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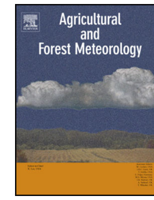

The effect of strip thinning on forest floor evaporation in a Japanese cypress plantation

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ABSTRACT

Thinning results in more open-stand canopies and then immediately modifies the environmental factors that influence forest floor evaporation (E_f). Thus, the changes in E_f induced by thinning would play an important role in the forest water cycle, whereas few studies have reported this topic. This study analyzes the effect of strip thinning on E_f, its spatial variation and identifies the factors influencing it in a Japanese cypress (*Chamaecyparis obtusa* Endl.) plantation in Tochigi Prefecture, Japan. Strip thinning, which removed 50% of the stems, was conducted in a headwater basin during the period of October 11–November 5, 2011. The E_f was monitored by weighing lysimeters before and after thinning. The daily E_f was strongly correlated with the daily solar radiation ($R^2 = 0.62$) followed by vapor pressure deficit ($R^2 = 0.41$) below the canopy, whereas the soil water content had a poor effect on it in post-thinning. After thinning, the daily E_f among the measuring points had no significant difference, indicating that the daily E_f had a small spatial variation. This responded to the small spatial variability in the daily solar radiation under the canopy. Additionally, on an annual scale, thinning resulted in the daily mean E_f increasing from 0.34 ± 0.23 to 0.68 ± 0.47 mm d^{-1}. The total E_f increased by 97.6% from 124.0 to 245.0 mm. These findings indicate that E_f composes a significant part of the forest water budget after thinning and emphasize the importance of E_f measurements for management practices. This study also provides useful information for modeling the changes in hydrological processes at the forest floor and for evaluating the E_f response to different management practices.

1. Introduction

Thinning, which reduces tree density, is a common practice to improve the quality of the residual stand for the production of commercial timber in central Europe, Canada, the eastern United States, Australia, and Japan (Vesala et al., 2005). Thinning opens up forest canopies and immediately modifies the microclimate and soil conditions within the stand (e.g., solar radiation, temperature, and soil water content) (Breda et al., 1995; Ishii et al., 2008; Vesala et al., 2005). These changes in stand structures and microclimate induced by thinning influence the growth rate of the remaining trees and the recovery of understory vegetation (Maleque et al., 2007; Thomas et al., 1999). Furthermore, because forests regulate the hydrological cycle, the thinning of forests thus can strongly affect the hydrological processes (e.g., runoff generation and tree water use) in forest ecosystems (Bosch and Hewlett, 1982; Dung et al., 2012; Limousin et al., 2008; Morikawa et al., 1986; Sun et al., 2014c; Teklehaimanot et al., 1991). Forest floor evaporation (E_f) is one component of the forest water cycle and may account for 3–21% of the total forest evapotranspiration in stands without an understory (Black and Kelliher, 1989). This percentage can be significantly greater in open forest canopies than in dense forest canopies (Baldocchi et al., 2000; Kelliher et al., 1997; Raz-Yaseef et al., 2010). Therefore, the thinning of forests can affect E_f. After thinning, E_f would occupy a significant component of the forest water cycle. However, studies regarding the effect of thinning on the forest water cycle mostly focus on runoff, rainfall interception, and tree transpiration; few data are available for evaluating the changes in E_f caused by thinning.

Previous studies have examined the factors affecting E_f in different forest species. In general, E_f was influenced by three main environmental factors: solar radiation, vapor pressure deficit, and soil water content (e.g., Daikoku et al., 2008; Raz-Yaseef et al., 2010; Schaap and Bouten, 1997; Wilson et al., 2000). For example, Schaap and Bouten (1997) reported spatial variations in soil water contents

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and this strongly determined E_f and its spatial variability in a dense Douglas fir stand in the central Netherlands. Daikoku et al. (2008) found that vapor pressure deficit and the available energy below the canopy strongly determined the daily E_f in a temperate deciduous forest in Japan. The thinning of forests alters the cover and structure of the stand canopies. Consequently, thinning can enhance the penetration of solar radiation into the canopies (Vesala et al., 2005), cause higher temperature on the forest floor (Ishii et al., 2008), increase the soil water content by decreasing rainfall interception (e.g., Molina and del Campo, 2012), and modify microclimatic conditions within the stand (e.g., temperature and humidity) (Vesala et al., 2005). Therefore, the examination of the determinant factors controlling E_f after thinning is necessary for characterizing the magnitude and for improving the reproducibility of E_f in hydrological models.

