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Measurements of Wet Canopy Evaporation in Forests: A Review

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산림에서의 젖은 군락 증발 관측: 고찰

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ABSTRACT

Wet canopy evaporation (E_{WC}) has been recognized as a significant component of total evapotranspiration, especially in forests and therefore it is critical to accurately assess E_{WC} to understand forest hydrological cycle. In this review, I focused on the measurement methods and evaluating the magnitudes of E_{WC} at diverse forest types (e.g., deciduous, coniferous, mixed, and rain forests). I also present the general issues to be considered for E_{WC} measurements. The commonly used measurement methods for E_{WC} include the water balance, energy balance, and the Penman-Monteith (PM) methods. The magnitudes of E_{WC} ranged from 5 to 54% of precipitation based on the literature review, showing a large variation even for a similar forest type possibly related to canopy structure, rainfall intensity, and other meteorological conditions. Therefore, it is difficult to draw a general conclusion on the contribution of E_{WC} to evapotranspiration from a particular forest type. Errors can arise from the measurements of precipitation (due to varying wind effect) and throughfall (due to spatial variability caused by canopy structure) for water balance method, the measurements of sensible heat flux and heat storage for energy balance method, and the estimation of aerodynamic conductance and unaccounted sensible heat advection for the PM method. For a reliable estimation of E_{WC}, the combination of ecohydrological and micrometeorological methods is recommended.

***Kew words* : Evaporation, Wet canopy, Water balance, Energy balance, Penman-Monteith, Forest**

I. INTRODUCTION

Evapotranspiration (*ET*) interconnects energy, water, and carbon cycles in terrestrial ecosystems. *ET* is the sum of transpiration, soil evaporation, and canopy evaporation and the quantitative estimation of each component is important for the process-based understanding of hydrological cycle.

During rainy periods, a portion of rainfall is intercepted by the vegetation canopy and evaporates back to the atmosphere (defined as wet canopy evaporation or interception loss; Fig. 1). Wet canopy evaporation (E_{WC}) has been recognized as a significant contributor to *ET*. Variation of the E_{WC} magnitude is associated with forest structure, distribution and intensity of rainfall, and climate conditions (Pypker *et al.*, 2005; Herbst *et al.*, 2008; Sraj *et al.*, 2008). Since radiation is low during rainy period, E_{WC} is mainly determined by aerodynamic conductance and the available energy, indicating that E_{WC} is fundamentally physical rather than biological. Forests, which have higher aerodynamic conductance and heat storage, have much higher rates of E_{WC} than short vegetation and thus most interception studies have focused on forest areas (Stewart, 1977; Dingman,

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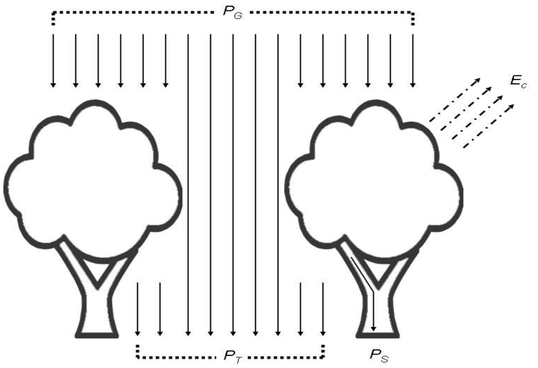

Fig. 1. Canopy interception loss. (P_G is gross fall, P_T is throughfall, P_S is stemflow, and E_{WC} is canopy interception loss)

2002).

Annual E_{WC} ranges from 10 to 40% of total precipitation in various plant communities (Dingman, 2002). Other earlier studies reported that E_{WC} ranged from 25 to 50% in coniferous forest (Rutter *et al.*, 1975; Gash *et al.*, 1980; Johnson, 1990) and from 10 to 28% in broadleaved forests (Rutter *et al.*, 1975; Sraj *et al.*, 2008). Considering the reported magnitude of E_{WC}, E_{WC} is one of the major hydrological processes that alter the quantity, timing, and distribution of water input and output in forested areas. Therefore, an accurate assessment of E_{WC} is critical in understanding of the forest hydrological cycle.

E_{WC} has been commonly measured by water balance (i.e., the difference between gross rainfall and the sum of throughfall and stemflow; Horton, 1919; Rutter *et al.*, 1975; Valente *et al.*, 1997). Energy balance method (i.e., the difference between net radiation and the sum of sensible heat, ground heat, and energy storage) is another approach to measure E_{WC}. In this approach, the Bowen ratio, eddy covariance, and temperature variance techniques have been applied (Gash *et al.*, 1999; Schellenkens *et al.*, 2000). The estimation of E_{WC} is also conducted using the Penman-Monteith combination equation by assuming that surface conductance is negligible. Rutter *et al.* (1975) was the first to estimate E_{WC} in forest using this method. Due to the shortcomings of each method, a combination of multiple methods is often used to improve the validity of the measurement (e.g., Gash *et al.*, 1999).

