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Effect of Slope Gradient and Litter on Soil Moisture Content in Temperate Deciduous Broadleaf Forest

Minyoung Lee [1], Dongmin Seo [1], Jeong Soo Park [2] and Jaeseok Lee [1,*]

[1] Department of Biological Sciences, Konkuk University, Seoul 05029, Republic of Korea; my991004@naver.com (M.L.); adrea5957@konkuk.ac.kr (D.S.)
[2] Ecological Observation Team, National Institute of Ecology, Seocheon 33657, Republic of Korea; jspark@nie.re.kr
* Correspondence: jaeseok@konkuk.ac.kr

Abstract

Although rainfall is a major determinant of soil moisture content (SMC), various factors affect SMC. The effects of these environmental factors contribute to spatial heterogeneity in SMC, which influences diverse ecological processes. To better understand the dynamics in SMC, litter and slope gradient should be considered. To this end, we analyzed the impacts of litter and slope gradient on SMC from 2020 to 2021 on Mt. Jeombong, located in a temperate deciduous broadleaf forest. We classified the study period into foliage (with a developed canopy) and non-foliage (after leaf fall) seasons. Our results indicated that SMC was affected by slope gradient and litter layer. Rainfall absorption occurred more at gentle slope, leading to higher SMC. Additionally, rainfall absorption was interpreted as being intercepted by the litter layer. Consequently, the correlation coefficient between SMC increment and rainfall was lower in the non-foliage season (R^2 = 0.37–0.56) than in the foliage season (R^2 = 0.72–0.84). With temporal progression, however, SMC response to rainfall increased where the litter was thickly accumulated, suggesting that litter interception was gradually diminished by decomposition. In this study, spatial heterogeneity in the litter layer and slope gradient substantially influenced the supply of soil moisture from rainfall.

Keywords: soil moisture content; temperate deciduous broadleaf forest; litter; slope gradient

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1. Introduction

Soil moisture is essential for the functioning of various biogeochemical cycles and ecosystems. For instance, as enzyme activity is influenced by soil moisture, the biomass of plants tends to be higher in wet soil environments and lower in dry soil environments [1]. The impacts of soil moisture on enzyme activity also affect the carbon cycle and nitrogen cycle by regulating ecological processes, including decomposition and soil respiration [2,3]. Furthermore, an increase in soil moisture contributes to the growth of soil microorganism biomass [4]. As global climate changes, this important moisture condition is affected due to several variations in environmental conditions, and one of them is variations in rainfall [5]. Climate change is causing regional rainfall to decline in subtropical and mid-latitude areas [6]. Moreover, climate change increases the seasonal variability of rainfall [7,8], leading to amplifying seasonal variations in soil moisture. Consequently, climate change leads to soil moisture drought, which aggravates vegetation, with a predicted reduction in net primary production exceeding 50% in some regions, depending on the future climate scenario [9]. Considering the role of soil moisture in ecosystems and the intensifying

drought under global warming, a more in-depth investigation of dynamics in the soil water regime is necessary.

To provide a more detailed understanding of the variations in soil moisture, it is essential to identify the factors that affect soil moisture. Primarily, rainfall is a key variable of soil moisture [10]. This suggests that changes in patterns and the amount of rain result in dynamics in hydrological conditions. Nevertheless, various environmental factors complicate the relationship between soil moisture and rainfall [11,12]. In particular, the relationship between soil moisture and rain is more complex in mountainous areas due to complex terrain [13,14]. Therefore, understanding variations in soil moisture solely by rain is challenging, especially in mountainous areas. These differences in soil water conditions can substantially impact ecosystems, such that distinct vegetation types can appear even in neighboring areas tens of meters apart [15,16]. Also, variations in soil moisture driven by slope topography are one of the influencing drivers that contribute to spatial fluctuations in soil respiration [17]. Additionally, variations in soil moisture across mountainous areas influence the activity of soil enzymes, which consequently alter the soil microbial biomass [18]. Thus, to acquire an in-depth knowledge of diverse ecological processes in mountainous areas, it is vital to comprehend the complexity of soil water fluctuations reflecting diverse environmental factors.

Although rain is a major contributor to soil moisture, various environmental factors, including vegetation, litter, elevation, slope aspect, and slope gradient, also affect soil moisture [19–23]. These environmental factors strongly control soil water conditions, especially in mountainous areas. Environmental variables cause substantial heterogeneity in soil moisture contents even between adjacent points [24], which results in spatial variations in soil moisture in mountainous areas. These spatial variations affect multiple ecological components of mountainous ecosystems, including soil respiration, plant diversity, and vegetation [25–27], and may ultimately alter the overall ecosystem functioning. Therefore, it is necessary to quantify the impacts of environmental drivers on soil moisture for a better understanding of mountainous ecosystems. However, research on the influences of environmental variables on hydrological processes in soil, particularly the combined effect of slope gradient and litter, has mainly been conducted under simulated rainfall conditions [28–30]. Although these research studies clarify the effects of litter interception, the process that affects the absorption of rainfall into the surface, they relied on controlled laboratory conditions, thereby overlooking spatial changes in environmental conditions. Because simulated studies are performed under standardized conditions, factors such as uneven accumulation of litter, vegetation effects, and heterogeneity of throughfall are not considered, in contrast to in situ measurements, which can capture these natural conditions. Among these environmental conditions, litter mass is particularly variable. Biological, climatic, and topographic influences cause heterogeneity in litter accumulation [31–33]. For instance, wind redistributes the produced litter in mountainous areas [31,32]. As a result, the thickness of the litter layer shows pronounced spatial variability in accumulation. This non-uniformity in litter distribution greatly affects the seedling establishment, vegetation community, and soil environment, including alterations of soil moisture [34–36]. Given the heterogeneity in litter accumulation and its ecological impacts, it is necessary to account for litter accumulation in soil moisture research. Nevertheless, studies conducted under laboratory environments are limited in capturing the influences of variation in litter conditions on soil moisture. Hence, previous studies are insufficient to clarify the actual impacts of environmental factors on variations in soil moisture, especially litter conditions. To accurately capture the heterogeneity in environmental conditions, it is essential to conduct in situ measurements that focus on the interactive effects of litter and slope gradient on soil moisture.

Previous studies on the combined effect of litter and slope gradient on soil moisture have insufficiently accounted for variability in environmental factors. The objective of this study is to address this limitation and clarify the actual influences of slope gradient and litter on variations in soil moisture content (SMC), considering the heterogeneity of litter conditions. To this end, we conducted an analysis of the impacts of slope gradient and litter on SMC variations based on field-based measurements in Mt. Jeombong, where a temperate deciduous broadleaf forest has developed. This study aims to deepen our comprehension of spatial variations in SMC and provides fundamental data for improving the accuracy of SMC estimation. We hypothesize that (a) the steeper slope position results in lower SMC, (b) spatiotemporal differences in litter environment lead to variations in litter interception, which affects SMC fluctuations during rainfall events, (c) the effects of these factors on SMC are modulated by seasonal changes.

