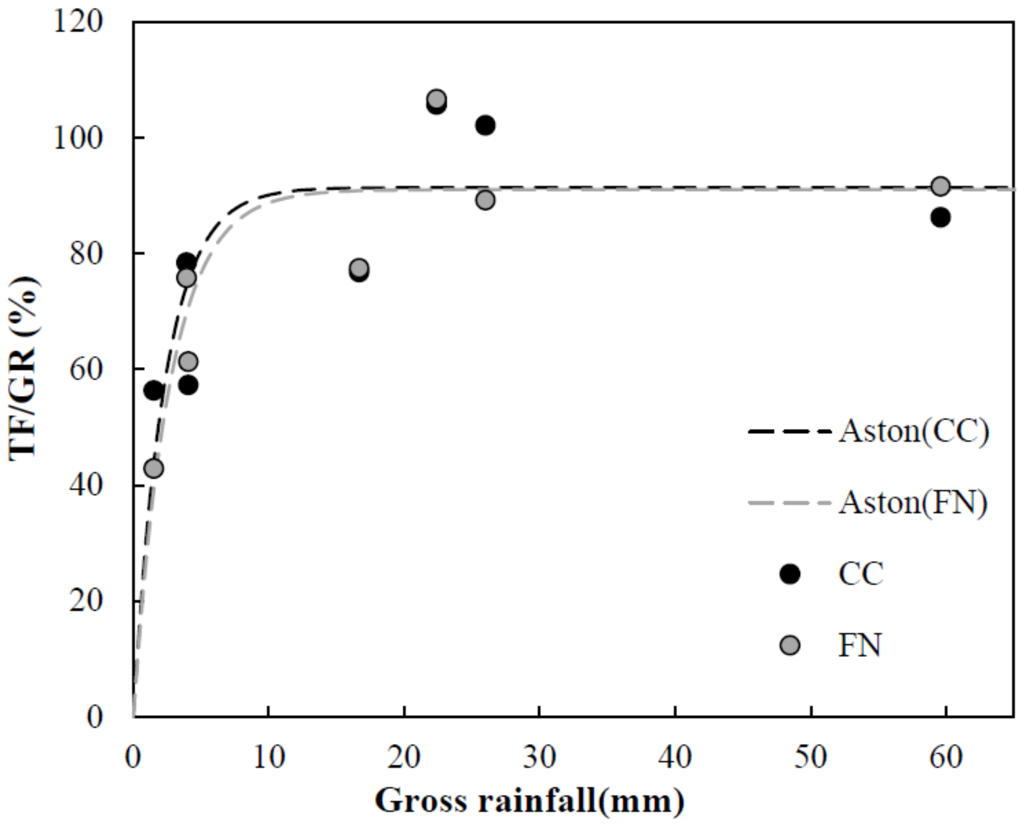


**Figure 4.** Aston curves for relative throughfall fraction (rTF) in crown-fuel consumption (CC) and foliage necrosis (FN) sites. GR indicates gross rainfall.

The Aston curve proposed by Aston [42] represents the average relative throughfall as a function of gross rainfall (GR). The relative throughfall fraction(rTF) increased linearly with lower rainfall and achieved marginal stability beyond the maximum values. The Aston curves of the relative throughfall at the CC and FN sites were derived as follows:

$$rTF_{CC} = 91.3609\left(1 - e^{-0.4255GR}\right)\ p < 0.001 \quad (1)$$

$$rTF_{FN} = 90.9956\left(1 - e^{-0.3676GR}\right)\ p < 0.001 \quad (2)$$

Using Equations (1) and (2), the threshold rainfall for marginal stability was found to be 14 and 18 mm at the CC and FN sites, respectively.

### 3.3. TOC and Calcium in Throughfall

The concentration of TOC in the throughfall, measured for two months after the fire outbreak, ranged from 1.4 to 26.0 mg/L in the CC site and 3.6 to 24.5 mg/L in the FN site. For all precipitation events, the average TOC concentration at the FN site was 49% higher than at the CC site ($p$ = 0.032) (Figure 5). The calcium concentration dissolved in throughfall was 0.2 to 4.1 mg/L at the CC site and varied from 0.4 to 4.7 mg/L at the FN site. The average calcium concentration at the FN site was 54% lower than that at the CC site for all rainfall events ($p$ < 0.001; Figure 5). Figure 5 also shows that the concentrations dissolved in throughfall decreased with time, implying that fire-burned leaves contained a large repository of leachable chemicals after the fire, which diminished over time.