Studies on E_{WC} have been reviewed and the most recent examples are Crockford and Richardson (2000), Dunkerley (2000), and Llorens and Domingo (2007). They reviewed the studies on E_{WC} mostly conducted by water balance method, focusing on the effect of forest types, ground cover, and climate on E_{WC} at various locations. Other methods of E_{WC} measurements have not been reviewed in these papers.

Despite the importance of E_{WC} in the hydrological cycle in the forested areas, which occupy approximately 65% of the total land area in Korea, little attention has been paid to the role of E_{WC}. Domestic researches on E_{WC} have been rare and several attempts have been made to measure E_{WC} by using water balance method (Kim and Woo, 1988; Min and Woo, 1995; Lee *et al.*, 1997; Kim *et al.*, 2005). Recently in Korea, the eddy covariance technique has been employed to measure E_{WC} simultaneously with the measurement of leaf wetness at multiple levels in deciduous and coniferous forests (Kang *et al.*, 2011).

In view of the proceedings, a general review is provided on the measurement methods and the reported magnitudes of E_{WC} in different forest types. In this review, I introduce the results of the studies on E_{WC} in various forest types and the diversity of the measurement techniques and to highlight the challenges and issues associated with each technique based on case studies.

II. MEASUREMENT TECHNIQUES

2.1. Determination of canopy wetness

Determination of wet canopy is important to differentiate canopy evaporation from evapotranspiration. Based on the literature review, three methods are suggested to determine whether a canopy is wet or not.

2.1.1. Precipitation intensity

Gash (1979) defined the period with more than 0.5 mm/hr of rain as wet canopy condition by assuming the canopy being saturated.

2.1.2. Wetness sensor

Stewart (1977) used wetness sensors to determine the canopy condition. He installed six wetness sensors in the forest canopy space at 45° to the horizontal plane to prevent standing water. If some of the wetness sensors indicate wetness, the canopy is defined as “partly” wet. If all the wetness sensors indicate that water is lying on the sensors, the canopy was described as “completely” wet. E_{WC} is then calculated when the canopy is completely wet.

2.1.3. Surface conductance

Stewart (1977) used surface conductance calculated from the Penman-Monteith equation (Eq. 1) as an indicator of canopy saturation status when surface conductance is within the range of 0 to 10 s m^{-1}.

2.2. Estimation of wet canopy evaporation

2.2.1. Penman-monteith method

Wet canopy evaporation (E_{WC}) can be estimated using the Penman-Monteith (PM) equation (Monteith, 1965).

$$E = \frac{1}{\lambda}\frac{\Delta A + \rho C_p(e_s - e_a)g_a}{\Delta + \gamma(1 + g_a/g_s)} \tag{1}$$

where l is the latent heat of vaporization of water, A (= $R_N - G - S$) is the available energy (here R_N is the net radiation, G is ground heat flux, and S is the heat storage between the measurement height and ground level), ρ is the air density, C_p is the specific heat of air, e_s is saturated vapor pressure, e_a is actual vapor pressure, g_a is the aerodynamic conductance, g_s is the surface conductance, Δ is the slope of vapor pressure curve, and γ is the psychrometric constant. When canopy is fully saturated, surface conductance is assumed to be negligible (i.e., $g_s \approx \infty$). Eq. 1 is then simplified to:

$$E_{WC} = \frac{1}{\lambda}\frac{\Delta A + \rho C_p(e_s - e_a)g_a}{\Delta + \gamma} \tag{2}$$

g_a is estimated by:

$$g_a = \frac{k^2 u}{(\ln(z-d)/z_{o,M})^2} \tag{3}$$

where k is the von Kármán constant, u is the wind speed at height z, d is the zero displacement height ($\approx$ 0.75hr, where def. of hr is the canopy height), and $z_{o.M}$ is the roughness length for momentum ($\approx$ 0.1hr). Estimation of E_{WC} using Eq. 2, however, is sensitive to the value of g_a (Gash *et al.*, 1980 and 1999) and it is critical to use the right equation to accurately present the transport of water vapor through the atmospheric surface layer (Gash *et al.*, 1999). Gash *et al.* (1999) suggested several ways of calculating g_a, which take different transfer mechanisms of heat and water vapor into account.

$$g_a = \frac{k^2 u}{\ln((z-d)/z_{o,M})(\ln(z-d)/z_{o,H})} \tag{4}$$

where $z_{o.H}$ is the roughness length for heat and water vapor. When friction velocity, u^* is measured, g_a can be written as:

$$g_a = \frac{ku^*}{(\ln(z-d)/z_{o,H})} \tag{5}$$

Following Lankreijer *et al.* (1993), $\ln(z_{0,M}/z_{0,H})$ is taken as 2, then

$$\ln(z_{o,H}) = \ln(z_{o,M}) - 2 \tag{6}$$

and Eq. 5 can be rewritten as:

$$g_a = \frac{k^2 u}{(\ln(z-d)/z_{o,M}) + 2} \tag{7}$$

g_a can be estimated only from u and u^*

$$g_a = \frac{u^*}{u/u^* + 2/k} \tag{8}$$

or, by following Thom (1975),

$$g_a = \frac{u^{*2}}{u} \tag{9}$$

A few studies suggested to use only $z_{0,H}$ to estimate E_{WC} during rainfall (e.g., Klaassen *et al.*, 1998), whereas other studies proposed to use only $z_{0,M}$ (e.g., Gash *et al.*, 1999).