2. Materials and Methods

2.1. Site Description

Mt. Jeombong (128°25′–128°30′ E, 38°0′–38°5′ N), where the research site is located, is situated in the middle of the Korean peninsula. The highest altitude of Mt. Jeombong is 1424 m while the altitude of the research site is located at 786 m above sea level.

The average annual temperature of Mt. Jeombong is 9.9 °C [37,38]. The average annual rainfall of Mt. Jeombong is 1114 mm, with most rainfall concentrated in the summer [37,38]. Mt. Jeombong is one of the main sites of Korean Long-Term Ecological Research, and numerous ecological studies have been conducted [39]. The presence of facilities for ecological monitoring and the occurrence of multiple studies in the same area provide substantial advantages for ecological research and the potential application of new scientific findings. This suggests that this site is suitable for ecosystem research, making it appropriate to conduct SMC measurements as well.

The Korean peninsula belongs to the temperate deciduous broadleaf forest zone [40], and Mt. Jeombong also falls within the same forest zone [38]. The dominant species of the research site is *Quercus mongolica* Fisch. ex Ledeb., which is also the principal species of *Q. mongolica* forests, the representative forest type on the Korean Peninsula [41]. In this research site, the average diameter at breast height (DBH) (cm) of *Q. mongolica* is 17.96 cm (Table 1), which is larger than the mean DBH of *Q. mongolica* in other mountains located in the Korean Peninsula [42].

Table 1. Average diameter at breast height (DBH, cm) of *Q. mongolica* in measurement site. The same letters at the same row indicate that there was no significant difference between the two points ($p = 0.427$).

Site	Average DBH (cm) of *Q. mongolica*
Ridge	19.34 ± 10.27 [a]
Southwestern slope	16.32 ± 11.10 [a]
Total	17.96 ± 10.76

Vegetation has a strong effect on soil moisture [19,43]. Accordingly, comparisons of soil moisture need to be conducted under similar vegetation. Since it is difficult to find environments where vegetation is homogeneous while the slope gradient and litter layer depth vary, measurements were conducted at two points. The measurement points were located on the ridge and the southwestern slope of Mt. Jeombong. The two measurement points were established close to each other, approximately 20 m apart. Both measurement points were set up in distinct subplots of 12 m × 12 m to capture the plot-scale variability of SMC. The slope gradient of the ridge is 4–6°, with an average of 5°, and the slope gradient

of the southwestern slope is 23–26°, with an average of 25°. The meridian angle of the ridge is 30–34°, with an average of 32°, and the meridian angle of the southwestern slope is 209–216°, with an average of 213° (Figure 1). The litter produced at the southwestern slope tends to be blown by the south wind and moved towards the ridge.

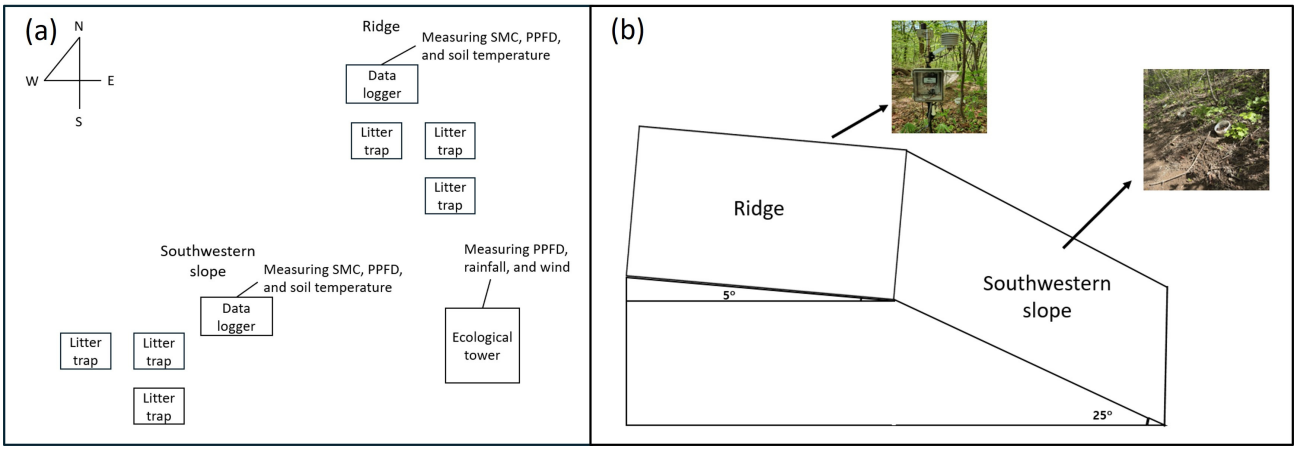

Figure 1. Schematic of the research site. (**a**) refers to the schematic layout of measurement points, including data loggers, litter traps, and the ecological tower. (**b**) shows the topographical profile of the ridge and the southwestern slope, with photographs illustrating representative topographic conditions at each point.

2.2. Environmental Factors

Soil moisture, rainfall, light, and soil temperature were measured from 2020 to 2021, and the measured data was collected through a data logger (HOBO Micro Station, Onset, Bourne, MA, USA). As soil moisture in the deeper layer is relatively less affected by topography [21], SMC was measured from 5 cm to 15 cm depth using a soil moisture sensor (S-TMB-005, Onset, Bourne, MA, USA) to better capture topographic influences. Furthermore, as this layer is closely related to processes such as soil respiration, it can also provide a basis for comparison with other studies. The rainfall was measured through a rain gauge (metric) data logger (RG3-M, Onset, Bourne, MA, USA). To avoid blockage of the rain gauge by litter, the rain gauge data logger was installed on a 21 m high ecological tower that extends above the forest canopy, which was established as a part of the facility for long-term ecological monitoring on Mt. Jeombong. Photosynthetic photon flux density (PPFD) was measured using a light sensor (M-NDVI, Onset, Bourne, MA, USA), and measurements were conducted at a 21 m high ecological tower that extends above the forest canopy and on the forest floor of the research site. The soil temperature was measured by a temperature sensor (S-TMB-M002, Onset, Bourne, MA, USA). We also measured wind speed and wind direction at the measurement site using a weather station (HP2000, Misol, Jiaxing, China).

Freshly fallen litter was collected monthly by litter traps, each measuring 1 m × 1 m in size. The collected litter was dried at 80 °C for 48 h in a litter dryer, and then the dry weight was measured. The thickness of the litter layer and litter production were measured at three points on the ridge and southwestern slope, respectively. The thickness of the litter layer was calculated by measuring the organic horizon.

