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Impact of Tree Canopy Elevation on Rainfall Attenuation and Soil Erosion Dynamics for Enhanced Erosion Control

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ABSTRACT Afforestation harvesting operations and the interception processes of tree canopies profoundly impact rainfall intensity attenuation, thereby altering both the magnitude and intensity of rainfall, which leads to changes in the production of runoff and sediment. Concurrently, the kinetic energy (KE) of raindrops is moderated by the presence of the canopy, with heightened attenuation observed during the canopy's full leaf-out phase. This attenuation of rainfall intensity under different tree canopy elevations, resulting from the dynamic interaction between rainfall and the tree canopy, is a fundamental component of the interception process, influencing water distribution and soil stability. This study evaluates the impact of rainfall interception by canopies of six trees of the same species at varying elevations (H1=5.90 m, H2=5.68 m, M1=4.02 m, M2=4.04 m, L1=2.19 m, L2=2.33 m) on soil erosion dynamics. A controlled experiment in the woodland of Ritsumeikan University involved plastic boxes (37 cm × 25 cm) placed under each canopy, filled with decomposed granite and silica sand, and set on a 20° slope. The experiment measured soil displacement within a designated erosion area (6 cm × 15 cm) in the boxes following three rainfall events with different durations and precipitation levels. Results showed that the eroded soil mass (measured in grams) in the boxes was lower at the lower elevation sites (L1 and L2) compared to the medium and higher canopy elevations (M1, M2, H1, and H2). Lower tree canopies not only attenuate raindrop KE but also enhance rainfall redistribution, increase litter-induced surface roughness, improve infiltration, and reduce runoff-driven erosion. Their proximity to the soil enhances microclimatic regulation, minimizing sediment detachment and transport.

KEYWORDS Rainfall Attenuation; Canopy; Kinetic Energy; Soil Erosion; Ritsumeikan University

1 INTRODUCTION

When rainfall reaches a tree-covered area, it undergoes a process of interception by the tree canopy. Some raindrops pass directly to the ground through gaps in the canopy, while others are intercepted by the leaves and branches. This interception reduces the kinetic energy (KE) of raindrops and alters their distribution. Consequently, a portion of the rainfall is captured and temporarily stored on the canopy surfaces, while the remainder reaches the ground as throughfall, either dripping from the canopy or falling through the gaps. This interception process significantly affects the spatial distribution and intensity of rainfall, influencing soil moisture, surface runoff, and overall hydrological dynamics (Li et al., 2019; Oliveira et al., 2024).

Afforestation is a widely used strategy to control soil erosion, with large-scale forest plantations established to prevent slope soil erosion. Despite significant vegetation coverage, moderate to severe soil erosion can still occur under forests, emphasizing the need to study the role of tree canopies in soil erosion dynamics. By quantifying precipitation redistribution, throughfall indices, and raindrop KE, canopy interception reduces the impact of rainfall on the soil, with stronger effects under low rainfall intensity. The findings highlight how changes in the KE influence sediment yield, showing that canopy interception is an important factor in sediment reduction (Li et al., 2019).

Trees are essential to the hydrological cycle, as their canopies alter the amount, route, and intensity of rainfall reaching the ground (Alivio, Šraj and Bezak, 2023). Having a variety of tree species not only enhances canopy coverage, which shields the soil from rain, but also promotes the development of soil crusts that stabilize the soil, both of which contribute to reducing soil erosion and sediment during the early stages of forest development (Song et al., 2019).

Rainfall interception by tree canopies significantly reduces KE and rainfall erosivity, particularly during the leafed period, with variations depending on seasonal and meteorological conditions (Zore et al., 2022; Li et al., 2019). Additionally, Yücesan et al. (2019) found that canopy density has a positive effects on the reduction of soil loss. According to the study by Zabret et al. (2017), rainfall characteristics significantly influence throughfall dynamics, with varying effects depending on the canopy's physical shape. It also demonstrates that the characteristics of throughfall, including KE, are notably altered by the tree canopy, with variations influenced by foliage presence and meteorological conditions (Alivio, Bezak and Mikoš, 2023).

