

Naturally grown understory vegetation after thinning reduces throughfall erosivity in Japanese coniferous plantations

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Abstract

Naturally grown understory vegetation after thinning can potentially mitigate throughfall erosivity. In this study, we observed throughfall kinetic energy (*TKE*) under the overstory canopies of Japanese cypress (*Chamaecyparis obtusa* Endl.) plantations in Fukuoka, Japan, using 12 sand-filled splash cups in each of three study plots, T_1 – T_3 , with different stem densities (*SD*) (T_1 : 1000 stems ha^{-1} , T_2 : 2400 stems ha^{-1} , and T_3 : 2900 stems ha^{-1}). T_1 was thinned and covered with naturally grown understory vegetation, whereas T_2 and T_3 were unthinned, resulting in an absence of understory vegetation. We also measured *TKE* beneath the understory vegetation of T_1 (T_{1U}) with 12 sand-filled splash cups, as well as free kinetic energy (*FKE*) in the nearby open space (**OP**) with four sand-filled splash cups as controls. The results showed that all stand-scale throughfall kinetic energy ($\overline{TKE}$) values were much higher than *FKE*. $\overline{TKE}$ was highly correlated with stand-scale throughfall in all study plots ($R^2 > 0.88$, $p < 0.001$). The $\overline{TKE}$ beneath the understory vegetation in T_{1U} was approximately half that under the overstory canopies in T_1 (406.6 vs. 772.1 $J\ m^{-2}$). This suggests that the understory vegetation layer decreased *TKE* by decreasing raindrop fall velocity. For the overstory canopies, the entire period unit rainfall stand-scale *TKE* in T_1 ($u\overline{TKE}_{total,1}$) of 17.1 $J\ m^{-2}\ mm^{-1}$ was much higher than that in T_2 ($u\overline{TKE}_{total,2}$) and T_3 ($u\overline{TKE}_{total,3}$), whereas the $u\overline{TKE}_{total,2}$ and $u\overline{TKE}_{total,3}$ of 11.4 and 11.1 $J\ m^{-2}\ mm^{-1}$, respectively, were similar because of the negative relationship between *SD* and $u\overline{TKE}_{total}$ ($r = -0.658$, $p = 0.028$). After thinning, naturally grown understory vegetation is important for soil conservation in Japanese cypress plantations. Our study further improves our knowledge of the mechanisms determining splash soil erosion processes and provides new insights into forest management strategies for soil conservation.

Key words: *Chamaecyparis obtusa*, Splash soil erosion, Thinning, Throughfall kinetic energy, Understory vegetation

1. Introduction

Splash soil erosion is the dominant soil erosion process among the four types of soil erosion (splash, sheet, rill, and gully) and is the initial stage in forest ecosystems (Miura *et al.*, 2002; Nanko *et al.*, 2004). When rainwater passes through a canopy, throughfall (*TF*) is partitioned into free and released *TF* (*TF* drips and splash water droplets). The size of their raindrops varies considerably depending on the forest stand structure (Levia *et al.*, 2017, 2019). Droplets from the leaves and branches coalesce within the canopy as a *TF* drip, which are three to five times larger than freefall raindrops, considerably increasing their erosive power on the forest floor (Tsukamoto, 1976; Nanko *et al.*, 2004). The throughfall kinetic energy (*TKE*) is a widely used indicator for estimating raindrop erosivity and predicting the soil erosion rate (Zhou *et al.*, 2002; Scholten *et al.*, 2011; Liu *et al.*, 2018a, b; Shinohara *et al.*, 2018; Song *et al.*, 2018). *TKE* is determined by the size, momentum, velocity, and number of raindrops, which can be changed by *TF* partitioning (Nanko *et al.*, 2006, 2008a, b; Katayama *et al.*, 2023). *TKE* can considerably increase under specific forest stand structures. For example, severe soil erosion can occur in forests where the floor is largely denuded without understory vegetation (shrubs, herbaceous plants, or both), even if the overstory canopies are well developed (Nanko *et al.*, 2008a; Miura *et al.*, 2015; Shinohara *et al.*, 2018). Thus, understanding whole forest stand structures, including understory vegetation, is essential for mitigating soil erosion in forest ecosystems (Thornes, 1990; Morgan, 2005).

In Japan, two dominant coniferous species (Japanese cypress [*Chamaecyparis obtusa* Endl.] and Japanese cedar [*Cryptomeria japonica*]) were planted primarily after World War II to meet the high demand for timber (Komatsu *et al.*, 2010). These plantations have not been appropriately managed through thinning and pruning since 1980 because of the economic recession in forestry caused by falling timber prices and enhanced labor costs (Onda *et al.*, 2010). This has resulted in low light conditions under dense overstory canopies that hinder the growth of understory vegetation, leading to sparse or no understory vegetation, especially in Japanese cypress plantations (Miura *et al.*, 2002;

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Fukuyama *et al.*, 2005; Onda *et al.*, 2010). The leaf litter of Japanese cypress on the forest floor decays readily over time (Yamashita *et al.*, 1998); therefore, soil erosion presents a serious problem in unmanaged Japanese cypress plantations (Miura *et al.*, 2002, 2003, 2015; Nanko *et al.*, 2008a; Miyata *et al.*, 2009).

Over the past decade, studies on *TKE* in Japanese cypress plantations have advanced chronologically, such as the development of a stand-scale unit *TKE* model for plantations using determinant forest stand structure parameters (crown length and bottom height; Nanko, 2013) and the discovery of additional influential factors on *TKE* (first branch height [H_b] and *TF*; Shinohara *et al.*, 2018). However, the changes in *TKE* with different stem density (*SD*) values induced by forest operations, such as thinning, has remained unexamined, although *TKE* has been observed in many Japanese cypress plantations with varying *SD* values (Nanko, 2013; Shinohara *et al.*, 2018; Jeong *et al.*, 2024). Furthermore, these studies only considered overstory canopies despite understory vegetation potentially protecting soil surfaces (Miura, 2003, 2015).