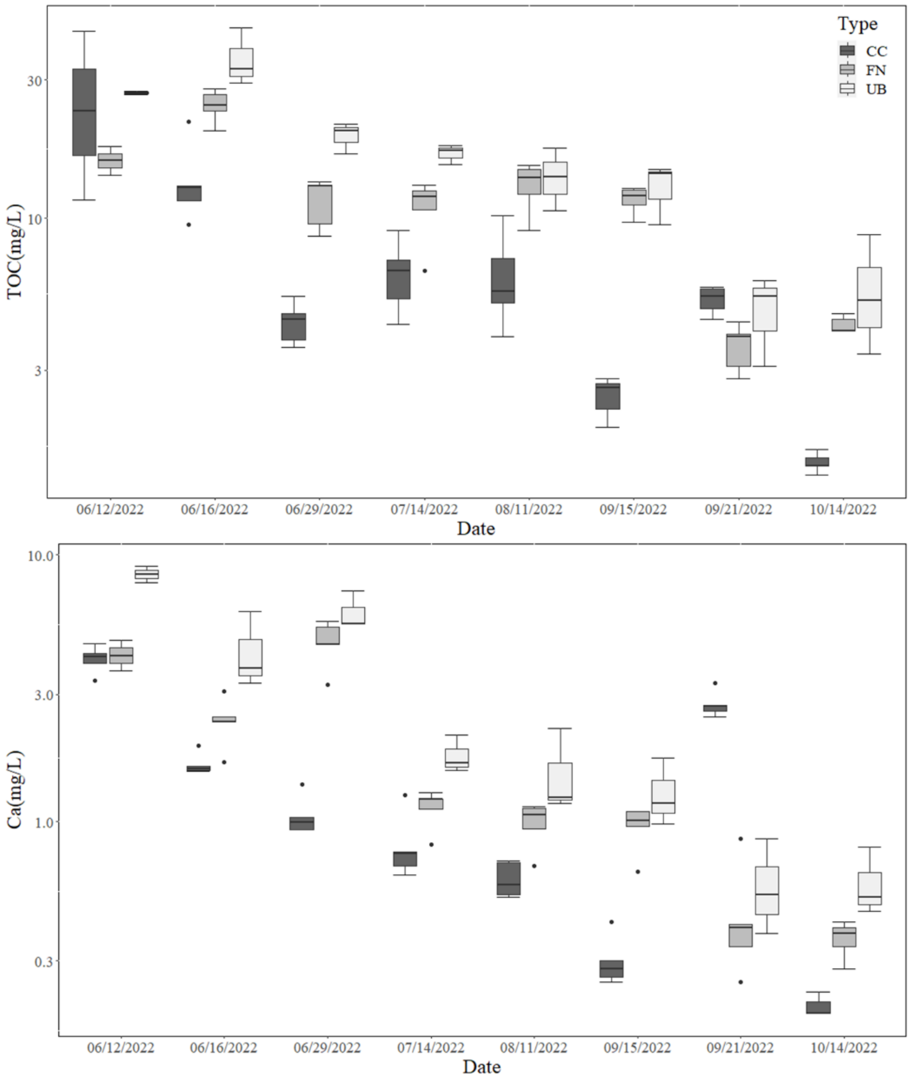


**Figure 5.** Variations of total organic carbon (TOC) and calcium (Ca) in throughfall with time. CC, FN and UB represent crown-fuel consumption, foliage necrosis, and unburned sites, respectively.

Figures 6 and 7 show that both TOC and calcium concentrations tend to decrease as the cumulative rainfall increases, regardless of fire damage. This trend has been observed in previous studies where the amount of nutrient release via throughfall decreased exponentially as rainfall intensity increased [43,44]. Table 3 shows the general equation of the nonlinear regression formula between rainfall and nutrient release, and the regression formula for TOC and Ca concentrations according to wildfire damage. As the canopy cover increased, initial calcium leaching increased. However, the initial leaching of TOC was unrelated to canopy cover or TF/GR, and the residual standard error of TOC was higher than that of calcium. This suggests that TOC is more influenced by external factors than calcium is, which is why there was no clear trend in the severity of forest fires. The fine dust in the atmosphere contained large amounts of organic carbon but relatively little calcium [45]. After a wildfire, a large amount of organic carbon is released into the atmosphere, and 10%–80% of this organic carbon is soluble organic carbon (water-soluble organic carbon), increasing the organic carbon concentration during rainfall [46,47]. Therefore, the TOC concentration in the throughfall was affected by a combination of canopy cover, throughfall mechanism, and TOC concentration in rainfall. No statistically significant relationships were observed between the study sites.