In contrast to these results, Zhou and Li (1999) and Cao (2008) did not verify the beneficial impact of afforestation on erosion control. Runoff exhibits notable seasonal changes and can rise rapidly if the canopy cover diminishes due to leaf drop or low stand density. Nanko et al. (2008) and Wu and Gu (2020) found that soil loss and runoff depth were highest in pure tree plots and lowest in tree-grass combinations, highlighting complex interactions between tree canopies and grass layers. Another study showed that high crown cover and leaf area reduced interrill erosion, while taller trees increased it, with tree species richness having no impact (Seitz et al., 2016). Likewise, areas with higher canopy covers experienced less erosion, while those with lower or disrupted cover had more erosion, highlighting the importance of maintaining dense canopy cover in forest management (Altieri et al., 2018).

As mentioned in previous studies (Li et al., 2019), the relationship between KE and accelerated soil erosion after large-scale afforestation, particularly in relation to canopy influence, remains insufficiently explored. Further research in this area could improve soil protection strategies and deepen the understanding of erosion mechanisms in afforested regions.

To advance our understanding, this study investigates how variations in tree canopy height influence soil erosion under different precipitation conditions during the leafed period. By examining six trees of the same species and canopy structure, each pair set at identical elevations, the research aims to elucidate the role of tree canopy height in modulating soil erosion. This approach will provide insights into how tree characteristics and rainfall dynamics interact to affect soil conservation, ultimately contributing to more effective forest management and erosion control strategies, and will also assist engineers and developers in making informed decisions.

2 MATERIALS AND METHODS

2.1 Study Area

The study was carried out at an experimental site located in Kusatsu, Shiga Prefecture, within the Ritsumeikan University (BKC) woodland (34°59’02”N, 135°57’47”E; see Figure 1). The annual temperature in this area ranges approximately from 3°C (38°F) to 27°C (82°F). July experiences the highest rainfall, averaging around 220 mm, while January is the month with the most snowfall, averaging about 50 cm. The period from July to September is the warmest, with temperatures reaching about 26°C (80°F), whereas January, February, and December are the coldest months, averaging around 3°C (38°F) (Climate Japan, 2020).

Figure 1 Map of the study area at Ritsumeikan University (BKC), showing all six sampling sites located within the rain-gauged area.

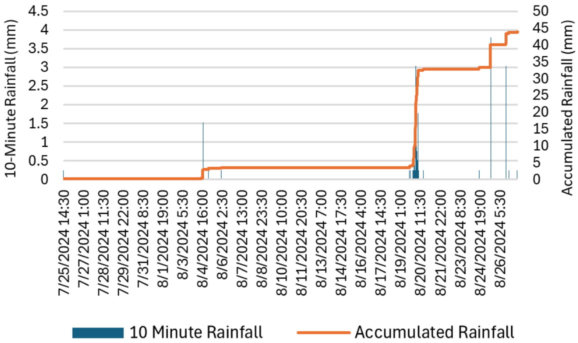
The experimental plot, spanning approximately 37,122 m^2 within the BKC campus, involved selecting six trees of the same species from the woodland. For each tree, experimental boxes were placed underneath the canopy at different elevations: high, medium, and low. To ensure precision, each elevation category featured two boxes positioned at similar heights within the canopy, with efforts made to maintain consistency within the same canopy for each tree. The six sampling points, designated as H1, H2, M1, M2, L1, and L2, were situated approximately 1.5 meters above the ground. These points were strategically selected to represent high, medium, and low elevations, with each elevation category covering varying distances from the tree canopy.