2.3. Rainfall Event

The starting point of rainfall events was defined as when rainfall of 1 mm or more per hour first fell, and the rainfall event period included up to 6 h if rainfall of 1 mm or more per hour finally fell and then rainfall of less than 1 mm per hour fell. This criterion, which has been used in hydrological hazard studies [44,45], was applied here to ensure a clear

separation of rainfall events. The increase in SMC due to a rainfall event was calculated by comparing SMC immediately before the rainfall event began and SMC immediately after the rainfall event finished, based on rainfall event criteria. To analyze SMC variations by rainfall, it is essential to set a threshold for the minimum time interval between rainfall events [46]. We set this threshold to 48 h to clearly separate individual rainfall events for the analysis of SMC variations.

2.4. Plant Phenology

For the analysis of changes in plant seasons, we compared the Photosynthetic photon flux density (PPFD) from the forest floor and from the section of the ecological tower, which is located above the canopy, to determine whether the forest canopy was open or closed.

We defined canopy closure as the day when the PPFD measured at the surface of two measurement points, ridge and southwestern slope, began to be maintained below 15% of the PPFD measured at the ecological tower, and we defined the day when it began to be maintained above 15% as canopy opening, a threshold that reflects seasonal changes in canopy openness.

2.5. Leaf Area Index Estimations

Leaf area index (LAI) is defined as the sum of the one-sided leaf area of the canopy per unit surface area [47]. We estimated LAI at the ridge and the southwestern slope based on litter production during the study period and leaf weight per leaf area, which were collected at both measurement points.

We measured the one-sided area of the leaf using grid paper. We also dried the sample at 80 °C for 48 h in a litter dryer and measured the dry weight. The ratio of leaf weight per leaf area (g m^{-2}) was calculated by the following equation (Equation (1)).

$$\text{Leaf weight per leaf area} = \text{weight of dried leaf (g)}/\text{one-sided area of leaf } (m^2) \quad (1)$$

And we calculated leaf area per surface area using Equation (1) and litter production, which is a commonly used method for measuring LAI [47]. LAI was calculated by the following equation (Equation (2)).

$$\text{LAI} = \text{one-sided leaf area } (m^2)/\text{forest floor area } (m^2) \quad (2)$$

We measured a total of five samples collected at the ridge and the southwestern slope, respectively.

2.6. Data Analysis

We analyzed the relationship between the SMC increasing ratio and rainfall through the Pearson correlation coefficient obtained from regression analysis. Additionally, since some samples did not meet the requirement of equal variances ($p < 0.05$), we consistently applied two-tailed Welch's *t*-test to analyze the differences in SMC by measurement points. The differences in litter and LAI by measurement points were also analyzed by two-tailed Welch's *t*-test. The statistical significance level was set at $p < 0.05$. The aforementioned data analysis was conducted using Microsoft Excel (Microsoft, Redmond, WA, USA) and verified through R 4.4.2 (R Core Team, Vienna, Austria). Furthermore, we conducted repeated measures ANOVA using the ez package in R 4.4.2 to examine interannual differences in SMC during August.

3. Results

3.1. Division of Seasons

The forest canopy tended to close in mid–May and open in late–October (Figure 2). The day of year (DOY) of the canopy closing date (spring canopy development) was 136 in 2020 and 134 in 2021. The DOY of canopy opening date (autumn leaf-fall) was 291 in 2020 and 294 in 2021 (Figure 2).

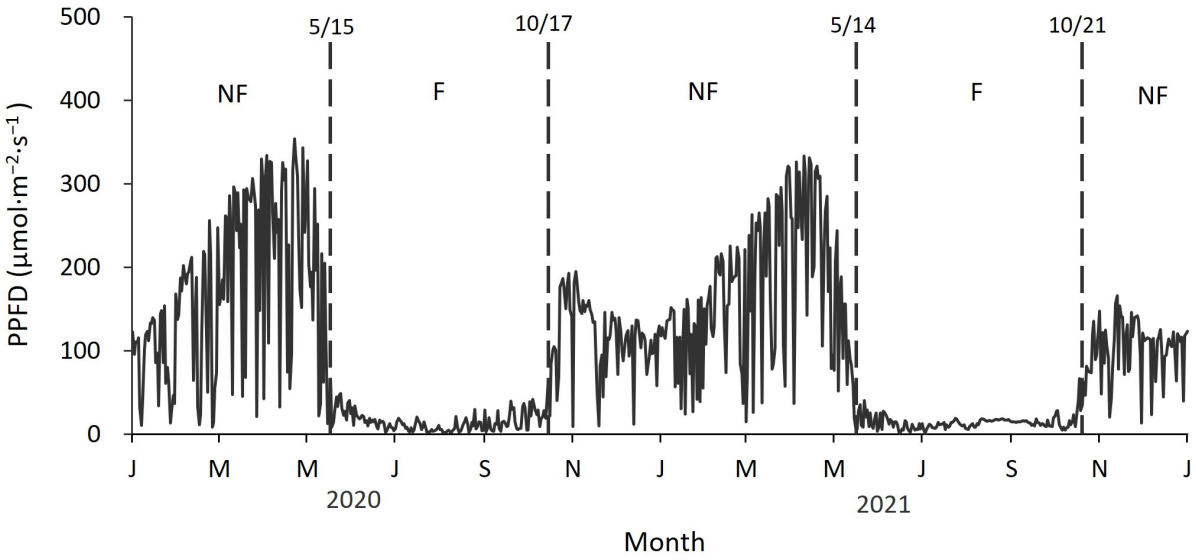

Figure 2. Average photosynthetic photon flux density (PPFD, μmol·m^{-2}·s^{-1}) measured from 2020 to 2021 at the forest floor of the ridge and the southwestern slope. Canopy closing/opening dates were defined by whether PPFD measured at the forest floor of two sites, ridge and southwestern slope, remained below or above 15% of the PPFD above the canopy. The period after the canopy closing date and before the canopy opening date was defined as the foliage season, and other periods as the non-foliage season. Abbreviation F indicates foliage season, and NF indicates non-foliage season.

Before analyzing the variations in SMC, the measurement period was divided into two seasons based on the canopy opening date and the canopy closing date. We defined the foliage season as the period between the canopy closing and canopy opening dates, and the rest was defined as the non-foliage season (Figure 2).

3.2. Rainfall and SMC

Since water and ice have notably different permittivity [48], only the period when the soil temperature at both the ridge and the southwestern slope remained positive was analyzed. Rainfall during the unfrozen period was 2345.6 mm in 2020 and 1262.0 mm in 2021 (Figure 3). Rainfall was low in April, and SMC was also low in April. As the monthly rainfall increased in May, SMC also increased. A large proportion of rainfall was concentrated in July–August, especially in August.