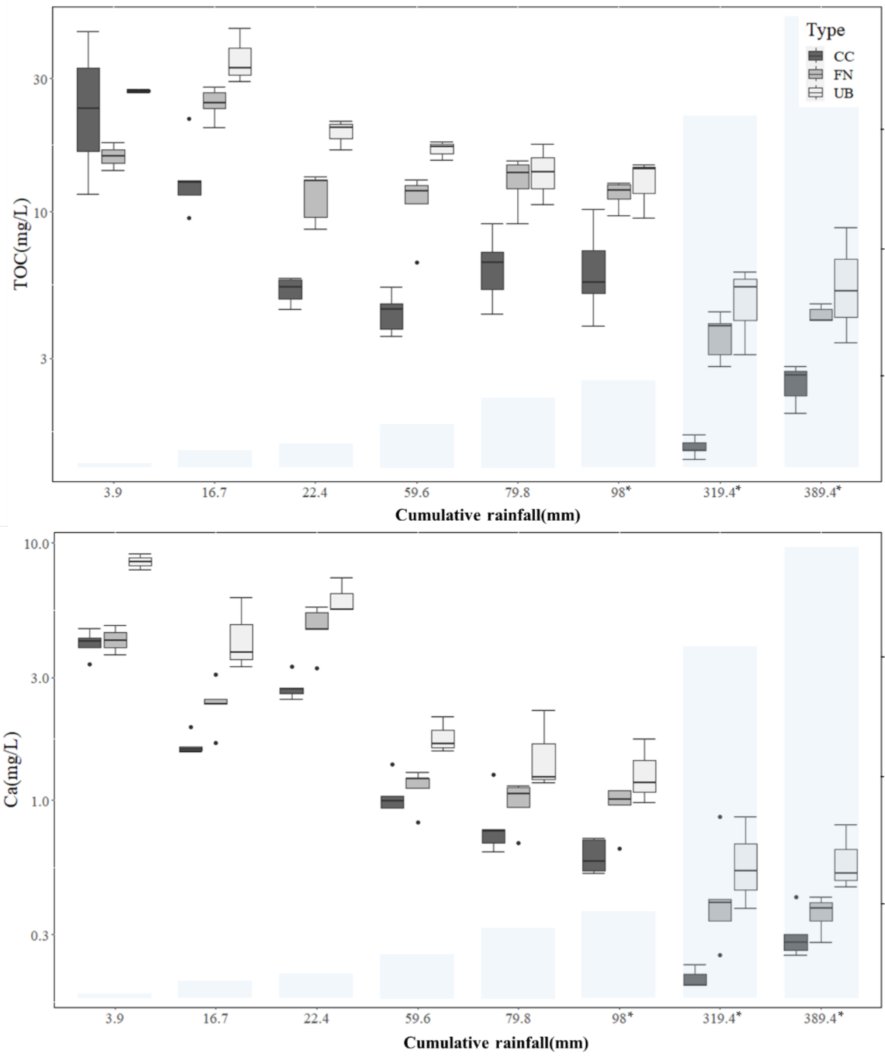


**Figure 6.** Variations of total organic carbon (TOC) and calcium (Ca) in throughfall with rainfall volume. CC, FN and UB represent crown-fuel consumption, foliage necrosis, and unburned sites, respectively. * denotes multiple rainfall events.