Forest thinning fundamentally alters stand structure to enhance the growth of residual trees. This process increases light transmission owing to a reduced overstory canopy, which stimulates the growth of understory vegetation (Tsai *et al.*, 2018; Ide *et al.*, 2016; Li *et al.*, 2019; Wang *et al.*, 2021; Su *et al.*, 2024). The impact of *TF* raindrops on the forest floor after passing through overstory canopies can be mitigated by understory vegetation (Miura, 2003, 2015; Ghahramani *et al.*, 2011; Liu *et al.*, 2018b; Song *et al.*, 2020). Yamagishi *et al.* (2022)

reported a decrease in soil splash detachment under shrub layers in mature Japanese cypress plantations and highlighted the importance of shrub layers in mitigating soil erosion. However, to our best knowledge, no study has examined the effect of naturally grown understory vegetation, including herbaceous plants, after thinning on *TKE* in such plantations.

In this study, we observed *TKE* in Japanese cypress plantations using sand-filled splash cups. The aims of this study were to (1) quantitatively characterize *TKE* in Japanese cypress plantations and (2) examine the effects of naturally grown understory vegetation after thinning on *TKE*. Therefore, we established three plots (T_1 , T_2 , and T_3) with different forest stand structures: T_1 with overstory and understory vegetation (shrub and herbaceous plants), and T_2 and T_3 with an overstory canopy and negligible understory vegetation. The effects of forest stand structure on *TKE* were examined by comparing the *TKE* values in the three plots for the overstory canopy. The effects of thinning on *TKE* were comprehensively examined by comparing *TKE* in T_1 (TKE_1) for the overstory canopy and TKE in T_{1U} (TKE_{1U}) for the understory vegetation.

2. Materials and methods

2.1. Study site

This study was conducted in Japanese cypress plantations at the Takada Experimental Site in the Kasuya Research Forest, Kyushu University, Fukuoka, Japan (33°38'N, 130°31'E, c.a. 100 m a.s.l.) (Fig. 1). The mean annual temperature and precipitation from 1986 to 2020 were 17.2 °C and 1663.0 mm,

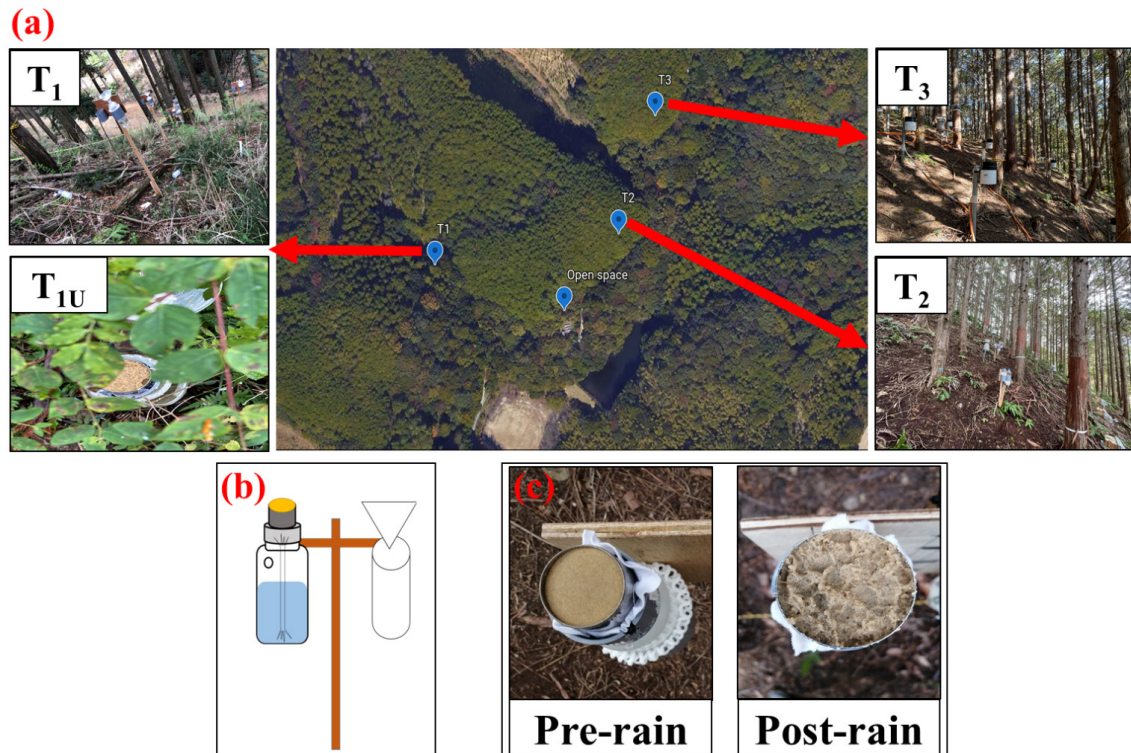


Fig. 1. (a) Location of the study plots and open space, and photos captured at each study plot; (b) measurements of loss of sand (left) and throughfall (right); (c) difference in sand-filled splash cups pre- and post-rain. T_1 , T_{1U} , T_2 , and T_3 denote plot 1 for overstory canopy, plot 1 for understory vegetation, plot 2 for overstory canopy, and plot 3 for overstory canopy in Japanese cypress plantations. (b) is adapted with permission from Jeong *et al.* (2024).

respectively, measured at the Fukuoka meteorological observatory 7 km from the study site. In this region, the rainy season is from June to September, and the snow season is from December to February (Shinohara *et al.*, 2010). The rainy season accounts for approximately 60% of the annual precipitation, and snowfall rarely occurs (Shinohara *et al.*, 2010; Jeong *et al.*, 2019). The soil type is classified as brown forest soil derived from serpentine bedrock (Jeong *et al.*, 2022). Serpentine, a hydrous, magnesium-rich silicate mineral ($\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$), typically contains 32–38% MgO and 35–40% SiO_2 , along with trace amounts of Fe, Al, Ca, Cr, and Ni (Wicks and O'Hanley, 1988). The soil texture is loamy sand, with a bulk density of 0.91 g cm^{-3} and soil organic matter content of 13.07%. More detailed soil properties at the study site is provided in Farahnak *et al.* (2019).