In August, when a large amount of rain was concentrated, 534.4 mm of rain fell in 2020, and 307.4 mm of rain fell in 2021 (Figure 3). The average daily SMC at the ridge in August 2020 was 40.43 ± 2.77%, and 35.50 ± 4.04% in August 2021, showing significantly higher SMC in 2020 ($p < 0.05$). By comparison, the average daily SMC at the southwestern slope in August 2020 was 27.45 ± 1.23%, and 27.86 ± 1.08% in August 2021, showing no significant difference between the two years ($p = 0.162$).

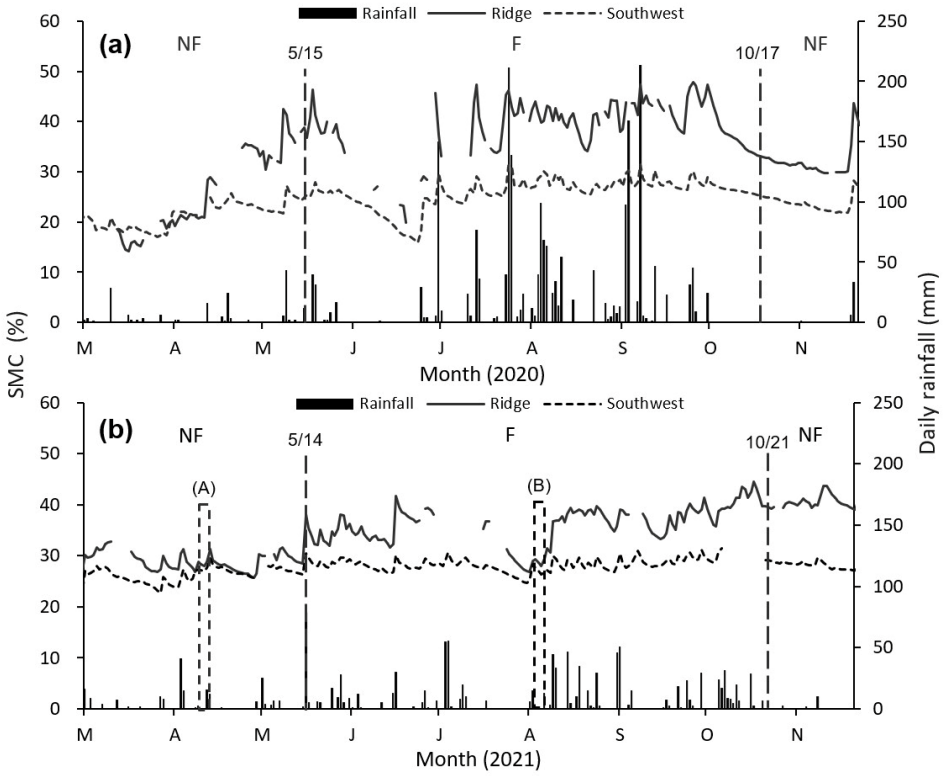

Figure 3. Soil moisture content (SMC, %) and daily rainfall (mm) measured in the unfrozen period at the ridge and the southwestern slope (Southwest). (**a**) shows SMC and rainfall during 2020 and (**b**) shows SMC and rainfall during 2021. Abbreviation F indicates the foliage season, and NF indicates the non-foliage season. (A) and (B) are selected rainfall events for analyzing the increase in SMC during rainfall events, which more than 10 mm of rain fell. Event (A) represents the rainfall event in the non-foliage season with 27.0 mm of rain, while event (B) occurred in the foliage season with 13.2 mm of rain.

The ridge showed a significantly higher SMC than the southwestern slope ($p < 0.05$). The SMC difference between the two measurement sites was higher in 2020, the year in which more rain fell (Figure 3). To analyze the differences in SMC variations at two points deeply, we chose two rainfall events in which more than 10 mm of rain fell. One event occurred during the non-foliage season and the other event occurred during the foliage season (Figure 4).

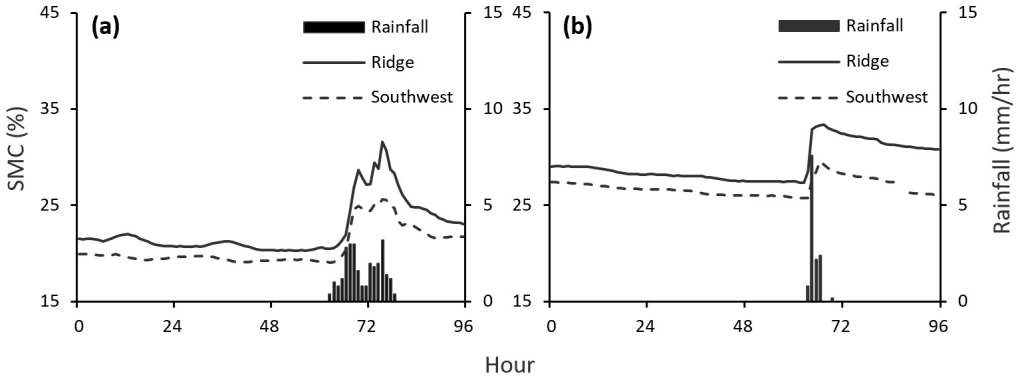

Figure 4. Variation of soil moisture content (SMC, %) during rainfall events at the ridge and the southwestern slope (Southwest). (**a**) shows a rainfall event with 27.0 mm of rain that fell during the non-foliage season and (**b**) shows a rainfall event with 12.4 mm of rain that fell during the foliage season.

In the non-foliage season, the minimum rainfall for an increase in SMC was 2.2 mm. When 27.0 mm of rain fell, SMC increased by 6.55% at the ridge, and by 4.32% at the southwestern slope. The SMC increasing ratio (%) per rainfall (mm) was 0.24 at the ridge, and 0.16 at the southwestern slope (Figure 4a). In the foliage season, the minimum rainfall for an increase in SMC was 0.8 mm. When 12.4 mm of rain fell, SMC increased by 4.15% at the ridge, and 2.70% at the southwestern slope. The SMC increasing ratio (%) per rainfall (mm) was 0.33 at the ridge, and 0.22 at the southwestern slope (Figure 4b). Additionally, LAI was estimated to compare canopy conditions at the ridge and the southwestern slope (Table 2). There was no significant difference in LAI between two sites ($p = 0.295$). To assess the difference in SMC variations between the two points, rainfall (mm) and SMC increasing ratio (%) was analyzed (Figure 5).

Table 2. Dried leaf weight per one-sided leaf area (g m^{-2}) and leaf area index (LAI) measured at both the ridge and the southwestern slope. Site differences were analyzed using two-tailed Welch's *t*-test, and the statistical significance level was set at $p < 0.05$. The same letters in the same row indicate that there was no significant difference between the two sites.