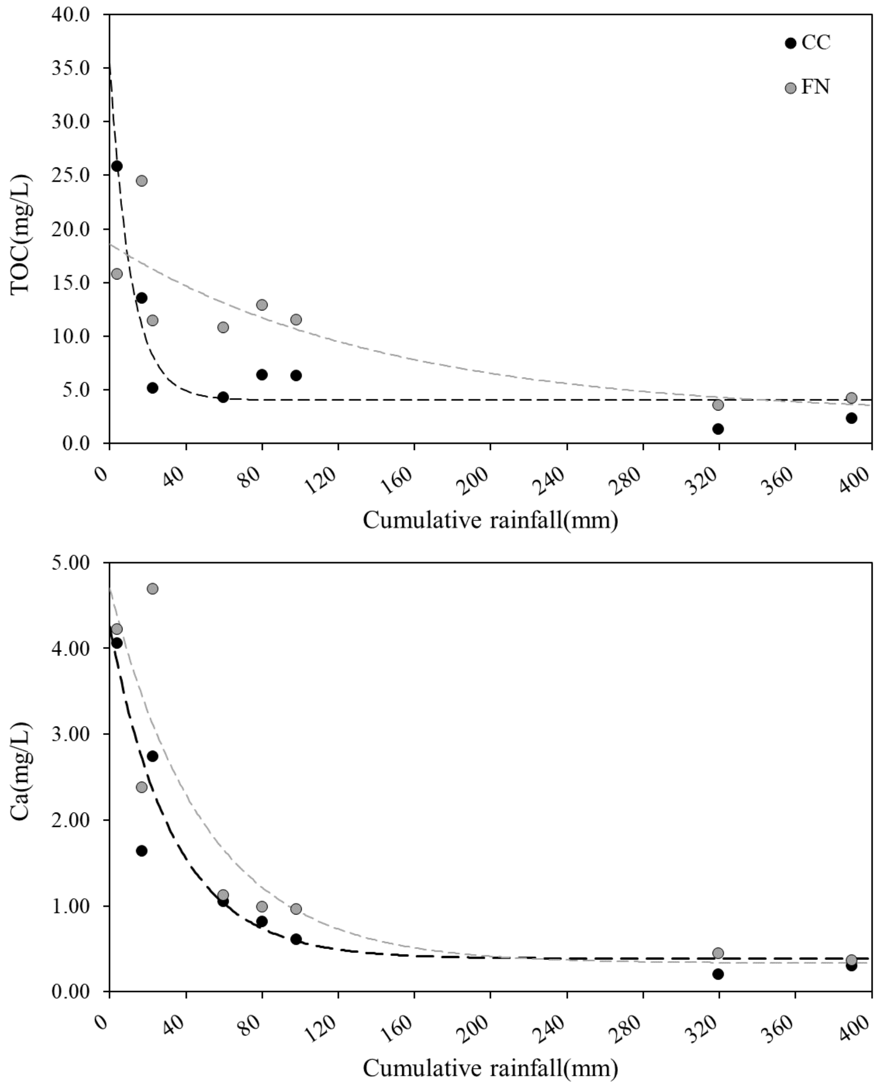


**Figure 7.** Depletion curves of total organic carbon (TOC) and calcium (Ca) with gross rainfall. CC and FN represent crown-fuel consumption and foliage necrosis sites, respectively.

**Table 3.** Depletion curves of total organic carbon (TOC) and Calcium ($Ca^{2+}$) in crown-fuel consumption (CC) and foliage necrosis (FN) sites.

| Item | Site | Depletion Curve | Residual Standard Error |
|---|---|---|---|
| TOC | CC | $TOC_{CC} = 31.36e^{-0.09GR} + 4.06$ ( $p < 0.01$) | 2.709 |
| | FN | $TOC_{FN} = 15.97e^{-0.007GR} + 2.61$ ( $p < 0.01$) | 4.368 |
| $Ca^{2+}$ | CC | $Ca_{CC} = 3.87e^{-0.03GR} + 0.39$ ( $p < 0.001$) | 0.527 |
| | FN | $Ca_{FN} = 4.37e^{-0.02GR} + 0.33$ ( $p < 0.001$) | 0.8945 |

## 4. Discussion

Fires cause drastic changes in canopy water storage by altering canopy openness, foliage volume, and bark absorbency [25]. At the CC site, stems and branches were directly exposed to rainfall, where more raindrops could accumulate and drop to the ground [40]. The canopy drip, which accounts for more than 50% of throughfall, has a considerable impact on the amount of throughfall because the rain particles that fall from the branches are larger than those from the leaves [41]. As stand density increases, the wind speed inside the stand decreases, and consequently, the proportion of branches in the crown that affect throughfall increases, while the clear height decreases [48,49]. When the canopy crown was thick, the throughfall decreased because the canopy drip was prevented from passing through the branches. The crown height of the crown-fuel consumption area accounted for 56% of the tree height, whereas that of the foliage necrosis area was 45%. This indicates that the crown fuel consumption area had well-developed branches, resulting in an increase in secondary interception by the branches and a maximum value of TF/GR similar to that of the foliage necrosis area.

The threshold rainfall reaching the maximum TF/GR at the CC site was higher than that at the FN site. Pine needles are densely distributed; therefore, rainwater entering the canopy is trapped in narrow spaces and does not move quickly through the branches [50,51]. However, the loss of crown foliage due to fire results in a relatively higher proportion of canopy drip and free throughfall [52,53]. The pine branches were horizontally distributed with thick bark and numerous cracks, which caused small amounts of rainfall to accumulate in the gaps between the branches. When rain arrives at the top of the canopy, water tends to adhere to the leaves and branches against gravity and consequently drips from the tree crown [43,44,54]. To form a canopy drip, a certain amount of rainfall must accumulate along the bark [51]. Therefore, the maximum TF/GR in burned areas indicates the development of canopy drip, which means that a larger amount of threshold rainfall is required for burned areas than for unburned areas [55,56].