Three $10 \times 10\text{-m}$ plots were established on relatively steep slopes ($29\text{--}32^\circ$) in each study plot (Fig. 1a). For T_1 , approximately 34% of the initial planting density of c.a. 3000 stems ha^{-1} was thinned once in 2015 after being planted in 1955 within a sub-compartment of approximately 6.8 ha. During the study period, T_1 contained 10 Japanese cypress trees (stem density (SD): 1000 stems ha^{-1}) and naturally grown biologically diverse understory vegetation with shrubs (*Damnacanthus macrophyllus*, *Zanthoxylum piperitum*, *Anodendron affine*, *Callicarpa mollis*, *Rubus buergeri*, and *Rubus palmatus* var. *palmatus*) and herbaceous plants (*Miscanthus sinensis*, *Dicranopteris linearis*, *Gleichenia japonica*, and fern). For T_2 and T_3 , no thinning was performed after planting in 1985 and 1984, respectively, and understory vegetation was negligible. T_2 and T_3 contained 24 and 35 Japanese cypress trees, respectively (SD : 2400 and 3500 stems ha^{-1}). Six dead standing trees in T_3 were excluded from the calculation of forest stand structure because of the negligible effect of dead standing trees on TF (Jeong *et al.*, 2022). The detailed forest stand structures of T_1 , T_{1U} , T_2 , and T_3 are provided in Table 1, with photographs captured in each study plot shown in Fig. 1a.

2.2. Measurement of forest stand structure

Canopy cover (CC) and plant area index (PAI) were measured on an overcast day to prevent direct sunlight at all sampling points from disturbing the manual-type throughfall rain gauges and sand-filled splash cups in each study plot using an omnidirectional camera fitted with a fisheye lens (THETA SC; Ricoh Co. Ltd., Tokyo, Japan). CC and PAI were calculated from the images using a Gap Light Analyzer ver. 2.0 (Frazer *et al.*, 1999).

Tree height (H), crown bottom height (CBH), crown length (CL), and the first branch height (H_b) from the floor were measured using a hypsometer (Haglöf Vertex IV-360, Haglöf Inc., Madison, MS, USA).

In addition, the height of the understory vegetation near the sand-filled splash cups for TKE_{1U} was measured using a measuring rod, and the mean height was calculated using data collected in July, October, and November 2021.

2.3. Gross rainfall and throughfall measurement

The gross rainfall (GR) and throughfall (TF) were measured over six months, from May to November 2021.

The GR was measured on an event basis using four manual-type rain gauges (GR_M), which were storage-type rain gauges using funnels with a diameter of 12.0 cm, in an open space approximately 50 m west of T_2 (Fig. 1a, b). The GR was also measured using a tipping-bucket rain gauge with a resolution of 0.2 mm ($GR_{0.2}$) (HOBO RG3-M rain gauge, Onset Computer, Bourne, MA, USA) connected to an Onset HOBO Event data logger installed at the top of a 2-m tower next to the GR_M measurement (Fig. 1b). $GR_{0.2}$ was strongly correlated with GR_M ($GR_{0.2} = 0.97 GR_M$; $R^2 > 0.98$). A rainfall event was classified as a separate event when the rainfall duration exceeded 8 h with no rainfall after its cessation (Shinohara *et al.*, 2015; Jeong *et al.*, 2022). In this study, we used GR_M for the GR amount and $GR_{0.2}$ to count rainfall events for our analysis. Seven datasets ($n = 7$) were obtained during the study period; three sets included one rainfall event, three sets included two rainfall

Table 1. Forest stand structures of three study plots (T_1 , T_2 , and T_3) established in Japanese cypress plantations. T_{1U} denotes the characteristics of understory vegetation including plant area index (PAI), understory vegetation height, and canopy cover ratio (CC) in T_1 .

Forest stand structure	T_1	T_{1U}	T_2	T_3
Age (year)	67		37	38
Slope angle ($^\circ$)	32		30	29
No. standing-live trees	10		24	35
No. standing-dead trees	0		0	6
Stem density (SD , stems ha^{-1})	1000		2400	2900
Diameter at breast height (DBH , cm)	28.2 ± 4.5		19.4 ± 3.4	17.5 ± 3.0
Basal area (BA , $\text{m}^2 \text{ha}^{-1}$)	62.5		70.6	76.1
Tree height (H , m)	21.2 ± 2.0		14.2 ± 1.1	12.5 ± 1.0
Crown length (CL , m)	7.1 ± 1.9		4.6 ± 1.0	4.0 ± 1.1
Crown bottom height (CBH , m)	14.1 ± 1.9		9.7 ± 0.9	8.5 ± 0.7
First branch height (H_b , m)	7.7 ± 5.7		2.5 ± 0.4	2.6 ± 0.6
Plant area index (PAI , $\text{m}^2 \text{m}^{-2}$)	2.2 ± 0.2	2.9 ± 0.8	3.9 ± 0.3	3.5 ± 0.3
Understory vegetation height (cm)		53.9 ± 31.7	–	–
Canopy cover ratio (CC , %)	80.0 ± 2.2	87.0 ± 6.0	93.8 ± 1.0	92.3 ± 1.1

Data are given as average $\pm$ standard deviation.

events, and one set included four rainfall events (Table 2).