Variable	Ridge	Southwestern Slope	*p*-Value
Dried Leaf weight per one-sided leaf area (g m^{-2})	96.41 ± 24.35 [a]	104.93 ± 28.89 [a]	0.628
LAI	5.91 ± 1.27 [a]	5.02 ± 1.25 [a]	0.295

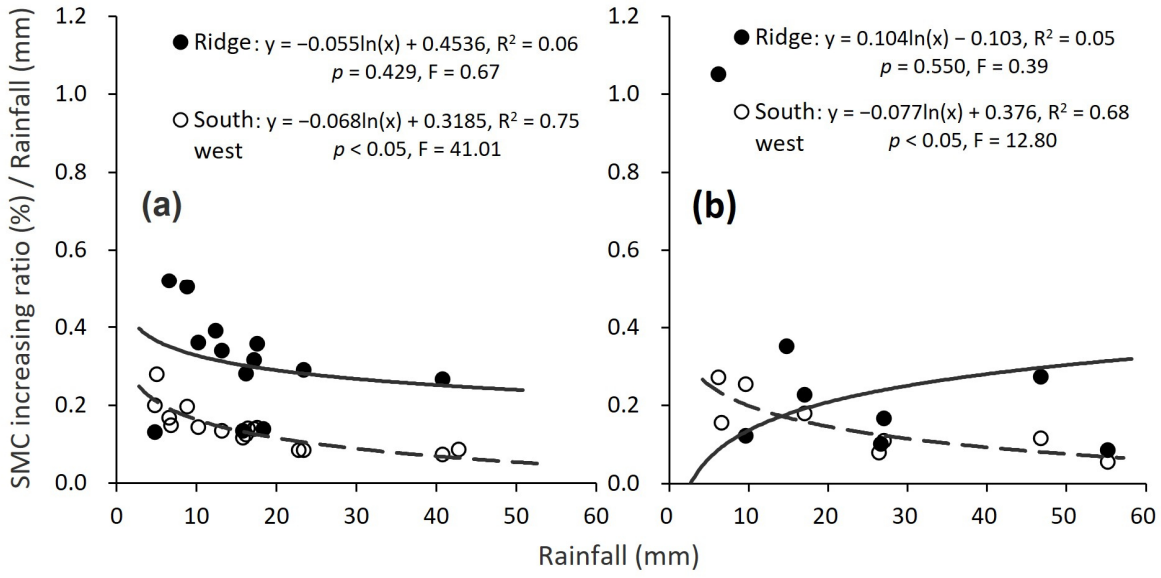

Figure 5. The relationship between rainfall (mm) and ratio between soil moisture content (SMC) increasing ratio (%) per rainfall (mm) at the ridge and the southwestern slope (Southwest). Selected events have a time interval of more than 48 h between other rainfall events. (**a**) shows the rainfall events occurred during the foliage season, and (**b**) shows the rainfall events occurred during the non-foliage season. The solid line represents the regression curve for the ridge, whereas the dashed line represents the regression curve for the southwestern slope. The statistical significance level was set at $p < 0.05$.

We analyzed events with a temporal interval of more than 48 h between other rainfall events. At the ridge, the relationship between rainfall (mm) and SMC increasing ratio (%) per rainfall (mm) was not significant ($p = 0.429$–0.550). At the southwestern slope, a significant correlation was found between rainfall (mm) and SMC increasing ratio (%) per rainfall ($p < 0.05$). And at the southwestern slope, SMC increasing ratio (%) per rainfall (mm) decreased significantly as the amount of rainfall increased (Figure 5).

3.3. Seasonal Characteristics of Soil Moisture Content

To analyze the seasonal characteristics of SMC variations, we examined the relationship between rainfall (mm) and SMC increasing ratio (%) during rainfall events analyzed in Figure 5, which is divided according to plant phenology. SMC increasing ratio (%) was higher at the ridge. The relationship between SMC increasing ratio (%) and rainfall (mm) varied from season to season. In the foliage season, correlation coefficient between SMC increasing ratio and rainfall ranged from 0.72 to 0.84 (Figure 6a). By comparison, the correlation coefficient between rainfall and SMC increasing ratio ranged from 0.37 to 0.56 in the non-foliage season (Figure 6b).

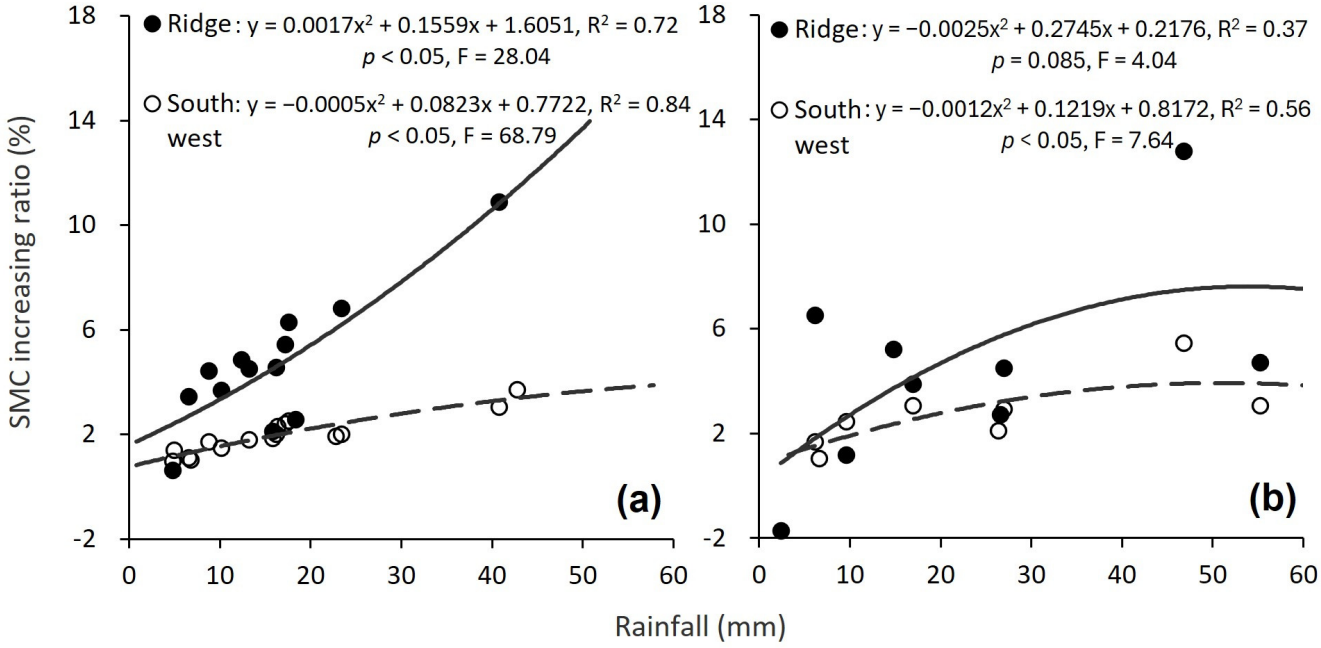

Figure 6. Soil moisture content (SMC) increasing ratio (%) at the ridge and the southwestern slope (Southwest). Selected events have a time interval of more than 48 h between other rainfall events. (**a**) shows the rainfall events that occurred during the foliage season and (**b**) shows the rainfall events that occurred during the non-foliage season. The solid line represents the regression curve for the ridge, whereas the dashed line represents the regression curve for the southwestern slope. The statistical significance level was set at $p < 0.05$.