Several studies have quantitatively examined E_f in various tree species worldwide using models or measurements (e.g., Deguchi et al., 2008; Hattori, 1983; Kumagai et al., 2014; Raz-Yaseef et al., 2010; Schaap and Bouten, 1997; Schaap et al., 1997; Wilson et al., 2000). For example, Hattori (1983) reported that the annual E_f was 137.2 mm, accounting for 8.9% of the annual precipitation, using soil evaporimeters (e.g., Walker, 1983) in a dense Japanese cypress (*Chamaecyparis obtusa* Endl.) plantation in Japan. Schaap and Bouten (1997) and Schaap et al. (1997) measured E_f with a weighing lysimeter and developed a Penman-Monteith approach with the input of soil water content data to estimate E_f in a Douglas fir stand in the central Netherlands. They found that the estimated yearly E_f ranged from 76 to 137 mm, accounting for 7–13% of the annual evapotranspiration depending on the average soil moisture status. Additionally, Vesala et al. (2005) examined the effect of thinning on surface fluxes (e.g., water vapor and CO_2) using the eddy covariance technique and measurements of soil respiration in a homogeneous Scots pine stand (*Pinus sylvestris* L.) in Southern Finland. Raz-Yaseef et al. (2010) reported the effect of tree shading on the spatial E_f variability and estimated E_f based on allometric equations in addition to solar altitude in a semi-arid pine forest (*Pinus halepensis*) in Southern Israel. However, there have been few studies evaluating the changes in E_f induced by thinning. The quantitative examination of E_f and its spatial variability is required to improve the understanding of hydrological processes on the forest floor and to provide a full picture of the influence of thinning on the forest water cycle.

The coniferous plantations of Japan constitute approximately 40% of the forested area and mainly consist of Japanese cedar (*Cryptomeria japonica* D. Don) and Japanese cypress. These plantation forests have been infrequently managed such as thinning because of the increased amount of imported timber and high labor costs after the Second War II (Iwamoto, 2002). As a result, these plantation forests are abandoned due to a high stand density, dense canopy cover and sparse or no understory vegetation. This abandonment presents many environmental issues, including low infiltration capacity, rain splash and the resulting soil erosion, increases in overland flow generation, suspended sediment concentrations, and nutrient loss from the watershed (Onda et al., 2010). Additionally, the majority of these plantations are situated in mountainous regions and supply almost all of the water resources to the lowlands (Sawano et al., 2005). These plantations could consume more water by evapotranspiration from their dense canopies and decrease watershed runoff and water resources (Kuraji, 2003; Sun et al., 2014a). In Japan, thinning practices have been applied widely in these poorly managed plantations. The influence of different thinning practices (strip thinning and selective thinning) on forest water use components needs to be examined to develop appropriate management practices for water resource management. Although previous studies have been conducted on the changes in various components of the forest water cycle (e.g., tree transpiration, rainfall interception, and runoff) by thinning practices (e.g., Dung et al., 2012; Hattori and Chikaarashi, 1988; Morikawa et al., 1986; Sun et al., 2014c), information on the effect of thinning on E_f is scarce. Therefore, the objectives of the study were (1) to identify the determinant factors influencing E_f and (2) to examine the effect of strip thinning on E_f and its spatial variation in a dense and mature Japanese cypress stand.

2. Methods

2.1. Study area

The study site is located on a southwest-aspect hillslope with an average slope of 31° in one headwater catchment K2 in Mt. Karasawa, Tochigi Prefecture, Japan (36°22′ N, 139°36′ E), at an altitude of 196 m above sea level (Fig. 1a). The climate in this area is humid and temperate. The 20-year (from 1991 to 2011) mean annual precipitation and mean annual temperature are 1265 ± 220 mm and 14.1 ± 0.6 °C, respectively, as obtained at the nearest national weather post. The study area has two dominant rainy seasons: the summer monsoon rainy season from late June to mid July and the autumn rainy season from late August to October. More than half of the mean annual precipitation occurs during the rainy season.

The stand in the catchment (drainage area: 13.3 ha) was planted in the 1980 and is covered by a Japanese cypress plantation. However, these plantations have suffered from lack of management practices since planting. The stand density was as high as 2198 trees ha^{-1}, and the corresponding basal area was 50.4 m^2 ha^{-1}. The understory vegetation was nonexistent or sparse. The canopy cover was dense as 0.974 (canopy cover fraction), as calculated from hemispherical photographs of the site. The mean diameters at breast height (DBH) and tree height were 19.1 cm and 16.0 m, respectively. Strip thinning with two plantation lines for cut and two lines for remain was conducted in the catchment during the period of October 11–November 5, 2011. To minimize the soil disturbance on the hillslope, all of the operations were performed by forest workers using non-heavy machinery, except for chainsaws. As a consequence of thinning, the stand density decreased by 50%, corresponding to 48% of the basal area. The canopy cover fraction diminished by 22%. The detailed description of stand characteristics of the study area before and after thinning can be found in Sun et al. (2014c). In this study, the observation period was divided into pre-thinning (November 2010–October 2011) and post-thinning (November 2011–October 2012).

2.2. Measurements

2.2.1. Meteorological measurements

An automatic weather station (HOBO U30-NRC Weather Station; Onset Computer Corporation, MA, USA) was installed to measure the meteorological conditions outside of the forest, including gross precipitation (P_g), wind speed and direction, solar radiation (R_s), temperature and relative humidity. This station was placed 2 m above the ground in an open space along a forestry road. The distance between the study site and the weather station was 250 m. The data were stored using a data logger at 5-min intervals. The potential evapotranspiration (PET) was calculated using meteorological data (Priestley and Taylor, 1972); the detailed calculation of PET and the complete description of the measurements were given by Sun et al. (2014c).

The meteorological conditions under the forest canopy were also measured. A three-up anemometer (AC750, Makino Applied Instruments Corporation, Tokyo, Japan) was installed to measure the wind speed and direction at a height of 2 m above the forest floor. The humidity and temperature were recorded 30 cm from