For TF measurements, 12 manual-type rain gauges identical to GR_M measurements were set in each study plot, of which three were randomly deployed in each 5×5 -m internal quarter sub-plot. This random arrangement was maintained throughout the study period. The manual-type rain gauges for TF measurement were placed approximately 160 cm above ground for T_1 to avoid splashes from nearby understory vegetation and approximately 80 cm above ground in T_2 and T_3 to avoid splashes from the forest floor's ground. At T_{IU} , they were placed beneath the understory vegetation approximately 30 cm above the ground (Fig. 1a).

2.4. Loss of sand for kinetic energy

The sand-filled splash cup invented by Scholten *et al.* (2011) has been widely used for TKE measurements because it is a reasonable, convenient, and sufficiently accurate piece of equipment (Goebes *et al.*, 2015; Liu *et al.*, 2018a; Shinohara *et al.*, 2018; Katayama *et al.*, 2023). In this study, we employed a commercially available stainless steel soil sampler with a diameter of 5.0 cm, height of 5.1 cm, and volume of 100 cm³ as a sand-filled splash cup (Fig. 1c), which was used by Shinohara *et al.* (2018) based on the concept of Tübingen splash cups (Scholten *et al.*, 2011). We utilized Toyoura standard sand, characterized by soil particles ranging in size from 100 to 250 μ m, which constituted > 80% of the mass (Kosugi *et al.*, 2004; Shinohara *et al.*, 2018). A splash cup was filled with oven-dried Toyoura standard sand (total mass of the sand: 155–160 g) (Kosugi *et al.*, 2004; Shinohara *et al.*, 2018). During the in situ measurements, the sand in the splash cup was saturated with distilled water. The sand-filled splash cups were set next to the manual-type rain gauges (4 splash cups in the open space and 12 splash cups in each study plot) (Fig. 1b, c). These sample sizes are considered reliable for stand-scale TKE estimation because Jeong *et al.* (2024) reported that 6–15 sand-filled splash cups are suitable for stand-scale TKE measurements in Japanese cypress plantations, with a 5–10% potential error. After the in

situ TKE measurement, we dried the sand-filled splash cups in a laboratory oven at 105 °C for 24 h and weighed the oven-dried sand (Liu *et al.*, 2018a). The loss of sand (LoS , g) was calculated from the difference in the mass of the oven-dried sand before and after the in situ TKE measurement. KE (J m⁻²) was calculated as follows (Shinohara *et al.*, 2018):

$$KE = 79.20 \times LoS \quad (1)$$

Using Equation (1), we estimated the freefall kinetic energy (FKE) in the open space (**OP**) and the throughfall kinetic energy (TKE) for each study plot. Seven datasets were obtained between May and November 2021 (Table 2). In total, data from 364 splash cups (28 for FKE and 336 for TKE) were collected.

2.5. Stand-scale throughfall, throughfall kinetic energy, and unit throughfall kinetic energy

The stand-scale throughfall and stand-scale throughfall kinetic energy are the arithmetic averages of TF and TKE during the measurement period in a plot, respectively.

$$\overline{TF} = \frac{\sum_{i=1}^m TF_i}{m} \quad (2)$$

$$\overline{TKE} = \frac{\sum_{i=1}^m TKE_i}{m} \quad (3)$$

where $\overline{TF}$ is the stand-scale throughfall (mm), $\overline{TKE}$ is the stand-scale throughfall kinetic energy (J m⁻²), and m is the number of measurements taken from the plot (typically 12).

The unit rainfall stand-scale throughfall kinetic energy is the stand-scale throughfall kinetic energy per 1 mm of GR in the plot (Nanko *et al.*, 2008b, 2015).

$$u\overline{TKE} = \frac{\overline{TKE}}{GR} \quad (4)$$

where $u\overline{TKE}$ is the unit rainfall stand-scale throughfall kinetic energy (J m⁻² mm⁻¹). The entire period $u\overline{TKE}$ was calculated as follows:

Table 2. Loss of sand (LoS) and stand-scale throughfall ($\overline{TF}$) in the three plots (T_1 with understory vegetation [T_{IU}], T_2 , and T_3) and an open space (**OP**). Mean values and coefficient of variation (CV; in parentheses) are shown for each rain event.

	Event	Period	OP	T_1	T_{IU}	T_2	T_3
LoS (g)	1	19–21 May 2021	7.3	16.0 (14.1)	10.0 (55.7)	11.2 (15.4)	11.3 (14.8)
	2	25–27 May 2021	1.4	5.8 (12.1)	3.1 (60.9)	3.6 (29.2)	3.5 (21.5)
	3	19 July ~ 02 Aug 2021	8.7	16.5 (17.9)	6.9 (57.3)	12.8 (13.0)	11.1 (31.4)
	4	07–08 Sep 2021	1.2	5.3 (21.3)	3.0 (50.1)	3.4 (14.7)	3.2 (28.5)
	5	11–18 Oct 2021	0.1	1.1 (47.9)	0.7 (81.4)	0.6 (44.6)	0.9 (59.0)
	6	05–09 Nov 2021	4.3	13.9 (18.9)	6.8 (69.2)	8.6 (30.5)	9.1 (28.6)
	7	09–24 Nov 2021	1.4	9.6 (12.6)	5.5 (54.1)	5.6 (26.5)	5.1 (24.7)
$\overline{TF}$ (mm)	1	19–21 May 2021	85.3	70.1 (10.7)	62.0 (27.2)	47.2 (13.2)	41.3 (11.1)
	2	25–27 May 2021	26.2	19.0 (11.1)	16.4 (29.5)	12.2 (21.8)	11.0 (13.4)
	3	19 July ~ 02 Aug 2021	75.2	67.6 (14.9)	61.2 (40.7)	48.6 (8.5)	40.8 (12.5)
	4	07–08 Sep 2021	18.0	14.7 (11.2)	12.9 (23.6)	10.3 (23.6)	9.2 (14.2)
	5	11–18 Oct 2021	7.2	4.4 (16.9)	3.9 (33.7)	3.0 (21.7)	3.0 (21.7)
	6	05–09 Nov 2021	66.4	51.2 (15.1)	46.0 (23.4)	34.3 (16.2)	30.8 (12.9)
	7	09–24 Nov 2021	38.6	29.0 (16.2)	25.4 (16.5)	20.6 (21.3)	18.5 (16.7)

$$\overline{uTKE}_{total} = \frac{\sum_{j=1}^n \overline{TKE}_j}{\sum_{j=1}^n GR_j} = \frac{\overline{TKE}_{total}}{GR_{total}} \quad (5)$$

where $\overline{uTKE}_{total}$ is the entire period unit rainfall stand-scale throughfall kinetic energy ($J m^{-2} mm^{-1}$) and n is the number of data sets ($n = 7$).