2.2 Measurements

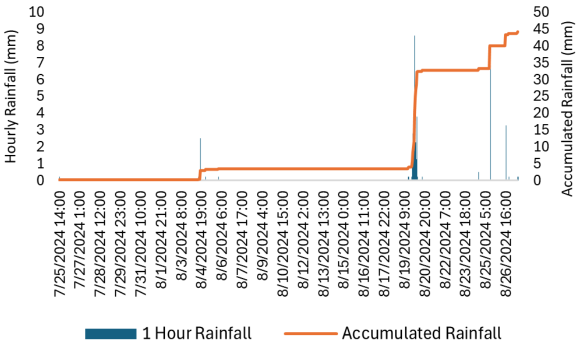
The six experimental boxes were positioned to evaluate the impact of canopy rainfall interception by six trees of the same species at varying elevations (H1 = 5.90 m, H2 = 5.68 m, M1 = 4.02 m, M2 = 4.04 m, L1 = 2.19 m, L2 = 2.33 m) on soil erosion dynamics. A controlled experiment was conducted using plastic boxes (37 cm × 25 cm) placed beneath the tree canopies approximately 1.5 meters above the ground. The boxes were divided into two trapezoidal compartments, each with a slope of 20°, a height of 13.5 cm, and widths of 15 cm and 20 cm. Each compartment was filled with 3510 g of soil at 10% moisture content. Two distinct soil types were used: decomposed granite and silica sand. Rainfall interception by the tree canopies was quantified, and the effect on soil erosion was assessed by measuring soil displacement within a designated erosion area (6 cm ×15 cm; Figure 2) in the boxes.

A rain gauge data logger (HOBOevent) was installed in an open area within the experimental plot to accurately measure and record rainfall data. This installation was

Figure 2 The left side of the picture shows the experimental box filled with two types of soil, along with the area designated for collecting eroded soil. On the right side of the picture, the installed rain gauge data logger is visible in an open area of the experimental plot.



(a) 10-minute rainfall data from the second phase (July 25–August 27, 2024).



(b) Hourly rainfall data from the second phase (July 25–August 27, 2024).

Figure 3 Rainfall data recorded during the second phase of the experiment (July 25–August 27, 2024).

crucial for capturing real-time precipitation information, essential for analyzing the impact of canopy interception on soil erosion. The data logger was positioned away from potential obstructions to ensure accurate measurements. Recent studies underscore the efficacy of rain gauge data loggers in hydrological research, emphasizing their vital role in ground-based precipitation measurements. Rain gauges are also essential for monitoring disasters such as flooding and landslides, and proper placement and calibration are critical for obtaining reliable data for environmental and hydrological analyses (Morbidelli et al., 2021)(Figure 2).

2.3 Data Analysis

The experiment began in late July 2024, with data collected from July 18 to September 5. Leakages in the experimental boxes during the first rainfall event prevented accurate soil collection, but the issue was resolved for subsequent events.

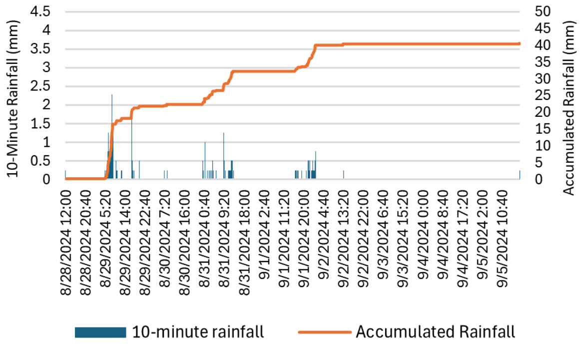
During the second phase (July 25–August 27, 2024), the total accumulated rainfall reached 44.19 mm. The peak 10-minute rainfall was recorded at 3.81 mm, while the peak hourly rainfall and maximum hourly rainfall were 8.63 mm and 9.65 mm, respectively. Figures 3a and 3b illustrate the characteristics of rainfall observed during this period.

During the third phase (August 28–September 5, 2024), the total accumulated rainfall, as recorded by the installed rain gauge at the site, was 40.64 mm. The peak 10-minute rainfall was 2.28 mm, while the peak hourly rainfall and maximum hourly rainfall were 7.87 mm and 8.38 mm, respectively. Figures 4a and 4b illustrate these rainfall characteristics.

