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Factors influencing the erosivity indices of raindrops in Japanese cypress plantations

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ABSTRACT

Severe soil erosion has been reported in monoculture forests without understory vegetation and litter on the floor. To clarify the factors that affect raindrop erosivity in monoculture forests, we measured raindrop erosivity in Japanese cypress (*Chamaecyparis obtuse* Endl.) plantations using splash cups. Splash cups can possibly measure raindrop erosivity from loss of sand (LoS). We first examined the relation between raindrop erosivity and LoS under natural rainfall in an open space. LoS was strongly correlated with raindrop erosivity factors, such as the kinetic energy and momentum multiplied by the drop diameter. We then observed LoS using 12–16 splash cups in seven plots with different canopy structures in Japanese cypress plantations. LoS at each point was compared with the amount of throughfall (T_f) and canopy structure factors, such as canopy openness (C_o) and distance to the closest branch (B_r). The relation between T_f and LoS was similar among the plots, except in one plot where the canopy and crown-base heights were the smallest. Our results imply that T_f is a dominant factor determining raindrop erosivity when canopy and crown-base heights are more than the threshold values (15.2 m for the canopy height and 10.5 m for the crown-base height in our forests). In plot 1, LoS was correlated with not only T_f but also B_r. When analyzing all the data together using generalized linear models, LoS was affected by B_r besides T_f. In monoculture forests with a high canopy, T_f measurements enable us to estimate raindrop erosivity. In monoculture forests with a low canopy, B_r (or the canopy height) should also be considered when estimating the erosivity of raindrops.

1. Introduction

Ground cover from low-growing plants and leaf litter promotes high infiltration rates and low soil erosion rates (Morgan, 2005). In general, little soil erosion is observed in forested areas because the ground surface is covered by litter and understory vegetation. However, severe soil erosion has been observed in some forests with neither litter nor understory vegetation. Recently, forest management (i.e., thinning and pruning) has not been practiced effectively in coniferous plantations in Japan because of low timber prices and high labor costs (Komatsu et al., 2010; Onda et al., 2010). The low light levels on the floor that arises due to the dense canopy hinder the growth of understory vegetation. In addition, Japanese cypress (*Chamaecyparis obtuse* Endl.) leaves disperse easily and are readily washed away from the soil surface shortly after falling (Sakai and Inoue, 1988). Therefore, severe soil erosion has been reported in unmanaged plantations of Japanese cypress (Miura et al., 2003, 2015; Miyata et al., 2009), which is one of two major plantation species in Japan. Similar situations have also been reported in monoculture forests of other countries (Zhou et al., 2002; Nanko et al., 2015; Liu et al., 2016).

Soil erosion is caused by the detachment and transport of soil by raindrops and surface flow (Morgan, 2005). There are four types of soil erosion: splash, sheet, rill, and gully erosion. Splash erosion is the first stage of the soil erosion process (Fernández-Raga et al., 2017). In addition, Miura et al. (2002) reported that splash erosion by raindrops was the dominant erosion process in Japanese cypress plantations. To understand the erosivity of raindrops, researchers have measured their kinetic energy (KE) in Japanese cypress plantations (Nanko et al., 2004, 2008a; Wakiyama et al., 2010).

As Nanko et al. (2008a) summarized, some indices, such as their KE and momentum (M) indicating the erosivity of raindrops, have been proposed. These indices are functions of raindrop mass and velocity. Heterogeneous canopy factors (e.g., canopy thickness) can cause spatial variation in throughfall raindrop mass and velocity (Nanko et al.,

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2008b). The amount of throughfall (T_f), which is the total volume of all raindrops, is highly variable spatially (Zimmermann et al., 2009; Shinohara et al., 2010; Nanko et al., 2016). Thus, although raindrop erosivity must vary spatially (Levia et al., 2017), spatial variation in raindrop erosivity has not been well investigated in monoculture forests.

This study aims to clarify the factors that influence raindrop erosivity in monoculture forests. Scholten et al. (2011) recently developed the Tübingen splash cup (TSC). Raindrops hit the sand in TSCs and erode the sand away. KE (or *M*) is obtained based on the relations between KE and the loss of sand (LoS) from the TSC. TSC enables us to measure KE at many points of forests with low cost (Scholten et al., 2011). Goebes et al. (2014, 2015) and Liu et al. (2016) observed considerable spatial variation in KE using TSCs in subtropical forests and in rubber forests, respectively. We used a splash cup with a structure similar to that of the TSC. Because we used a different type of sand from that used in the TSC, we first examined the relation between the soil erosivity of raindrops and LoS under natural rainfall. We then measured LoS using 12–16 splash cups in seven plots in Japanese cypress plantations. LoS was compared to T_f and canopy structure factors (i.e., canopy openness and the distance to the lowest branch).