The $\overline{uTKE}$ is a valuable index for evaluating the effect of overstory canopy structure on TKE (Nanko, 2013; Liu *et al.*, 2018b; Katayama *et al.*, 2023; Jeong *et al.*, 2024). In addition, $\overline{uTKE}$ is an appropriate index to use because some of the datasets in this study included more than one rain event (Liu *et al.*, 2018b; Jeong *et al.*, 2024).

2.6. Statistical analysis

The total GR (GR_{total}) and $\overline{TF}$ ($\overline{TF}_{total}$) data collected during the study period were examined to determine the impact of overstory canopies and understory vegetation on $\overline{TF}_{total}/GR_{total}$ (%) in each study plot. To compare the distribution of kinetic energy ($J m^{-2}$) in terms of free kinetic energy (FKE) in **OP** and TKE across different study plots, box plots with the maximum, mean, median, interquartile range, minimum, and potential outliers were utilized. The relationships between $\overline{TKE}$ and $\overline{TF}$ for each study plot were analyzed using linear regression, and the coefficients of determination were calculated to assess the strength of these correlations. One-way analysis of variance (ANOVA) followed by Tukey's post hoc test were used to test for significant differences in the ratio of LoS to $\overline{TF}$ ($LoS / \overline{TF}$) among each study plot. Pearson's correlation coefficient was used to examine the correlation between $\overline{uTKE}_{total}$ and SD across various Japanese cypress plantations using the previous data

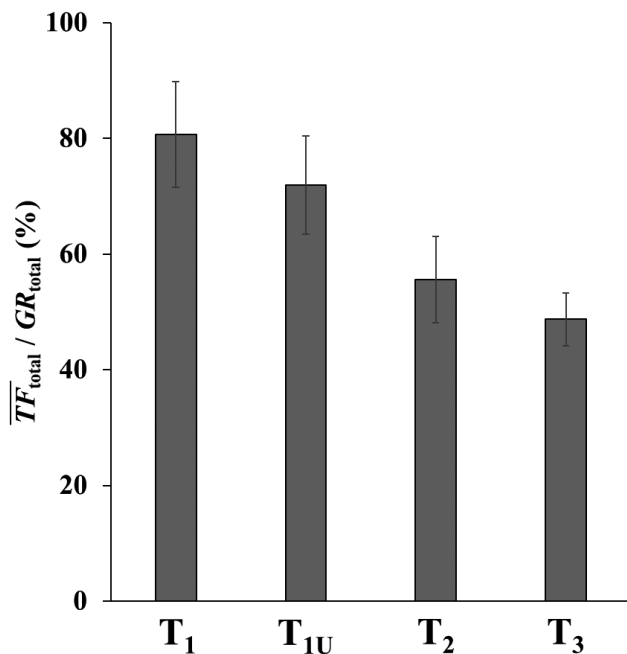


Fig. 2. Comparison of the ratio of the entire period total throughfall ($\overline{TF}_{total}$, mm) with total gross rainfall (GR_{total} , mm) ($\overline{TF}_{total}/GR_{total}$, %) among the study plots (T₁, T_{1U}, T₂, and T₃) in Japanese cypress plantations. The bars indicate the standard deviation.

obtained from Nanko (2013) and Jeong *et al.* (2024), including the current data (see Table S1). A significance level of $p < 0.05$ was considered for all analyses, and all statistical analyses were performed in SPSS Ver. 27.0 and Microsoft Excel 2016.

3. Results and discussion

3.1. Gross rainfall and throughfall

The total gross rainfall (GR_{total}) for the seven data sets was 316.9 mm (range: 7.2–85.3 mm with a mean of 45.3 mm), which accounted for 22.3% of the 25-year mean annual precipitation (1663.0 mm) in this region.

The total stand-scale throughfall ($\overline{TF}_{total}$) values, which were influenced by the overstory canopy for T₁ ($\overline{TF}_{total,1}$), T₂ ($\overline{TF}_{total,2}$), and T₃ ($\overline{TF}_{total,3}$), were 255.8 mm (80.7% of GR_{total}), 176.2 mm (55.6%), and 154.5 mm (48.8%), respectively (Fig. 2). As TF/GR (%) has a strongly negative relationship with SD in Japanese coniferous plantations (Sun *et al.*, 2017; Shinohara *et al.*, 2018; Jeong *et al.*, 2019), the $\overline{TF}_{total}/GR_{total}$ in T₁ with the lowest SD among the study plots, was greater than that of T₂ and T₃ (Table 1 and Fig. 2).

The understory vegetation of T_{1U} decreased TF by 8.8% before and after passing through the understory vegetation; $\overline{TF}_{total,1}/GR_{total}$ was 80.7%, whereas $\overline{TF}_{total,1U}/GR_{total}$ was 71.9% (Fig. 2). Tanaka *et al.* (2005) found that TF from overstory canopies was decreased by understory shrub layers in Japanese cypress plantations. This decrease occurred because TF from the overstory canopies was intercepted and redistributed by the understory shrub layers. Additionally, when herbaceous plants are present beneath shrubs, they can contribute to a decrease in TF (Jiang *et al.*, 2019).