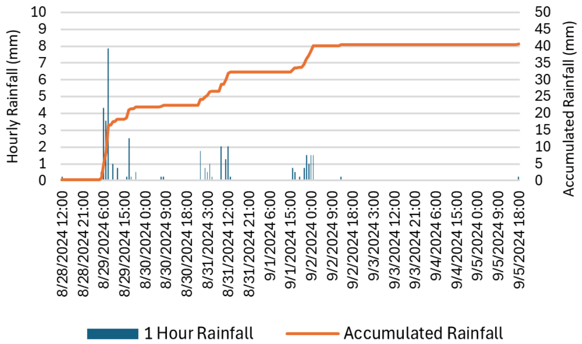
After each rainfall event, eroded soil samples were weighed to assess the interaction between rainfall, soil erosion, and canopy elevation within the experimental boxes at different canopy heights: low (L1, L2), medium (M1, M2), and high (H1, H2). The observations provided insights into rainfall-induced soil displacement under varying canopy elevations. Consistent with the findings of Mohamadi and Kavian (2015), storms with increasing rainfall intensity were associated with soil loss and sediment concentration.

3 RESULTS AND DISCUSSION

During the measurement period at the study area, the total recorded rainfall was 103.12 mm. According to Japan Meteorological Agency (2024) data, the average annual precipitation in Otsu near Kusatsu city is approximately 1,550 mm. Therefore, the measured rainfall accounts for roughly 6.65% of the annual average. Alongside rainfall measurement, the corresponding eroded soil was analyzed in the latter two and three phases. However, due to leakages in the boxes, the rainfall and soil data within the canopy elevation from the first phase were not fully analyzed.



(a) 10-minute rainfall data from the third phase (August 28–September 5, 2024).

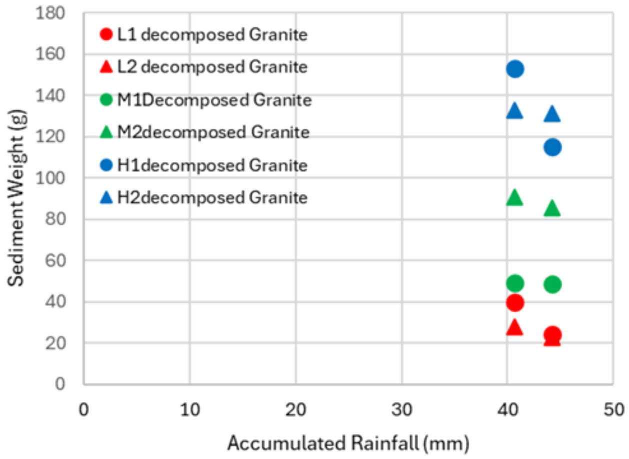


(b) Hourly rainfall data from the third phase (August 28–September 5, 2024).

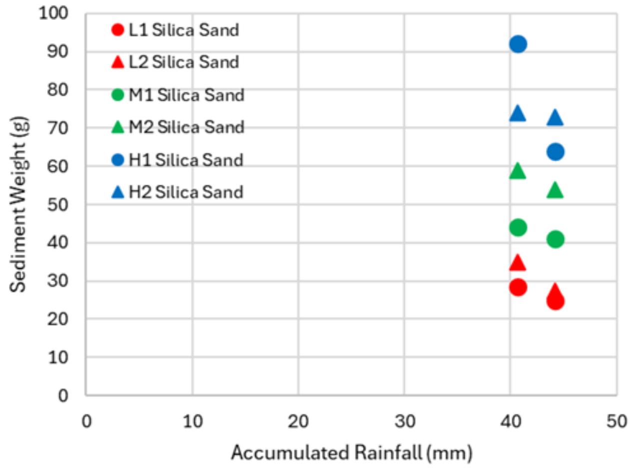
Figure 4 Rainfall data recorded during the third phase of the experiment (August 28–September 5, 2024).