2. Materials and methods

2.1. Structure of the splash cup

We developed a splash cup (Fig. 1) based on the TSC concept. The detailed structure (i.e., materials used and the size of the cup) of our splash cup differed slightly from that of the TSC. The diameter and height of our splash cup were 5.0 and 5.1 cm, respectively, slightly wider and taller than those of the TSC (4.6 and 3.6 cm, respectively). We used well-dried Toyoura standard sand, in which soil with a particle size of 100–250 μm accounts for > 80% of the mass (Kosugi et al., 2004). The cup was first filled one third full with well-compacted sand. This procedure was repeated three times (i.e., sand was then filled to two thirds full and well compacted and then to the top of the cup and well compacted) to fill the cup. The total mass of the sand was about 155–160 g. We then saturated the sand and used it for experiments. After the experiments, we dried the sand in an oven at 100 °C for > 6 h. LoS was calculated as the difference in the mass of the dried sand before and after an experiment (Scholten et al., 2011).

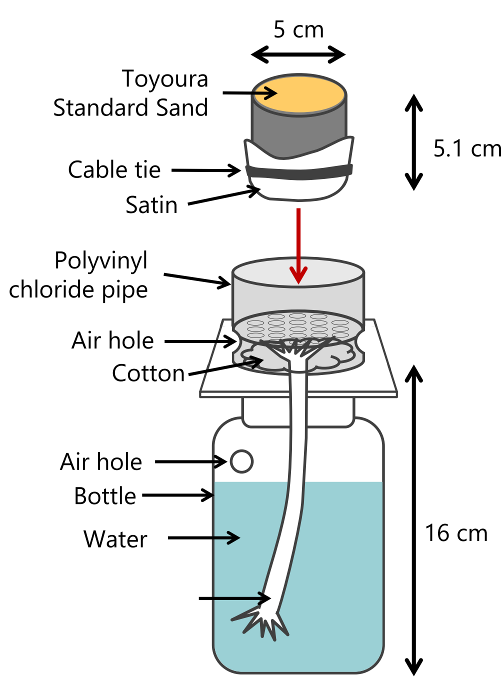

Fig. 1. Structure of the splash cup.

2.2. Calibration of the splash cup

LoS was compared to the erosivity indices of raindrops under natural rainfall. We placed five splash cups and a laser disdrometer (Nanko et al., 2006, 2008a) on the roof of Building No. 2 of the Faculty of Agriculture, Kyushu University (33° 37′N, 130° 25′E). In the same location, we also placed four storage-type bottles with a funnel (diameter: 12 cm) for rainfall measurements. The laser disdrometer consists of a pair of a laser transmitter and receiver (IB-10; Keyence Corp., Osaka, Japan) and an amplifier (IB-1000; Keyence Corp., Osaka, Japan). When a raindrop passes through the laser beam, the output voltage from the receiver is reduced in proportion to the intercepted area. This voltage is digitized using a USB 6009 A/D Converter (National Instruments Corp., TX, USA) and stored in a Windows-based laptop. Consequently, we can obtain the diameter (*D*; mm) and fall velocity (*V*; m s^{-1}) of raindrops and time at which the raindrops pass through the disdrometer.

KE has generally been used as an erosivity index of raindrops (van Dijk et al., 2002; Fornis et al., 2005; Morgan, 2005; Abd Elbasit et al., 2010). Salles and Poesen (2000) indicated that momentum multiplied by drop diameter (MD) was the best raindrop variable to describe splash detachment. In this study, KE and MD were used as the erosivity indices of raindrops. We calculated KE (J m^{-2}) and MD (kg m s^{-1} mm m^{-2}) as follows:

$$\mathrm{KE} = 1/S \sum_{i=1}^{n} e_i \tag{1}$$

$$\mathrm{MD} = 1/S \sum_{i=1}^{n} p_i D_i \tag{2}$$

where e_i and p_i are the kinetic energy (J) and momentum (kg m s^{-1}) of a raindrop (*i*) and *S* is the sampling area of the disdrometer (800 mm^2). *e* and *p* can be calculated as follows:

$$e = 1/2mV^2 \tag{3}$$

$$p = mV \tag{4}$$

where *m* is the mass (g) of a raindrop.

The calibration was conducted for 19 rainfall events between August 16, 2015, and December 13, 2016. The amount of rainfall based on the disdrometer was 0.96 (± 0.19) times the average of the four storage-type bottles. We corrected it using the ratio in each event. Consequently, the rainfall amounts and the maximum rainfall intensities of the 19 events ranged from 0.1 to 75.0 mm (average: 23.2 mm) and from 0.1 to 42.7 mm h^{-1} (average: 11.7 mm h^{-1}), respectively. LoS (g) was compared to the maximum KE and MD at intervals of 1 min, 5 min, 10 min, 30 min, 1 h, and 3 h and was also compared to the total KE and MD.

2.3. LoS measurements in Japanese cypress forests

LoS was measured at seven plots in Japanese cypress plantations in Kasuya Research Forest, Kyushu University (33° 38′N, 130° 31′E). At the nearest long-term meteorological observatory (Fukuoka, about 15 km west of the plots), the annual air temperature and annual precipitation for 1981–2010 were 16.0–18.1 °C (mean: 17.0 °C) and 891–2085 mm (mean: 1612 mm), respectively. In this region, precipitation has seasonality. Monthly precipitation in summer (June–August) and that in winter (December–February) are larger and