3.2. Free kinetic energy and throughfall kinetic energy

The free kinetic energy (FKE) in the open space (**OP**) ranged from 3.6 to 687.9 $J m^{-2}$, with a mean of 274.6 $J m^{-2}$ and a coefficient of variation of 97.1%. All the stand-scale throughfall kinetic energy ($\overline{TKE}$) values for overstory canopies were much higher than those of FKE : $\overline{TKE}_1$ (772.1 $J m^{-2}$), $\overline{TKE}_2$ (517.4 $J m^{-2}$), and $\overline{TKE}_3$ (501.0 $J m^{-2}$) were 2.8-, 1.9-, and 1.8-fold higher than FKE , respectively (Fig. 3). Overstory canopies produce larger drops as leaf drips (Nanko *et al.*, 2004, 2008b; Shinohara *et al.*, 2018; Liu *et al.*, 2018a, b; Goebes *et al.*, 2015). Tsukamoto (1976) reported that TKE was greater than FKE when CBH was higher than 4–5 m. Nanko *et al.* (2004) also reported that TKE was more than 2-fold higher than FKE in Japanese plantations.

Although the stand-scale throughfall kinetic energy beneath understory vegetation $\overline{TKE}_{1U}$ (406.6 $J m^{-2}$) in T₁ was also 1.5-fold higher than that for FKE ; it was approximately half of $\overline{TKE}_1$, possibly due to the reduction in $\overline{TF}/GR$ (%) (Fig. 3).

$\overline{TKE}$ showed strong linearity with $\overline{TF}$ in the Japanese cypress plantations (coefficients of determination for T₁, T_{1U}, T₂, and T₃ were 0.97, 0.88, 0.99, and 0.99, respectively) (Fig. 4). This supports the finding that TF is a dominant factor in TKE in Japanese cypress plantations (Shinohara *et al.*, 2018) and rubber-based agroforestry systems (Liu *et al.*, 2018b).

The ratio of LoS to $\overline{TF}$ ($LoS/\overline{TF}$) was similar for the overstory vegetation (T₁:0.29, T₂:0.26, and T₃:0.30), which was consistent

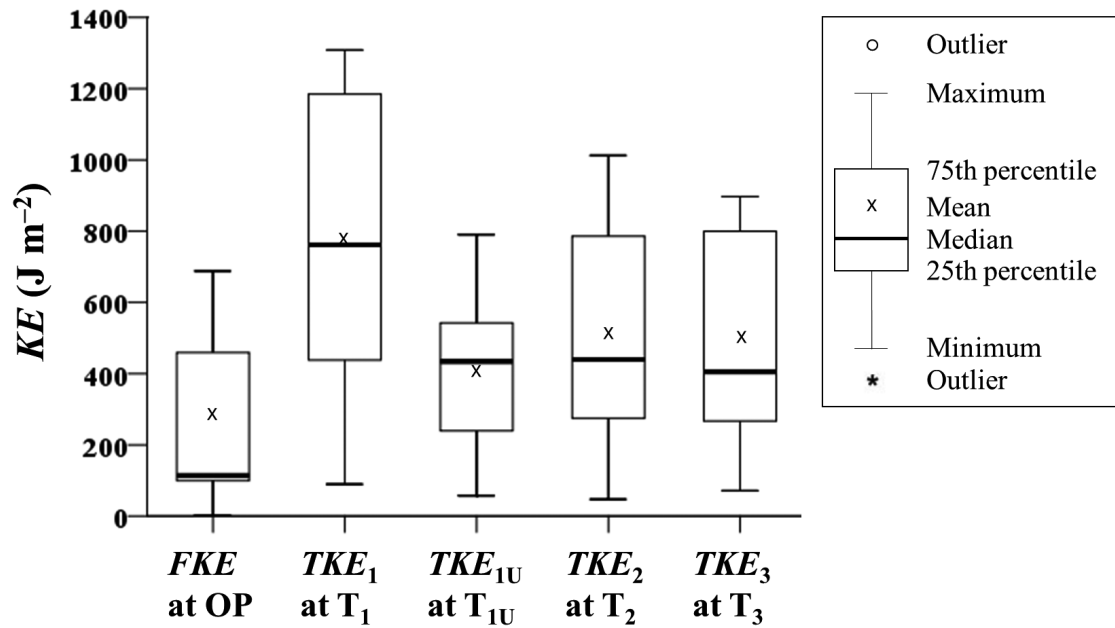


Fig. 3. Comparison of kinetic energy (KE) for free kinetic energy (FKE) in open space (OP) and throughfall kinetic energy (TKE) in each study plot of T₁ (TKE₁), T_{1U} (TKE_{1U}), T₂ (TKE₂), and T₃ (TKE₃).