Many studies have examined the effects of canopies and their relationship with soil erosion, as well as the impact of canopy density and tree characteristics on throughfall from rainfall (Zaw and Oue, 2024). Additionally, a study on afforestation in southern China's red soil region found that forest canopy interception reduces soil erosion more effectively under moderate rainfall intensity. Although, despite increased vegetation, significant soil erosion still occurred, emphasizing the importance of canopy interception in sediment reduction (Li et al., 2019). However, this study aims to investigate the effects of canopy elevation on soil erosion under different precipitation conditions.

After considering the rainfall period, soil erosion data from the six positioned boxes revealed distinct variations in surface degradation from the two soil types. Analysis of the experimental period showed that the surfaces of boxes at positions L1 and L2 exhibited less degradation compared to those at M1, M2, H1, and H2. Notably, H1 and H2 experienced the highest levels of surface degradation, indicating a greater susceptibility to rainfall impact at higher elevations within the canopy. Interception loss plays a key role in managing watershed water balance by reducing stormwater runoff and delaying precipitation, particularly in urban areas with tree coverage (Asadian and Weiler, 2009).



(a) The scatter plot compares sediment weight across accumulated rainfall for Decomposed Granite soil.



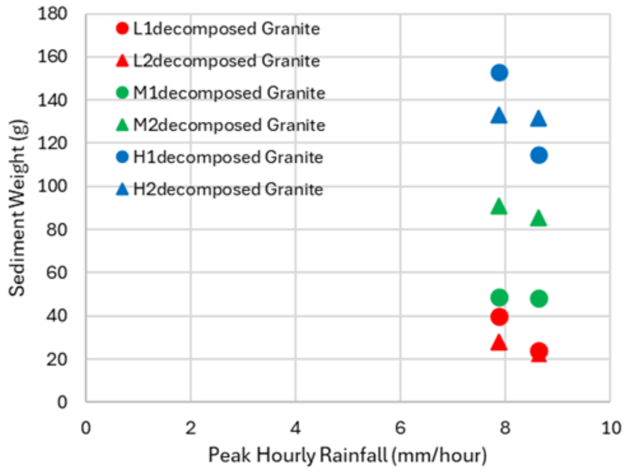
(b) The scatter plot compares sediment weight across accumulated rainfall for Silica Sand soil.

Figure 5 Scatter plots showing the relationship between sediment weight and accumulated rainfall for two soil types.

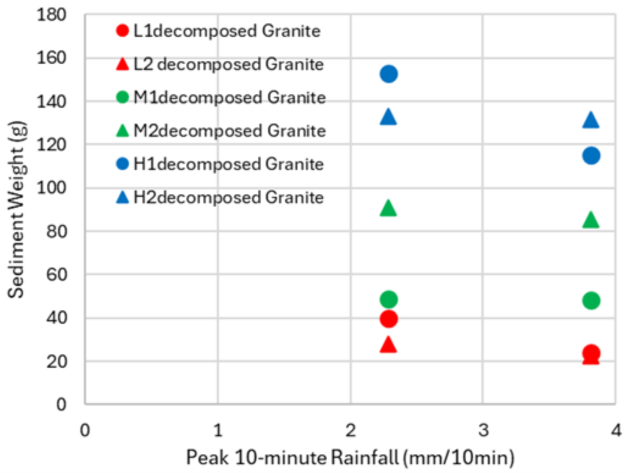
3.1 Comparative Analysis of Soil Erosion Across Rainfall Data and Canopy Elevation

As mentioned previously, the first phase of the experiment, which involved a 4-hour rainfall event with 18.28 mm of precipitation, demonstrated the least erosion in the low elevation boxes (L1, L2), intermediate erosion in the mid-elevation boxes (M1, M2), and the greatest erosion in the high elevation boxes (H1, H2). However, due to leakage in the boxes, we were unable to analyze the exact weight of the eroded soil for calculations.