Wind and litter environments were examined to better understand the environmental conditions of the measuring site (Figure 7). The difference in litter production between the ridge and the southwestern slope was not significant ($p = 0.316$) and litter layer depth was significantly thicker at the ridge ($p < 0.05$). The wind direction is mainly southwest in the non-foliage season (Table 3).

Table 3. Daily wind direction (°) and daily wind speed (m/s) in the non-foliage season measured at the research site.

Variable	Daily Mean Value
Wind direction (°)	194.39 ± 20.01
Wind speed (m/s)	0.95 ± 0.89

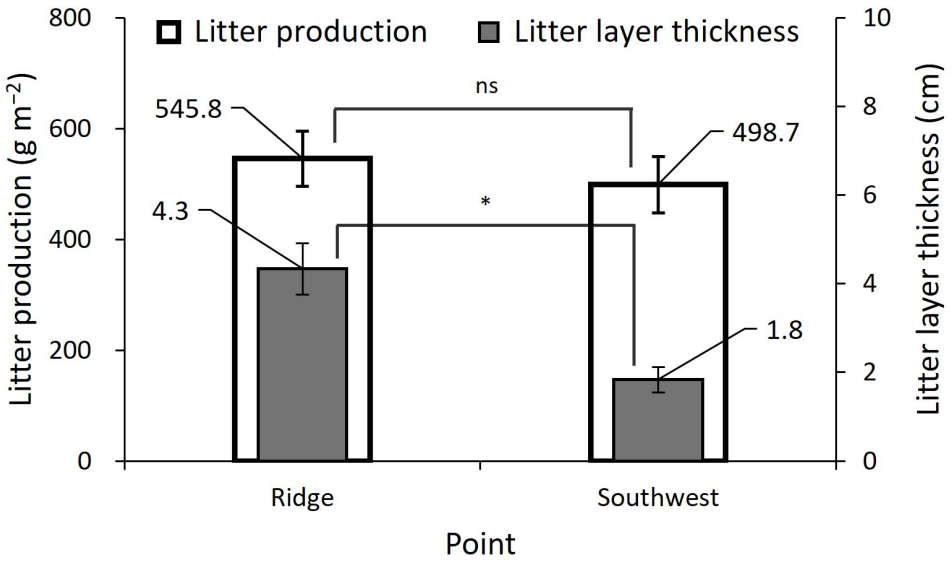

Figure 7. Litter production (g m^{-2}) and litter layer thickness (cm) at the ridge and the southwestern slope (Southwest). The difference in litter production and layer depth between ridge and southwestern slope were analyzed using a two tailed Welch's *t*-test and the statistical significance level was set at $p < 0.05$. * Indicates $p < 0.05$, and ns indicates $p > 0.05$.

To explore potential seasonal changes in SMC variations, we selected four rainfall events (Figure 8). Before analyzing seasonal changes on SMC increment, we divided the foliage season into two periods: the period before the highest temperature in the year was recorded as the early period of foliage season, and the period after the highest temperature in year was recorded as the late period of foliage season. One event occurred in the non-foliage season, one event occurred in the early period of foliage season, and the others occurred in the late period of foliage season. Events to be compared were selected as those with similar amount of rain fall. In the four events, a similar amount of rain fell, with 17 mm on 27 March, 16.2 mm of rainfall on 25 May, 17.2 mm of rainfall on 26 August, and 17.6 mm of rainfall on 21 September, respectively (Figure 8).

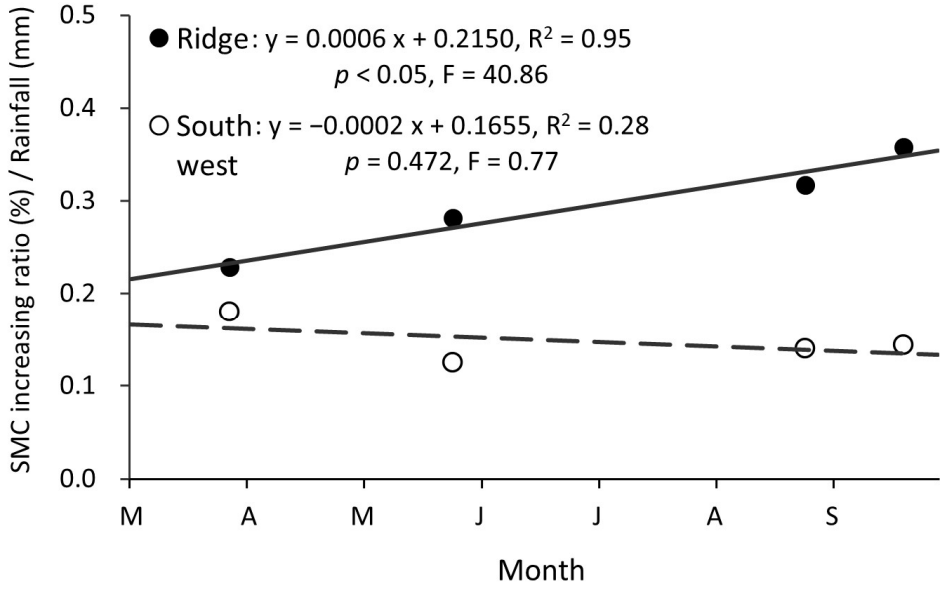

Figure 8. Seasonal difference in soil moisture content (SMC) increasing ratio (%) per rainfall (mm) at both the ridge and the southwestern slope (southwest). Rainfall events with similar rainfall amounts (16.2–17.6 mm) were selected. The statistical significance level was set at $p < 0.05$.

At the ridge, the SMC increasing ratio (%) per rainfall (mm) in the selected events was 0.23 on 27 March, 0.28 on 25 May, 0.32 on 26 August, and 0.36 on 21 September. At the southwestern slope, the SMC increasing ratio (%) per rainfall (mm) in the selected events was 0.18 on 27 March, 0.12 on 25 May, 0.14 on 26 August, and 0.14 on 21 September, respectively (Figure 8). At the ridge, SMC increasing ratio (%) per rainfall (mm) increased as the time passed ($p < 0.05$). At the southwestern slope, the SMC increasing ratio (%) per rainfall (mm) did not decrease in the non-foliage season. The difference in SMC increasing ratio between the ridge and southwestern slope increased (Figure 8).