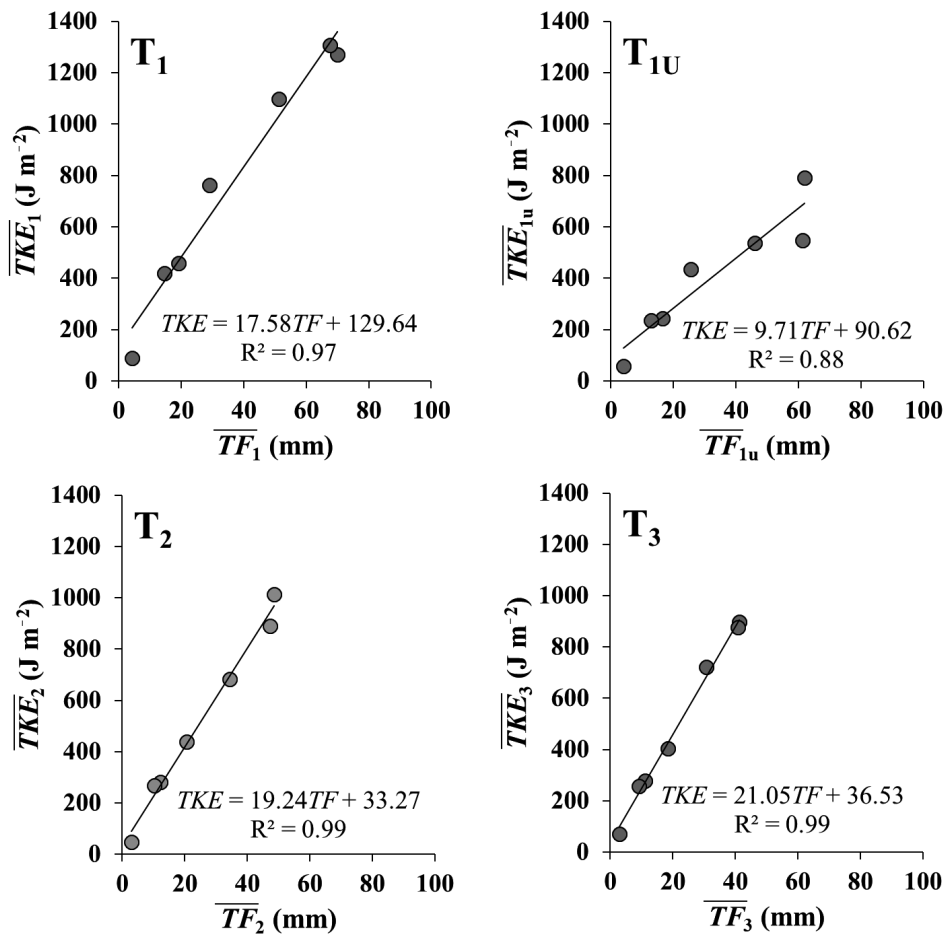


Fig. 4. Relationship between stand-scale throughfall ($\overline{TF}$) and throughfall kinetic energy ($\overline{TKE}$) in T₁, T_{1U}, T₂, and T₃. The black solid line represents the regression line.

with the finding that no significant difference was observed in $LoS/\overline{TF}$, even under significantly different TF values in Japanese cypress plantations (Shinohara *et al.*, 2018). However, the $LoS/\overline{TF}$ of 0.18 for the understory vegetation in T_{IU} was significantly smaller than that in the other study plots (ANOVA followed by Tukey's test, $p < 0.05$) (Fig. 5). This suggests that the understory vegetation layer reduced the raindrop fall velocity.

3.3. Unit rainfall stand-scale throughfall kinetic energy and forest stand structure

For the overstory canopies, the unit rainfall stand-scale throughfall kinetic energy was determined for each event using Equation (4); $u\overline{TKE}_1$, $u\overline{TKE}_2$, and $u\overline{TKE}_3$ were 17.4 ± 3.4 , 11.1 ± 2.6 , and $11.2 \pm 1.4 \text{ J m}^{-2} \text{ mm}^{-1}$, respectively. The entire period unit rainfall stand-scale throughfall kinetic energy was determined using Equation (5); $u\overline{TKE}_{total,1}$, $u\overline{TKE}_{total,2}$, and $u\overline{TKE}_{total,3}$ were 17.1, 11.4, and $11.1 \text{ J m}^{-2} \text{ mm}^{-1}$, respectively (Fig. 6). The value of $u\overline{TKE}_{total,1}$ was within the range of those reported for Japanese cypress plantations in Nanko (2013) ($u\overline{TKE}_{total}$ range: $16.4\text{--}28.2 \text{ J m}^{-2} \text{ mm}^{-1}$ with a mean of $19.7 \text{ J m}^{-2} \text{ mm}^{-1}$, SD range: $670\text{--}2675$ with a mean of $1658 \text{ stems ha}^{-1}$, $n = 7$), while the values of $u\overline{TKE}_{total,2}$ and $u\overline{TKE}_{total,3}$ were not within that range. The terminal velocity of raindrops falling from a height of 10 m was almost the same, regardless of their particle size (Wang and Pruppacher, 1977).

Including the data of the $u\overline{TKE}_{total}$ reported by Nanko (2013) and Jeong *et al.* (2024), a strong negative correlation was observed between $u\overline{TKE}_{total}$ and SD ($r = -0.658$, $p = 0.028$, $n = 10$) (SD range: $670\text{--}2900 \text{ stems ha}^{-1}$ with a mean of $1830 \text{ stems ha}^{-1}$) (Fig. 6 and Table S1). Nanko (2013) reported two key forest stand structural factors that affect $u\overline{TKE}_{total}$: crown bottom height (CBH) and crown length (CL). Shinohara *et al.* (2018) reported an additional key forest stand structure factor, H_b , in Japanese cypress plantations. Therefore, in addition to CBH , CL , and H_b , SD could be another important forest stand structure factor determining $u\overline{TKE}_{total}$ in Japanese cypress plantations.