The figures (Figures 5a and 5b) illustrate the relationship between accumulated rainfall during the second and third phases (44.19 mm and 40.64 mm, respectively) and sediment weight (g) for two different soil types: decomposed granite and silica sand. Each



(a) The scatter plot compares sediment weight across peak 10-minute rainfall for Decomposed Granite soil.



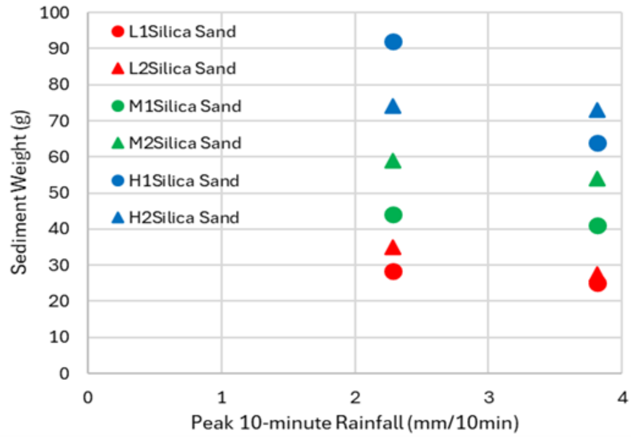
(b) The scatter plot compares sediment weight across peak 10-minute rainfall for Silica Sand soil.

Figure 6 Scatter plots showing the relationship between sediment weight and peak 10-minute rainfall for two soil types.

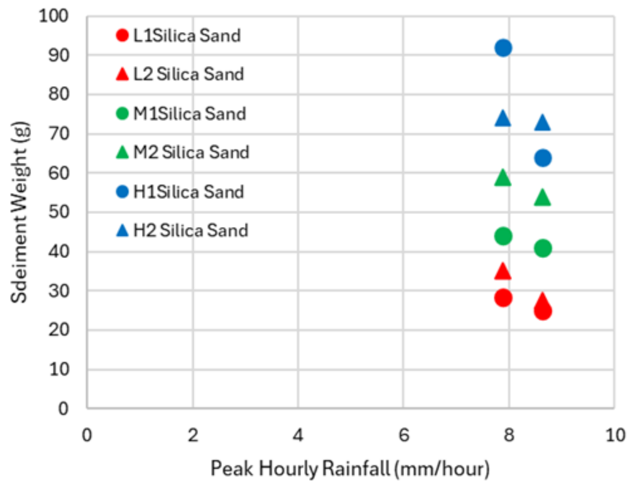
data point represents the erosion response at different canopy elevations, categorized as low (L1, L2), medium (M1, M2), and high (H1, H2).

In the decomposed granite graph, sediment weight increases with accumulated rainfall, with higher elevations (H1 and H2) exhibiting the most significant erosion rates. This trend suggests that rainfall impact is more pronounced at higher canopy positions, leading to greater soil displacement. In contrast, lower canopy positions (L1 and L2) experience reduced erosion, likely due to greater interception of rainfall energy.

Similarly, in the silica sand graph, a comparable pattern emerges, with higher elevations accumulating greater sediment weight than lower positions. However, the total sediment weight for silica sand remains lower than that of decomposed granite under similar rainfall conditions, indicating a difference in soil stability and resistance to erosion.



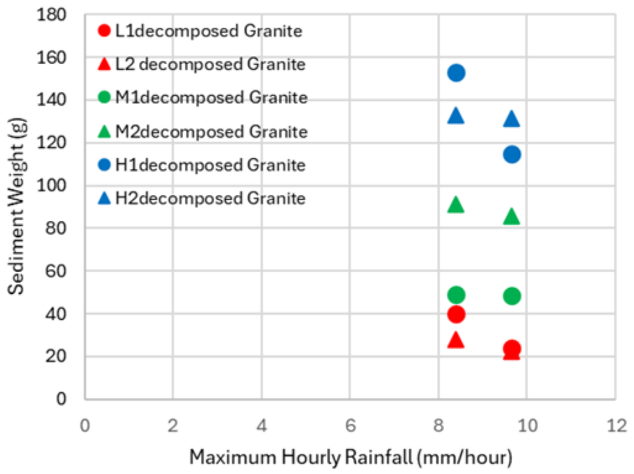
(a) The scatter plot compares sediment weight across peak hourly rainfall for Decomposed Granite.