4. Discussion

Changes in rainfall patterns due to global climate change affect soil moisture, which is a key component in ecosystem functions. Additionally, environmental conditions further contribute to variability in soil moisture, including litter and slope gradient. However, previous research on the interactive effects of these two elements was conducted under laboratory environments [28–30]. Given that litter accumulated unevenly by biotic and abiotic factors [32,33], which induce plot-scale differences in SMC [34], the limitations of previous studies were evident. To analyze the effect of litter and slope gradient on SMC, we conducted in situ measurements in Mt. Jeombong from 2020 to 2021, located in a temperate deciduous forest.

Accumulated litter substantially affects hydrological processes [49,50], including litter interception. As litter is seasonally supplied from the forest canopy in temperate deciduous forests, seasonal canopy changes and subsequent litter accumulations need to be accounted for in SMC investigations. During the season when the canopy is fully developed, litter input is limited, and ongoing litter decomposition leads to a decrease in the effect of litter on SMC. Conversely, in the season when the canopy falls, a large amount of litter is supplied to the forest floor, thereby increasing litter interception, a mechanism that reduces the amount of rainfall that is absorbed by the soil [29]. Therefore, before analyzing the effects of litter and slope gradient on SMC, it is essential to consider plant phenology. It is well established that plant canopy reduces the light availability at the forest floor [51,52]. Canopy light transmission, which is the ratio between the irradiance of the open area and the irradiance of the ground under the canopy, varies seasonally as the canopy opens and closes [53]. Thus, we used canopy light transmission as an indicator of changes in plant phenology. We compared the PPFD from the surface and the ecological tower to determine whether the forest canopy opened or closed. Due to limited canopy data, analysis of canopy phenology was restricted to seasonal division.

The DOY of the canopy closing date was 136 in 2020 and DOY 134 in 2021, which is later than the average plant season start in South Korea [54]. As low air temperature results in a late start of the plant growing season [55], this result indicates that the low temperature at the measurement site likely led to this phenomenon. The canopy opening date was DOY 291 in 2020 and DOY 294 in 2021 (Figure 2). This date was earlier than the end of the growing season in Mt. Jeombong, reported by a previous study, and later than the date the canopy began to fall [56]. Although a previous study reported dynamics in plant phenology in the Korean Peninsula under climate change [57], such a trend was not clearly observed in this study. This indicates that the duration of the study was limited to capturing long-term changes in the ecosystem. According to the applied criteria, the measurement period was divided into two seasons based on the canopy opening date and the canopy closing date. We defined the foliage season as the period between the canopy closing and the canopy opening, and the rest was defined as the non-foliage season (Figure 2).

Although snow melting is essential for comprehending soil moisture [58], since water and ice have notably different permittivity [48], only the period when the soil temperature

at both the ridge and the southwestern slope maintained a positive value was analyzed. A large proportion of rainfall was mainly concentrated in summer, and the soil moisture content during this period was also high. Jeong et al. [59] reported that a large proportion of rainfall was concentrated in July–August, and in September, the dry season began, so SMC decreased. In this study, SMC decreased in mid–September, and this is consistent with the previous study [59]. The ridge showed a significantly higher SMC than the southwestern slope, and in 2020, a year of higher rainfall, the SMC difference between the two measurement sites was greater, particularly during August (Figure 3). Despite their proximity, SMC was markedly different between the ridge and the southwestern slope. To examine the cause of this phenomenon, we chose two rainfall events in which more than 10 mm of rain fell, one event occurring during the non-foliage season, and the other occurring during the foliage season (Figure 4).

The ratio between rainfall (mm) and SMC increasing ratio (%) was remarkably different between the ridge and the southwestern slope (Figure 4). The increase in SMC resulting from rainfall varied considerably at the ridge and the southwestern slope, which is potentially related to the observed difference in seasonal variation in SMC at the two points (Figures 3 and 4). As the two measurement points were adjacent to each other, it is reasonable to assume that the amount of rainfall above the forest canopy was the same at the two points. Still, since there is no rainfall data measured under the canopy at both measurement points, we additionally analyzed the canopy conditions to demonstrate that the surface rainfall was similar at the two points.

Although the rainfall was assumed to be similar, it is important to consider the canopy interception, which alters the amount of rainwater that reaches the ground [60]. While microclimatic conditions can influence canopy interception [61], the close distance between measurement points, approximately 20 m, indicates that spatial differences in these factors were negligible. Consequently, we used LAI as a proxy variable for canopy interception, which is widely used in canopy investigations [47]. This analysis focused on spatial disparity in LAI, reflecting vegetation structure that was similar between the two sites based on DBH (Table 1). It is known that as LAI increases, canopy interception tends to increase, resulting in a decrease in the amount of rain reaching the surface [60,62]. However, in this study, LAI was similar between the ridge and the southwestern slope (Table 2). This indicates that the amount of rainfall reaching the forest floor is nearly equal at both points, and the observed SMC difference is attributed to different degrees of rainfall absorption. To investigate the difference in SMC increment to rainfall between the two measurement points, we analyzed the relationship between rainfall and the rate of SMC increase.

To analyze SMC variations by rainfall, it is essential to set a threshold for the minimum interval between rainfall events [46,63]. Therefore, before analyzing changes in SMC following rainfall, we selected the rainfall events that were separated from other events by more than 48 h to clearly isolate event-induced effects on SMC. At the southwestern slope, SMC increasing ratio (%) per rainfall (mm) was significantly negatively correlated with rainfall (Figure 5). Consequently, the SMC increase per rainfall decreased with increasing rainfall of the event. In contrast, it was insignificant at the ridge (p = 0.429–0.550). This result demonstrates that even though the two points were close to each other, the rainfall absorption was significantly different.

This study revealed that the characteristics of SMC differed significantly between measurement points. The ridge, which is a gentle slope, showed higher SMC than the southwestern slope, which is a steep slope (Figure 3). Also, in selected rainfall events, the SMC increment was substantially lower at the southwestern slope (Figure 4). This result was consistent with a previous study that conducted under simulated rainfall conditions at a similar slope gradient to this study, which reported that the increase in SMC and

rainfall infiltration was higher at a gentle experimental site [64]. Topographical factors remarkably affect spatial variations in SMC in mountainous areas, and among topographical factors, slope gradient is one of the main drivers that play a major role [21]. As the slope gradient increases, surface rainfall runoff increases [64–66], and this phenomenon results in a negative correlation between slope gradient and soil moisture [21,67]. Given that the southwestern slope has a steep slope gradient of 25°, while the ridge has a gentle slope gradient of 5°, which suggests that the amount of rainfall runoff was higher at the southwestern slope, resulting in lower SMC at the southwestern slope. Accordingly, as the rainfall increased, the ratio between SMC increment and rainfall reduced at the southwestern slope (Figure 5). Consequently, the pronounced spatial heterogeneity of SMC was attributed to slope gradient, particularly during a period of heavy rainfall (Figure 3).

