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Application of three canopy interception models to a young stand of Japanese cypress and interpretation in terms of interception mechanism

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Summary Three canopy interception models were applied to a stand of young Japanese cypress to obtain a better understanding of the dependence of canopy interception on rainfall intensity (DOCIORI) and the mechanism of splash droplet evaporation (SDE). The applied models were the heat budget model, the newly proposed DOCIORI model, and the revised Gash model. The heat budget model underestimated observed interception by 62.9% in 1999 and 63.4% in 2000; these amounts could be regarded as approximately equal to the amount of SDE. Canopy interception comprises SDE and evaporation from the canopy surface, but the heat budget model calculates evaporation only from the canopy surface. Estimates derived from both the DOCIORI model and the revised Gash model are consistent with observed interception; these models are mathematically equivalent. Reanalysis of previously published data yielded DOCIORI values for interception sites in Spain, Puerto Rico, and the USA. In addition, the relation between mean rainfall intensity and mean evaporation rate calculated using the original and revised Gash models was examined using combined data from the present study and previously published studies; a positive correlation was found between the two values especially in the areas where the rainfall intensity is high. These results support the proposal that DOCIORI and SDE are universal phenomena especially in the high rainfall intensity areas. As literature data indicate that mean evaporation rate is independent of tree height and leaf area index, it can be concluded that canopy interception is mainly governed by rainfall regime rather than forest architecture in the high rainfall intensity areas.

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Introduction

Canopy interception is a function of canopy structure, rainfall regime and climatic variables. Among those factors Murakami (2006) focused on rainfall regime, especially rainfall intensity and revealed that canopy interception loss is clearly proportional to rainfall intensity in a young stand of Japanese cypress, which was termed the dependence of canopy interception on the rainfall intensity (DOCIORI). This phenomenon can be explained by evaporation from splash droplets that are produced when raindrops intercept the canopy (Murakami, 2006). As both the number of raindrops and their size increase with increasing rainfall intensity (Marshall and Palmer, 1948), so does the kinetic energy of the raindrops. This in turn acts to increase the number of splash droplets, which promotes evaporation from their surfaces due to their large combined surface area.

A conventional heat budget method such as the Penman–Monteith equation (Monteith, 1965) is unable to explain DOCIORI because it does not include rainfall intensity as input data and/or parameters. The Rutter model (Rutter et al., 1971, 1975) that includes a conventional heat budget component also cannot explain DOCIORI. The heat budget approach considers evaporation from the canopy surface but not from splash droplets. This commonly leads to underestimates of canopy interception and/or evaporation during rainfall, especially at sites with high rainfall intensity (Calder et al., 1986; Schellekens et al., 1999; Iida et al., 2005). The other major canopy interception models are the original Gash model (Gash, 1979) and its revised version (Gash et al., 1995). The three primary aims of the present study are concerned with the application of three canopy interception models: the heat budget model, the new DOCIORI model, and the revised Gash model. The first aim is to estimate the percentage of splash droplet evaporation (SDE) using the conventional heat budget model for a wet surface that considers evaporation only from the canopy surface. The difference between observed and estimated canopy interception using the heat budget model is expected to represent the difference between the total canopy interception and evaporation from the canopy surface, i.e., evaporation by splash droplets. Toba et al. (2006) applied this approach and conducted a canopy interception experiment using imitation Christmas trees of 60 cm in height and an artificial rainfall simulator to estimate the amount of splash droplet. The amount of splash droplet (termed 'mist' in their study) M was estimated from the measurement of rainfall for the rain event P_G, net rainfall TS, evaporation from the canopy surface $E\tau$ (using the Penman–Monteith equation), and water storage on the canopy 10 min following the cessation of rainfall d. Where E is the mean evaporation rate from the canopy during rain event, τ is the duration of the rain event

$$M = P_G - \mathrm{TS} - E\tau - d \quad (1)$$

P_G was measured using a raingauge, TS was collected on a tray and measured using a tipping bucket, d was measured by weighing the tree with an electric balance, and $E\tau$ was estimated via the Penman–Monteith equation by conducting micrometeorological observations above the canopy. The experiments were conducted for four different values of plant area index (PAI): 9.1, 7.2, 4.5, and 2.7. The PAI was changed by cutting leaves and branches from the trees. The authors concluded that the amount of splash droplet represented approximately 60% of total canopy interception. The authors also pointed out that M increased with rainfall intensity but was independent of PAI. Validity of this estimation is evaluated in the present study.

The second aim is to interpret the Gash models in terms of DOCIORI. The third aim of the study is to assess the universality of DOCIORI and SDE by highlighting the limitations of the heat budget model, mainly based on a literature review. The relationships between vegetation height, leaf area index (LAI), and mean evaporation rate during rainfall are also discussed.

Study site and observation data

Canopy interception was observed from 1999 to 2000 within a stand of young Japanese cypress (*Chamaecyparis obtusa*) that was planted in 1988 at the Hitachi Ohta Experimental Watershed on the Pacific coast of eastern Japan (latitude 36°34′ N, longitude 140°35′ E; altitude: 320 m; Murakami et al., 2000; Murakami, 2006). Total dimension of the stand is 13.2 ha that comprises of Japanese cedar (*Cryptomeria japonica*, areal ratio of 12%) and *C. obtusa* (88%). Annual precipitation was 1707.9 mm and 1452.9 mm in 1999 and 2000, respectively, with annual average precipitation of 1467.7 mm for the period 1991–2000. Winter is the dry season in this area, and snowfall was 34.3 mm and 21.3 mm in 1999 and 2000, respectively.

Average tree height and average diameter at breast height (DBH) were 5.8 m and 7.0 cm in May 1999, and 6.3 m and 8.1 cm in October 2000, respectively. LAI measured in 2000 using a LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE, USA) changed seasonally from 3.9 to 5.7. The stand density was 2944 stems per hectare, and the canopy was almost closed.

Throughfall was collected using two troughs of 590 cm in length and 18 cm in width, and stemflow collectors were set at eight trees. The area of the canopy interception plot was 29.63 m^2. Throughfall and stemflow flowed into separate tanks, and both tanks were drained automatically once the collected water reached the maximum level. Throughfall and stemflow were then calculated from the changes in water level in the tanks with the resolutions of 0.1 mm and 0.07 mm, respectively. Two raingauges were installed within open areas at the ground level in the watershed. One had the resolution of 0.5 mm installed at the clearing of some 4 m in radius (about 170 m away from the canopy interception plot), and another, which was at a meteorological station described later, had that of 0.1 mm installed at the clearing of about 3 m in radius. Since both the raingauges were located at the ridges (Fig. 1 of Murakami, 2006) the effects of trees on the measurements were small in spite of small clearing radii. Rainfall was considered to be a single rain event in the case that rainfall was not observed for a period of more than 6 h following the cessation of the rainfall event of interest. If rainfall of the single rain event was less than 5.0 mm the data obtained by the raingauge with the resolution of 0.1 mm was employed, and if rainfall was more than or equal to 5.0 mm the averaged data of the two raingauges was regarded as gross precipitation and used to calculate canopy interception. The meteorological