Organic carbon and calcium are the major components of plants, particularly in the cell walls. When a fire occurs, the structure of the cells is destroyed by heat, and organic carbon and calcium are extracted from the stems and leaves [22]. Most organic carbon is completely combusted by fire and emitted as carbon dioxide; however, 10%–20% of organic carbon remains in the form of ash owing to incomplete combustion [21]. The concentration of chemical compounds in the throughfall increased as canopy density increased because a large number of water drops resided in the canopy. Calcium is mainly released from the leaf surface and is greatly influenced by both the canopy cover and the cross-sectional area of the leaves [57]. In areas affected by fires, there could be a consequential difference in canopy cover according to the vegetation burn intensity.

Calcium is not volatilized by a typical wildfire and is not emitted into the atmosphere but is mainly transported to the soil in the form of ash by wind or rainfall [47,58]. Plants in fire-damaged areas absorb soil calcium through their roots to compensate for and supplement calcium loss. As a result, high concentrations of TOC and calcium are observed in the throughfall owing to wildfire residues [44,59]. White [13] demonstrated that more organic carbon and calcium are released during throughfall from burned areas than from unburned sites.

A common challenge in post-fire hydrology studies is the lack of control over the location and timing of fires, which limits the ability to capture pre-disturbance data. In this study, two burned sites with similar physiographies and meteorologies were instrumented immediately after the fire to enable comparison. However, studies that have used this approach typically employ limited or no replication and short study periods (<one year).

When assessing the impacts of fire on forest hydrology it is necessary to measure one or more hydrological components that will provide information about the hydrological responses at fire-affected sites and compare these measurements against similar measurements collected in the absence of impact or disturbance named control site. Thus, the selection of a control site is crucial to the experiment study that can be used to assess the impacts of a disturbance. The control site is usually placed in the same watershed boundary or in another location in the vicinity of the fire-affected area, and therefore, not impacted by fire activity. However, it was not possible to find unburned sites that met these requirements.

As the reference for comparisons, the control site was selected in this study at an unburned forest near a village. This caused wide variations in rainfall amount and intensity between the experiment sites and the control site, and thus influenced throughfall amount and timing. In addition, the control site was located near a residential area and it is believed that anthropogenic pollutant sources may have influenced the water quality of throughfall. This led to considerable uncertainty because of the severely limited conditions.

Quantifying the variation in interception loss and its response to fire disturbances would enhance our understanding of canopy-mediated hydrologic dynamics in the context of increasing disturbances under ongoing global change. This flux plays a substantial role in the water balance of forest ecosystems and can be measured directly in the field under different conditions. However, additional studies of rainfall partitioning in fire-affected forests are required. Due to the insufficient replication of throughfall gauges and inconsistent stemflow collection protocols, many studies still lack credibility.

## 5. Conclusions

The volume of and chemicals in throughfall were analyzed in 2022 fire-damaged forests. Only 73.0% of gross rainfall was able to penetrate through the tree canopy at the FN site, whereas 80.4% of rainfall at the CC site reached the ground. It is evident that foliage loss can decrease interception capacity and increase throughfall rate after a fire. Based on the Aston curve, the TF/GR ratio at the CC site was slightly higher than that at the FN site because the presence of heat-damaged needles attached to the branches at the FN site resulted in greater rainfall interception.

The results showed that, as vegetation damage became more severe, the fraction of throughfall to rainfall increased. The maximum throughfall rate was attained in the following increasing order: unburned, foliage necrosis, and crown fuel consumption areas; although, there was no statistically significant difference between the groups. In addition, throughfall quality analysis revealed that TOC and calcium concentrations increased as the canopy cover increased, whereas nutrient release decreased with increasing rainfall. It was confirmed that the canopy cover, canopy layer thickness, understory density, and rainfall characteristics affect the amount and quality of throughfall. This study analyzed the short-term effects of a wildfire on throughfall for approximately four months after its occurrence. In this study, the changes in the amount and water quality of throughfall due to fire were examined over a relatively short period, providing fundamental data for nutrient cycle management of wildfire-damaged soil. However, the contribution of throughfall to soil chemistry has not been demonstrated, and the influence of wind characteristics on throughfall has not been considered. Future studies with longer durations in different forest stands are essential to provide a more quantitative evaluation of the impact of wildfires on throughfall.

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