3.4. Effects of thinning on throughfall kinetic energy

Thinning encourages understory vegetation growth, which can positively affect the mitigation of soil erosion. Ide *et al.* (2016) reported that understory vegetation, three years after thinning in Japanese coniferous plantations, naturally emerges with a height of $< 50\text{--}89 \text{ cm}$, similar to T_{IU} (Table 1), and forest floor cover percentage of $89\text{--}100\%$ owing to the improvement in the light environment under the overstory canopies. After thinning, this naturally grown understory vegetation can effectively mitigate the impact of raindrop erosive power on the forest floor because it can act as a protective layer by decreasing the fall velocity of raindrops (Miura *et al.*, 2003; Morgan, 2005). In T_1 , the unit rainfall stand-scale throughfall kinetic energy ($u\overline{TKE}$) and entire period unit rainfall stand-scale throughfall kinetic energy ($u\overline{TKE}_{total}$) significantly decreased after passing through the understory vegetation ($u\overline{TKE}_1: 17.4 \pm 3.4$ vs. $u\overline{TKE}_{IU}: 9.5 \pm 2.1 \text{ J m}^{-2} \text{ mm}^{-1}$ and $u\overline{TKE}_{total,1}: 17.1$ vs. $u\overline{TKE}_{total,IU}: 9.0 \text{ J m}^{-2} \text{ mm}^{-1}$). Yamagishi *et al.* (2022) reported that the splash soil detachment in a mature Japanese cypress plantation with shrub layers (*Aucuba japonica* and *Eurya japonica*) was lower than that in its

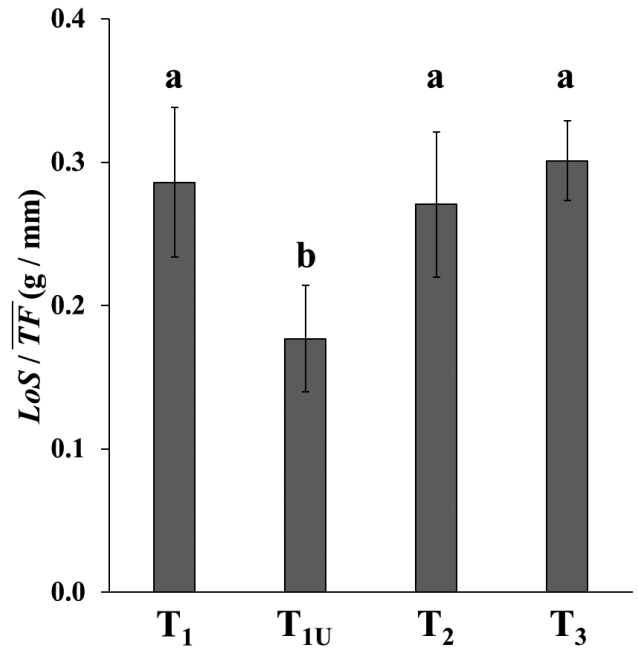


Fig. 5. Ratio of loss of sand (LoS , g) to stand-scale throughfall ($\overline{TF}$, mm) in T_1 , T_{IU} , T_2 , and T_3 . Vertical bars denote the standard deviation. Different letters on the vertical bars indicate significant differences among the plots according to Tukey's test ($P < 0.05$). The ratio differed among the study plots by ANOVA ($P < 0.05$).

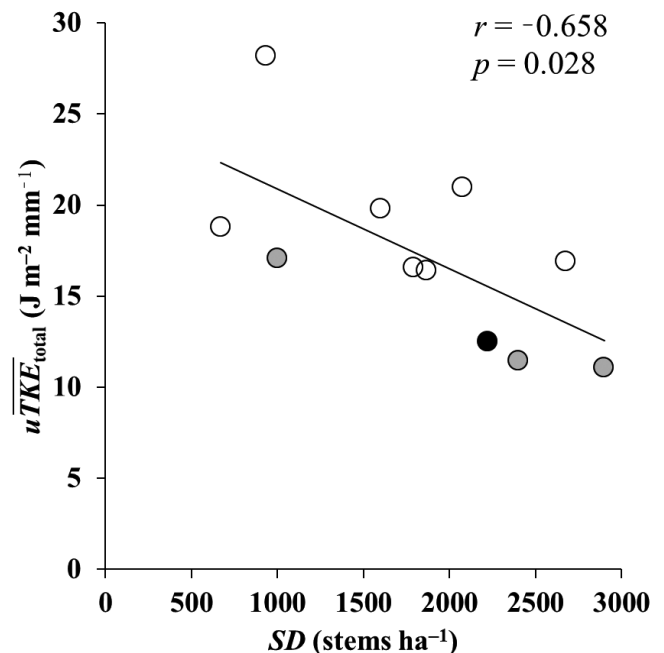


Fig. 6. Relationship between stem density (SD) and the entire period's unit rainfall stand scale throughfall kinetic energy ($u\overline{TKE}_{total}$) for Japanese cypress plantations. White, black, and grey circles denote the data obtained from Nanko (2013), Jeong *et al.* (2024), and the data of this study for T_1 , T_2 , and T_3 , respectively.

counterpart with no shrub layers. This implies that the negative effect of an overstory canopy with higher erosive power on splash soil detachment in Japanese cypress plantations can be mitigated by naturally grown shrubs and herbaceous plants after thinning in such plantations. This highlights the importance of shrub and herbaceous layers for soil conservation in Japanese cypress plantations.

4. Conclusion

This study examined the effects of naturally grown understory vegetation after thinning on throughfall erosivity in Japanese cypress plantations. $\overline{TKE}$ under the canopy in all study plots was much higher than FKE in the nearby open spaces. $\overline{TF}$ significantly affected $\overline{TKE}$ in both the overstory canopies and understory vegetation. For the overstory canopies, $u\overline{TKE}_{total}$ in T_2 and T_3 was similar, whereas $u\overline{TKE}_{total}$ in T_1 was much higher because of the negative relationship between SD and $u\overline{TKE}_{total}$, which confirmed that SD could be another important forest stand structure factor determining $u\overline{TKE}_{total}$ in Japanese cypress plantations. The understory vegetation layer in T_{IV} considerably decreased TKE , probably due to a decrease in raindrop fall velocity. This study is the first to report that naturally grown understory vegetation after thinning plays an important role in controlling soil erosion in Japanese cypress plantations. Variations in thinning frequency and intensity could create differences in the light environments beneath the overstory canopies, influencing the composition and coverage of understory species. These forest management practices can differently mitigate the erosive power of raindrops on the forest floor, affecting soil erosion processes. This could provide practical insights into forest management strategies for enhancing soil conservation in Japanese cypress plantations.

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