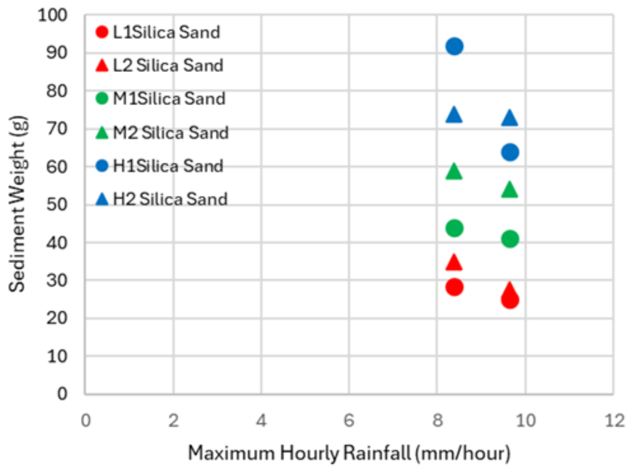
(b) The scatter plot compares sediment weight across peak hourly rainfall for Silica Sand.

Figure 7 Scatter plots show the relationship between sediment weight and peak hourly rainfall for two soil types.

The figures (Figures 6a and 6b) illustrate the relationship between sediment weight, canopy elevation, and peak 10-minute rainfall during the second and third phases (3.81 mm and 2.28 mm, respectively) for both decomposed granite and silica sand. These results highlight key differences in erosion susceptibility between the two soil types. In both cases, sediment yield increases with canopy elevation within the boxes, underscoring the significant influence of elevation on erosion processes during short-duration, high-intensity rainfall. However, decomposed granite consistently exhibits higher sediment displacement than silica sand, suggesting greater vulnerability to rainfall impact due to differences in particle size, cohesion, and permeability. Elevation-based trends indicate that higher canopy elevations from placed soil within the boxes (H1, H2) generate the highest sediment yield for both soil types, likely due to increased rainfall KE or reduced canopy interception effectiveness at these sites. Middle elevations of canopy within the boxes (M1, M2) exhibit mod-



(a) The scatter plot compares sediment weight across maximum hourly rainfall for Decomposed Granite.



(b) The scatter plot compares sediment weight across maximum hourly rainfall for Silica Sand.

Figure 8 Scatter plots showing the relationship between sediment weight and maximum hourly rainfall for two soil types.

erate erosion rates, while lower elevations of canopy from the placed boxes (L1, L2) consistently show the least sediment displacement. This pattern suggests that lower canopy elevations more effectively attenuate rainfall energy, reducing erosion potential.

Similarly, the graphical analysis (Figures 7a and 7b) of sediment weight in relation to peak hourly rainfall and canopy elevation from the boxes for decomposed granite and silica sand reveals distinct patterns of sediment transport influenced by soil type and rainfall intensity. The peak hourly rainfall was recorded at 8.63 mm during the first phase and 7.87 mm during the second phase, highlighting the significant role of rainfall intensity in sediment displacement. For decomposed granite, sediment weight exhibits a strong positive correlation with increasing peak hourly rainfall across different canopy elevations. Higher rainfall intensities, particularly at the H1 and H2 canopy elevations, result in significantly elevated sediment yields, reaching peak values. This suggests a pronounced erosive response under intense rainfall, especially at higher canopy elevations where KE is greater. In contrast, the L1 and L2 samples consistently show lower sediment yields, indicating reduced erosion due to the mitigating effect of lower canopy elevation and weaker rainfall impact. For silica sand, sediment weight also increases with peak hourly rainfall, but the rate of increase is more uniform across different rainfall intensities. The granular nature of silica sand facilitates greater sediment transport even under moderate rainfall conditions. However, peak sediment yields for the H1 and H2 samples remain lower compared to decomposed granite, suggesting relatively lower erosion susceptibility.

