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Estimation of throughfall with changing stand structures for Japanese cypress and cedar plantations

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ABSTRACT

Throughfall (*TF*) is a critical component of the hydrological and biogeochemical cycles and is greatly influenced by stand structures in forested watersheds. Previous studies have examined the relationships between *TF* and stand structures for different species and regions. However, there remains acknowledged difficulty in estimation of *TF* with changing stand structures due to forest management (e.g., thinning) for specific species and regions. This study conducted intensive thinning with 43–50% stem removal at seven experimental plots with various structures (e.g., stand density, canopy cover and basal area) across Japan that were covered by Japanese cypress (*Chamaecyparis obtusa* Endl.) and cedar (*Cryptomeria japonica* D. Don) plantations. *TF* was measured by a set of 20 tipping-bucket rain gauges placed in a lattice-like pattern within the plots before and after thinning. Results showed that during the study periods, thinning caused an increase in the mean *TF* rate from 63.2 ± 7.0% to 75.4 ± 6.0%. The *TF* rate was significantly negatively correlated with stand density, canopy cover, and basal area on a stand scale. Additionally, the slope (a_{TF}) of event-based linear TF-P_g (gross rainfall) equation was significantly higher in post-thinning (0.782 ± 0.077) than that in pre-thinning (0.663 ± 0.078), whereas it's intercept (b_{TF}) showed no significant difference (−0.707 ± 0.810 mm in pre-thinning and −0.441 ± 0.607 mm in post-thinning). The a_{TF} significantly decreased with increasing stand density and canopy cover, whereas the b_{TF} was not significantly correlated with any forest-structure variables. Further, the *TF* rate and a_{TF} were estimated, respectively, by their related stand-structural variables in multiple regression models with high determination coefficients and moderate relative errors. The b_{TF} was assumed to be a constant and its mean value obtained from all the experimental plots in each (pre- and post-thinning) period. Thus, the models of stand-scale *TF* rate and event-based *TF* amount were developed with input of commonly forest inventories. These models were validated by using the dataset of this study and earlier publications for Japanese cedar and cypress plantations, and showed good fit between the estimated and measured values. These models are practical tools that can be readily used for assessing the changes in *TF* with changing stand structures at both stand and event-based scales, and have also potential implications in evaluating the spatial *TF* patterns at catchment scale and exploiting similar models in other species and regions.

1. Introduction

Throughfall (*TF*) is a key component that links hydrological and biogeochemical cycles in forested watersheds (Levia and Frost, 2006). Forest structure (e.g., stand density, canopy cover and basal area) has a significant influence on the *TF* process (Llorens and Domingo, 2007; Levia et al., 2017), which affects the water inputs to forests (Levia and Frost, 2006), and causes it extremely spatial and temporal variability (Staelens et al., 2006; Nanko et al., 2011; Sun et al., 2015a). As a result of differences in *TF* and its spatial patterns, forest stand characteristics are a primary cause of hydrological differences between watersheds, and notable differences in water discharge (Crockford and Richardson, 2000; Levia and Frost, 2006; Llorens and Domingo, 2007). In addition, changes in forest structure induced by forest management (e.g., thinning) alter the *TF* process (Sun et al., 2015a), and could increase *TF* and thus watershed runoff (e.g., Mazza et al., 2011; Dung et al., 2012; Komatsu et al., 2015). Forest management is thus considered as an effective method to secure water resources under changing climate (Ford et al., 2011). Therefore, an understanding of relationships between stand characteristics and *TF* is important for quantitatively estimating

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the *TF* by forest stand structures, and contributing to proposing an optimized forest and water management approach in securing water resources.

Numerous studies have attempted to examine the relationships between *TF* and stand structures, and quantitatively evaluate the changes in *TF* caused by forest management in different species (e.g., conifer, deciduous, and mixed stands) around the world (e.g., Teklehaimanot et al., 1991; Aboal et al., 2000; Staelens et al., 2006; Andre et al., 2011; Molina and del Campo, 2012; Saito et al., 2013; Sun et al., 2015a). The cumulative *TF* was found significantly increased with decreasing canopy cover under a dominant beech tree (Staelens et al., 2006). The reduction in stand structures induced by thinning resulted in an increase in free *TF* (i.e., rainfall without contacting any forest canopies) and a decrease in canopy water storage (Sun et al., 2015a). These changes in *TF* process tend to decrease the spatio-temporal variability of *TF* and increase *TF* (Zimmermann et al., 2010; Sun et al., 2015a). Molina and del Campo (2012) reported that *TF* significantly increased to 83.8%, 67.7% and 61.3% after high-, moderate-, and low-thinning treatments, respectively, compared with 55.9% in the control treatment in Aleppo pine plantations. Further, some studies established the linear relationship of *TF* with the single stand structural variable (Aboal et al., 2000; Molina and del Campo, 2012). These linear equations are helpful for estimating the effect of thinning on *TF* in these types of forest plantations, whereas there remains large uncertainty in characterizing forest stand structures using the single stand structural variable (Manrique-Alba et al., 2015). Moreover, *TF* has significantly positive linear relationship to gross rainfall (P_g) at event scale (e.g., Saito et al., 2013; Sun et al., 2015b). This strong relationship is useful for estimating event-based *TF* with input of P_g, whereas the slope of TF-P_g equation varies with stand-structure variables among different plots even for the same species (Sun et al., 2015b). This suggests that the equation is limited for estimating *TF* from plot to plot. Overall, previous studies greatly improve our understanding of *TF* in relation to stand structures. However, most of them are cases for specific species within specific study plots. This hampers the applications of these relationships to other plots and species, because of the variations in forest structures on a stand scale and the different physiologic characteristics among different species (Teklehaimanot et al., 1991; Baldocchi and Meyers, 1998; Komatsu et al., 2014). Therefore, for a better understanding of changes in the *TF* with changing stand structures, examining relationships of *TF* for given species with various structures would be useful and widely applicable for accurately estimating the *TF* patterns.

