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Simple modeling of the global variation in annual forest evapotranspiration

Hikaru Komatsu [a,b,*], Jaeil Cho [a], Kazuho Matsumoto [a,c], Kyoichi Otsuki [a]

[a] Kasuya Research Forest, Kyushu University, 394 Tsubakuro, Sasaguri, Kasuya, Fukuoka 811-2415, Japan
[b] School of Forestry and Resource Conservation, National Taiwan University, Taipei 106, Taiwan
[c] Faculty of Agriculture, University of the Ryukyus, Chihara 1, Okinawa 903-0213, Japan

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SUMMARY

Annual forest evapotranspiration (*ET*) is highly variable among various sites. Zhang's model (Zhang et al., 2001) has been widely used for predicting the spatial variation in *ET*. The forest component of the model employs limiting theory and assumes constant annual potential evaporation (E_0 = 1410 mm) by regressing data recorded at 56 forest sites. However, most of the data used in determining E_0 were recorded for limited regions (Australia, African countries, and the United States). We summarized 829 forest *ET* data items obtained for sites around the world from earlier publications. Using the dataset, we showed that Zhang's model overestimates forest *ET* in temperate and boreal regions with low annual mean temperature (*T*) owing to the E_0 value. We revised the E_0 term of Zhang's model so as to consider the dependency of E_0 on *T* using the dataset. The revised model did not overestimate forest *ET* in temperate and boreal regions. Consequently, we recommend revising the E_0 term of Zhang's model when predicting forest *ET* in these regions.

1. Introduction

Forests are one of the major biomes around the world (Hansen et al., 2003), and return a large portion of precipitation water to the atmosphere through evapotranspiration (Bosch and Hewlett, 1982; Zhang et al., 2001). Thus, forest evapotranspiration greatly affects the global and regional climate (Bala et al., 2007; Bonan, 2008) and river flow (Bosch and Hewlett, 1982; Brown et al., 2005), which further influence water resources, flooding, and sediment transport (Syvitski et al., 2005; Oki and Kanae, 2006; Bradshaw et al., 2007). In addition, forest evapotranspiration relates to carbon fixation (Leuning, 1990, 1995; Law et al., 2002) and biodiversity of the forest (Hawkins et al., 2003; Kreft and Jetz, 2007).

Forest evapotranspiration has been observed at numerous sites globally (Ruprecht et al., 1991; Kosugi and Katsuyama, 2007; Komatsu et al., 2008a; Matsumoto et al., 2008). Annual evapotranspiration (*ET)* has been found to be highly variable among various forest sites primarily owing to variations in meteorological conditions such as precipitation and potential evaporation (Zhang et al., 2001; Komatsu et al., 2008b). *ET* accounted for less than 20% of annual precipitation (*P*) at a Japanese site, where *P* was 2405 mm (Komatsu et al., 2008a). *ET* accounted for more than 90% at an Australian site, where *P* was 1179 mm (Ruprecht et al., 1991). Therefore, examining the spatial variation in forest *ET* is necessary to clarify the functional performance of forests in global and regional water cycles.

Many models (Budyko, 1974; Zhang et al., 2001; Gerten et al., 2004) have been proposed to predict the spatial variation in *ET*. These models are roughly classified into two groups according to complexity. The simple models generally employ limiting theory and the concept of potential evaporation (Schreiber, 1904; Budyko, 1974; Turner, 1991; Zhang et al., 2001) and/or regression of observed *ET* data (Lu et al., 2003; Komatsu et al., 2008b, 2010a; Sun et al., 2011). The complex models employ more process-based formulations including the Penman–Monteith equation or the bulk equation (Gerten et al., 2004; Mu et al., 2007; Jung et al., 2010; Zhang et al., 2010). The simple and complex models have different advantages. The simple models require data for only a few meteorological components at a coarse time resolution (e.g., annual precipitation (*P*), annual mean temperature (*T*), and annual net radiation) and require no (or little) information about forest properties such as forest type (i.e., broadleaf/coniferous and evergreen/deciduous), age, and leaf area index. Thus, these models have practical use (Sun et al., 2005, 2006; Brown et al., 2007) especially when available data are limited. The complex models formulate

* Corresponding author at: Kasuya Research Forest, Kyushu University, 394 Tsubakuro, Sasaguri, Kasuya, Fukuoka 811-2415, Japan. Tel.: +81 92 948 3109; fax: +81 92 948 3119.
E-mail address: kmthkr@gmail.com (H. Komatsu).

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forest evapotranspiration as process-based functions of various meteorological components including radiation and humidity at high time resolution (e.g., daily time resolution) and the forest properties. Thus, these models are useful for predicting changes in evapotranspiration and water cycles with changing climate and vegetation (Gerten et al., 2004; Jung et al., 2010).

Among the simple models, Zhang's model (Zhang et al., 2001) has been widely used (Herron et al., 2002; Nordblom et al., 2006; Brown et al., 2007; Wang et al., 2008). Zhang's model expresses *ET* as a weighted average of forest and herbaceous components. The former component formulates forest *ET*, on the basis of data recorded at 56 sites in various regions (Zhang et al., 1999, 2001), as functions of *P* and annual potential evaporation (E_0). Similar to classic studies (Schreiber, 1904; Budyko, 1974), this model employs limiting theory and assumes that *ET* is limited by *P* where *P* is low and by E_0 where *P* is high. Although most classic studies (Schreiber, 1904; Budyko, 1974) formulate E_0 as functions of incident radiation and temperature, the forest component of Zhang's model assumes E_0 is a constant, which was determined as 1410 mm by regressing the data recorded at 56 forest sites. According to the constant-E_0 assumption, Zhang's model calculates forest *ET* with only the input of *P* data. This is a distinct advantage of this model for practical use, because radiation data are often unavailable for specific regions and in historical datasets (Hunt et al., 1998; Thornton and Running, 1999; Shinohara et al., 2007) and because radiation predicted from temperature and precipitation data could contain relatively large errors (Thornton and Running, 1999; Meza and Varas, 2000; Shinohara et al., 2007). Despite the simplicity of the model, it demonstrated high predictability for data recorded at the 56 forest sites. The simplicity and predictability led to the wide use of Zhang's model.