The results presented in Figures 8a and 8b illustrate the relationship between maximum hourly rainfall intensity, 9.65 mm during the first phase and 8.38 mm during the second phase, and sediment yield for decomposed granite and silica sand across different canopy elevations. A distinct trend emerges, showing that increased rainfall intensity at higher canopy elevations corresponds to greater sediment yield, highlighting the critical role of rainfall KE in driving soil erosion. Notably, the highest sediment yield is observed at the H2 position for decomposed granite, suggesting that upper canopy elevation sites experience greater erosion due to increased rainfall impact. In contrast, lower elevation positions (L1, L2) consistently exhibit reduced sediment displacement, indicating that lower canopy interception effectively attenuates the KE of raindrops, thereby minimizing soil detachment. Furthermore, silica sand shows a relatively lower sediment yield compared to decomposed granite under similar conditions, reflecting differences in particle cohesion and infiltration capacity. This suggests that while both soil types are affected by rainfall intensity and canopy elevation, decomposed granite is more susceptible to erosion due to its coarser texture and lower cohesion.

Despite a slightly higher total rainfall of 44.19 mm in the second phase, the weight of eroded soil was lower compared to the 40.64 mm of rainfall in the third phase over 24 hours. However, the extended duration of 32 hours in the third phase appears to have resulted in increased soil erosion by weight, highlighting the impact of prolonged rainfall periods. Moreover, continuous rainfall generally accelerates soil erosion compared to intermittent rainfall, which slows the saturation process (Li et al., 2019). On the other hand, canopy interception is crucial for effective rainfall management, significantly influenced by rainfall intensity and rainfall duration (Wang and Guo, 2024). Further analysis, consistently applied across both phases of rainfall data collection, reveals that decomposed granite exhibited higher sediment yield across all canopy elevations compared to silica sand. The erosion patterns for both soil types followed a clear trend, with the highest erosion occurring at high-elevation points (H), moderate erosion at mid-elevation points (M), and the lowest erosion at low-elevation points (L).

Additionally, in rainfall-induced surface erosion experiments, decomposed granite is selected due to its similarity to natural soil conditions, allowing for a realistic replication of erosion mechanisms. In contrast, silica sand is primarily utilized for its uniform particle size, which facilitates the observation of soil particle movement, thereby enhancing the reproducibility and objectivity of the experiment. This characteristic is particularly advantageous in educational settings, where the clear visualization of sediment transport processes is essential. To ensure precise quantification of soil erosion, the eroded soils from designated areas were collected. To obtain accurate weight measurements, a Shinko heating machine was employed, which circulates and pumps hot air to effectively remove moisture from the samples. The collected soil samples were placed in a drying oven at a controlled temperature for 24 hours until fully desiccated, after which their weight was measured. Following the drying process, the soil samples were weighed to assess erosion dynamics under canopy elevation.

4 CONCLUSION

This study underscores the significant influence of canopy elevation on soil erosion rates. The findings reveal that higher canopy elevations (H1, H2) result in greater erosion, likely due to increased rainfall KE, while lower canopy elevations (L1, L2) exhibit reduced erosion, suggesting a protective effect against rainfall impact. Additionally, the comparison of soil types—decomposed granite and silica sand—demonstrated that decomposed granite is more prone to erosion due to its coarser texture. The extended rainfall duration in the third phase further highlighted the role of rainfall duration in exacerbating erosion. These results emphasize the importance of canopy elevation in determining soil erosion rates, contributing valuable insights into erosion processes under varying canopy heights.

Future studies should investigate the role of leaf type, leaf density, canopy structure, and openness at different elevations to provide further insights into how canopy characteristics influence soil stability and erosion.

DISCLAIMER

The authors declare no conflict of interest.

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