Alternatively, *TF* can be estimated from some physically-based models of canopy interception (e.g., Rutter, Gash and its improved version) (Muzylo et al., 2009). Among of these models, the original and its revised Gash models (Gash, 1979; Gash et al., 1995) are found to be the most commonly used models (Muzylo et al., 2009). Both the models have been widely applied for different vegetation types and validated for robustly estimating and predicting the magnitude of interception. However, the models may be limited for practical purposes, such as those related to forest thinning. Shinohara et al. (2015) reported that the canopy interception models performed well before thinning while they might not be applicable after heavy thinning of Japanese cedar (*Cryptomeria japonica* D. Don) plantation. Furthermore, the practical application of these models are difficult to implement because they need high temporal resolution data records and require a large number of input variables, such as meteorological (e.g., evaporation rate during rainfall and aerodynamic resistance) and structural parameters (e.g., canopy water storage and free throughfall coefficient), which are the outstanding drawbacks. Therefore, the use of relationships of *TF* to stand-structural variables, common in forest inventories, would be much more conversant to a forester.

Japanese cypress (*Chamaeryparis obtusa* Endl.) and Japanese cedar are the two main plantation species, occupying 28% of the forested area in Japan (Japan Forestry Agency, 2014). Because of high labor costs and low timber prices, these plantations have been paid less attention to manage and therefore have overstocked stand densities and dense canopy cover (Onda et al., 2010), which could consume more water via evapotranspiration and thus reduce water resources (Kuraji, 2003). Forest thinning has been widely applied to quantitatively examine its impact on forest water cycles (e.g., Dung et al., 2012; Komatsu et al., 2013; Sun et al., in press). Summarizing dataset from previous evapotranspiration studies, models relating to commonly forest inventories for estimating canopy interception and transpiration were developed, respectively (Komatsu et al., 2007, 2014). Based on the above two models, Komatsu et al. (2015) further provided models to improve the predictability of the increases in annual runoff induced by forest thinning. However, few studies have attempted to examine the relationships between *TF* and changing stand structures for these plantations. Accompanying with previous developed models, these models with input of easily measured stand structure variables would contribute to assessing changes in forest water cycles with changing forest structures, and improving our understanding of underlying processes of the changes in water balance.

The purpose of this study is to examine the relationships of *TF* with changing stand structures induced by thinning practices. By synthesizing the dataset of this study and summarizing previous throughfall studies for these species, we seek to develop *TF* as a function of stand structures with commonly available data for estimating *TF* and assessing the changes in *TF* by forest management.

2. Materials and methods

2.1. Study sites

Seven experimental plots with areas ranging from 68.9 to 156 m^2, were established in watersheds with different climate and geology condition at Tochigi, Aichi, Kochi, and Fukuoka sites across Japan (Table 1; Fig. 1). The climate of these sites is humid and temperate. The mean annual gross precipitation and annual temperature is 1265 mm

Table 1
Stand characteristics of the experimental plots in the pre- and after thinning periods. BT represents before thinning. AT represents after thinning.

Site	Plot code	Species	Plot area m^2	Age yrs	Thinning method	Number of trees		Stand density stems ha^{-1}		Basal area $m^2\ ha^{-1}$		Mean DBH cm		Mean height m		Canopy cover %	
						BT	AT	BT	AT	BT	AT	BT	AT	BT	AT	BT	AT
Tochigi	KS22	Cypress	156	31	50% Strip thinning	28	13	1795	833	50.4	26.2	19.1	18.9	16	16	97.4	75.8
	KS24	Cypress	100	40	50% Strip thinning	17	8	1700	800	74.2	46.1	22.7	23.0	16	16	95.5	74.0
	KS31	Cedar	92.3	41	43% Selective thinning	12	7	1300	758	89.6	51.3	29.0	29.5	18	18	93.6	70.0
Fukuoka	LZ-h	Cypress	68.9	42	44% Selective thinning	9	5	1307	726	45.4	29.1	19.2	19.9	17	17	96.9	81.2
	LZ-s	Cedar	91.6	42	50% Selective thinning	13	6	1420	655	66.6	34.9	27.4	28.1	23	23	97.4	83.5
Aichi	A-h	Cypress	75.7	27	48% Selective thinning	23	12	3038	1585	101.2	57.2	21.2	22.0	13	13	98.3	86.7
Kochi	Y-h	Cypress	100	43	46% Selective thinning	24	13	2400	1300	107.6	60.4	24.7	25.1	18	18	85.5	60.0