However, most of the data used by Zhang et al. (1999, 2001) for E_0 determination were recorded in limited regions (Australia, African countries, and the United States). Only a few data were for Asia, South America, Europe, and boreal regions, despite their large forested areas. Thus, the constant-E_0 assumption might not be useful for explaining the global variation in forest *ET*. Indeed, Komatsu et al. (2008b) noted that the model systematically overestimates forest *ET* in Japan, because Zhang's E_0 value is higher than that for Japan. Similar problems are expected for regions at high latitude, because E_0 for these regions would be no more than that for Japan (Budyko, 1974; Choudhury, 1997; Ward and Robinson, 2000). Their finding implies that applying the constant-E_0 assumption at a global scale is problematic.

This work extends Zhang's model to explain the global variation in forest *ET*. Using a comprehensive collection of *ET* observation data recorded around the globe, we show that predictability of Zhang's model is improved when considering the dependency of E_0 on *T*.

2. Materials and methods

2.1. Methods of analysis

Zhang's model formulates forest *ET* as (Fig. 1)

$$ET = P(1 + wE_0/P)/(1 + wE_0/P + P/E_0), \quad (1)$$

where *w* is a coefficient representing plant water availability. *w* and E_0 were determined as 2.0 and 1410 mm, respectively, by regressing the data recorded at 56 forest sites. Changes in *ET* with *P* are small where *P* is high (Fig. 1). This indicates small variations in *ET* among sites for regions with high *P*. *P* was greater than 2000 mm at nine sites among the data collected by Zhang et al. (2001). The mean and standard deviation of *ET* for the nine sites were 1353 and 107 mm, respectively. The mean value was approximately identical

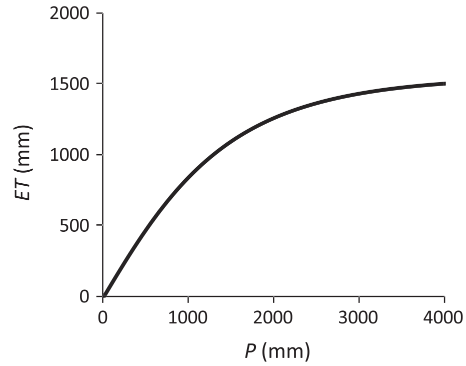

Fig. 1. Relationships of annual forest evapotranspiration (*ET*) with annual precipitation (*P*) predicted using Zhang's model.

to the E_0 value determined by Zhang et al. (2001). The standard deviation accounted for only 8% of the mean value, suggesting the validity of the constant-E_0 assumption within the limit of the data they collected.

We first collected forest *ET* data globally and showed that Zhang's model systematically overestimated forest *ET* especially for regions at high latitudes, because the E_0 value determined by Zhang et al. (1999, 2001) was too large for the regions. We then revised the E_0 term of Zhang's model to reduce the overestimation at high latitudes. For this, we classified *ET* data into different *T* classes and determined E_0 to minimize the root-mean-square error (RMSE) for *ET* estimates for each class. We further developed a map indicating the regions where Zhang's model overestimated forest *ET* and the use of the revised model is recommended. For this, we calculated global forest *ET* variations using the revised model and Zhang's model, respectively, and developed a map showing the difference between these two *ET* estimates. Additionally, we showed that the revised model was useful for predicting the difference in the sensitivity of forest *ET* to temporal variations in *P* among sites. The sensitivity for each site was evaluated using the slope of the linear regression line between *P* and *ET* during the measurement period for the site. A greater slope indicated that *ET* was sensitive to *P*. We compared the slope value derived from observations with that predicted using the revised model.

2.2. Evapotranspiration data

We collected forest *ET* data from earlier papers using three criteria. Firstly, *ET* must be determined from one or a combination of measurements of the catchment water balance (Pearce et al., 1982; Iroumé et al., 2006), soil water balance (Calder et al., 2003; Muller, 2009), micrometeorology (Wilson and Baldocchi, 2000; Oishi et al., 2010), porometry (Bigelow, 2001), sap flux (van Wijk et al., 2001; McJannet et al., 2007), and throughfall (Van der Salm et al., 2006; Huber et al., 2008). If *ET* data obtained using different methods were available for a specific site (Wilson et al., 2001; Shimizu et al., 2003), we treated these data independently. This treatment did not alter our results and conclusions, because only 10 sites satisfied this condition (i.e., *ET* data obtained using different methods were available for a specific site). Among the data derived from catchment water balance measurements, some data were derived from catchments that were not fully covered with forest. We accepted data only for catchments for which no less than 70% of the area was covered with forest. This definition of a forest catchment would generally agree with that used by Zhang et al. (1999, 2001), although they did not clearly state the definition. They also used data for catchments partially covered with forest (Sharda et al., 1998) for developing the forest component of their model. For