In addition to the effect of slope gradient, we also investigated how the rainfall–SMC relationship varies seasonally. The difference between SMC increasing rates at the two measurement points was relatively low in the non-foliage season. Also, the minimum rainfall required for SMC increment was different from season to season. Moreover, the SMC increasing ratio per rainfall was higher in the foliage season (Figure 4). These results indicate that plant phenology strongly influences SMC responses per rainfall. To examine the seasonal characteristics of SMC variations, we analyzed the SMC increment per unit rainfall during rainfall events shown in Figure 5. In the foliage season, the correlation coefficient between rainfall and SMC increasing ratio was relatively high (Figure 6a). In contrast, the correlation coefficient between rainfall and SMC increasing ratio was relatively low in the non-foliage season (Figure 6b), the period after the forest canopy leaves fell and became litter. Litter has various effects on hydrological processes in forests [49,50], and one of them is rainfall interception. Taking into account that the litter layer causes rainfall interception [28–30], this suggests that rainfall interception by litter likely contributed to the observed phenomenon. To investigate this phenomenon further, we measured the litter production and layer depth.

As shown in Figure 7, the difference in litter production between the ridge and the southwestern slope was not significant ($p = 0.316$), indicating the similarity in canopy litter input between the two sites. However, litter layer depth was significantly thicker at the ridge ($p < 0.05$). This result is consistent with a previous study conducted in this research site, which indicated that due to the influence of wind in the canopy-opened period, more litter was accumulated at the ridge [31]. In mountainous areas, produced litter is redistributed by wind [32]. Based on the location of measurement points and the effect of wind on litter redistribution, the south wind that blew at the research site in the non-foliage season likely contributed to the spatial heterogeneity of litter layer thickness (Table 3 and Figure 7). Considering that litter interception increases with litter layer thickness [68,69], the thick litter layer accumulated at the ridge may have contributed to rainfall interception (Figure 7). In contrast, there was no significant spatial difference in LAI (Table 2), which suggests that LAI is not a confounding factor, and heterogeneity of the litter layer thickness is a major differentiator for SMC variability. Consequently, SMC variations in response to rainfall were relatively irregular at the ridge, particularly in the non-foliage season (Figure 6b).

To analyze the seasonal variations in the effect of litter on SMC variations, we selected four rainfall events according to plant phenology (Figure 8). Since the amount of rain affects rainfall runoff (Figure 5), we selected events for comparison that recorded similar amounts of rainfall, with 16.2–17.6 mm. At the ridge, the SMC increasing ratio per rainfall increased over time ($p < 0.05$). Comparing the SMC increasing ratio in the late foliage season and non-foliage season, the ridge showed a 36.2% reduction in SMC increase per rainfall. In contrast, the SMC increasing ratio per rainfall did not increase at the southwestern slope

(p = 0.472). These seasonal variations in rainfall absorption are likely related to seasonal changes in the physical properties of the litter layer. Litter decomposition depends on climatic conditions, and as the temperature increases, the decomposition rate of litter also increases [37,70]. Litter decomposition, as measured using litter bags, reduces the mass of autumn litter by up to 50% by the following September [71]. These results suggest that as the accumulated litter decomposed in the warm period, rainfall interception by the litter layer gradually decreased. This contributed to an increasing difference in SMC increment per rainfall between the ridge and the southwestern slope (Figure 8).

The relationship between rainfall and SMC increment is presumed to have been strongly affected by litter. In the non-foliage season, when the litter layer was more accumulated, the increase in SMC per rainfall was irregular mainly due to the influence of litter, especially at the ridge where the litter layer was thickly developed (Figure 7). As time passed and the season varied, SMC response to rainfall increased at the ridge, suggesting that the effect of litter on SMC gradually reduced due to decomposition.

This study demonstrated that litter and slope gradient substantially influence the fluctuations of soil moisture. Considering the importance of soil moisture, it is essential to assess it accurately [72]. Although various modeling approaches have been attempted to estimate and predict soil moisture [73–75], considerable uncertainty in soil moisture estimation persists due to the effects of environmental variables [73,76]. To improve soil moisture estimation, it is essential to investigate the actual effects of environmental variables. To address this issue, we investigated the on-site influences of slope gradient and litter to clarify the in situ influences of these environmental factors on SMC. Our findings are expected to improve the accuracy of estimation models of soil moisture, especially in temperate forests developed in mountainous areas. This understanding provides an empirical basis for enhancing the predictions of variation in SMC and the consequent shifts in ecological processes. Furthermore, this study revealed the distinct influence of slope gradient on SMC at a steep slope forest stand, which underscores the necessity of careful conservation of these areas in forest management under climate change and rainfall regimes.

Although this research concentrated on slope gradient and litter, multiple factors influence SMC. Among those, vegetation and soil depth, which were held consistently in this study, considerably affect SMC [19,21,77]. While this study did not address the relationship between these factors and SMC, a comprehensive analysis of their impact is also required. To overcome the limitations of this study, future research should consider measurements across various vegetation types and soil depths. Furthermore, incorporating more detailed information on seasonal canopy changes, which were not comprehensively addressed in this study, can provide deeper insight into the relationship between vegetation dynamics and SMC. Subsequent studies incorporating these components together will help generalize and expand upon the findings of this study.

5. Conclusions

At the research site, spatial variation in SMC was observed. SMC was higher at the ridge, where the slope gradient is gentle. This implies that more rainwater infiltrated at the flatter point and rainfall runoff was higher at the steeper point. Moreover, the litter layer is also a factor contributing to spatial variation in SMC. In the foliage season, when the litter layer was less developed, the relationship between rainfall and the increase in SMC was stronger than in the non-foliage season. The effects of litter on SMC were higher at the ridge, where the litter layer was thickly developed. Furthermore, over time with seasonal changes, the SMC increased more following rainfall events at the ridge, suggesting that the effect of litter on SMC gradually reduced by decomposition. Our findings supported the

hypotheses (a) that a steeper slope position results in lower SMC due to enhanced runoff, (b) that spatiotemporal variations in litter accumulation cause changes in litter interception, which influence SMC fluctuations, and (c) that the impacts of litter on SMC vary seasonally.

In this study, SMC of temperate deciduous broadleaf forest was significantly influenced by slope gradient and litter. This result indicates that slope gradient and litter also need to be considered to understand the variations in SMC in deciduous broadleaf forests. These findings are expected to contribute to improvements in soil moisture modeling in forest ecosystems. To extend these insights and deeply understand the control of slope gradient and litter on SMC variations, it is essential to conduct multiple measurements under diverse environmental conditions. These findings are expected to be validated through future research conducted in various vegetation types and topographic conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

SMC	Soil moisture content
DBH	Diameter at breast height
PPFD	Photosynthetic photon flux density
LAI	Leaf area index
DOY	Day of year
F	Foliage season
NF	Non-foliage season
Southwest	Southwestern slope

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