2.2.2. Water balance method

Interception loss is the sum of canopy and ground surface interception loss. By assuming that the ground surface interception loss could be minimal compared to the canopy interception loss particularly in forest stands, the canopy interception is regarded as interception loss (i.e., wet canopy evaporation). E_{WC} can be calculated as the difference between gross rainfall and net rainfall (the sum of throughfall and stemflow):

$$E_C = P_G - P_T - P_S \tag{10}$$

where P_G is the gross rainfall, P_T is the throughfall, and P_S is the stemflow. Since E_{WC} is the subtle balance between the two large numbers, a small fractional uncertainty in each component can generate large errors in E_{WC}. Application of this method contains uncertainties because of the difficulties in accurate measurement of P_G (especially at low rainfall intensities when interception losses are relatively large), the spatial variability of P_T, and the difficulty of measuring stemflow (Dingman, 2002). The largest uncertainties stem from the measurement of P_G during the leafless period due to higher wind speed in winter at forest sites (Herbst *et al.*, 2008). Herbst *et al.* (2008) also stated that P_T measurement can be problematic under the leafed canopy due to a large spatial variability and higher rainfall intensities specially in deciduous forests. For coniferous forests, such spatial variability is often lower and the structural parameters hardly change during the season and thus the measurement of P_T can be less problematic than for deciduous forests.

2.2.3. Energy budget method

Energy budget equation is as follow:

$$R_N = H + \lambda E + G + S + P \tag{11}$$

where H is the sensible heat flux and P is the energy absorption by photosynthesis and respiration. Because the amount of P is negligible, P can be ignored in Eq. 11. By assuming that $\lambda E \approx E_{WC}$ when the canopy is wet, Eq. 11 can be rewritten as:

$$E_{WC} = \frac{1}{\lambda}(R_N - H - G - S) \tag{12}$$

Another approach to estimate E_{wc} is to use the concept of the Bowen ratio ($\beta = H/\lambda E = (C_p \partial\theta/\partial z)/(\lambda \partial q/(1+\beta))$, where $\partial\theta/\partial z$ and $\partial q/\partial z$ are the gradients of potential temperature and specific humidity against height z). Substituting β in Eq. 12, Eq. 12 becomes

$$E_C = \frac{1}{\lambda}\frac{A}{(1+\beta)} \tag{13}$$

Most of errors in the Bowen ratio are associated with the errors in the measurements of the small temperature and humidity gradients during the rainy days.

In order to measure H during the rainy period, temperature variance and eddy covariance methods are frequently used. Temperature variance method evaluates H from the standard deviation of temperature fluctuations (e.g., Schellenkens *et al.*, 2000) using the following equation (Tillman, 1972):

$$H = \rho C_p \left[\left(\frac{\sigma_T}{C_1}\right)^3 \left(kg\frac{z}{T}\right) \frac{\left(1 - C_2\frac{z}{L}\right)}{-\frac{z}{L}} \right] \tag{14}$$

where σ_T is the standard deviation of temperature, g is the gravity acceleration, T is the air temperature, z/L is the stability parameter, and C_1 and C_2 are the empirical constants (2.9 and 28.4, respectively; De Bruin *et al.*, 1993). Under unstable atmospheric condition, z/L equals the Richardson number and Eq. 14 can be simplified to (Vugts *et al.*, 1993)

$$H = 1.075 \rho C_p \sigma_T^{3/2} \left(\frac{kgz}{T}\right)^{1/2} \tag{15}$$

Eddy covariance method estimates H from covariance between vertical wind velocity and temperature fluctuations by averaging these variables over any desired averaging time:

$$H = \rho C_p \overline{w'T'} \tag{16}$$

where w is the vertical wind velocity. Instrument measuring temperature fluctuation is sensitive to water drop, which can cause malfunction of the instrument and generate unreliable data. Therefore, it is necessary to evaluate reliability of data obtained from the eddy covariance instrument for possible malfunction due to water.

III. CASE STUDIES

3.1. Coniferous forest

Rutter *et al.* (1975) calculated E_{WC} for coniferous forest (Corsican pine, *Pinus nigra* and Douglas fir, *Pseudotsuga menziesii* at Bramshill forest, Hamsphire in England; Norway spruce, *Picea abies* at Bagely wood, Oxford in England) using the water balance method for periods from 8 to 18 months. P_G was measured, while P_T and P_S were calculated by considering the canopy gap fraction and the proportion intercepted by trunks. The results showed that monthly mean values of E_{WC} was 23 mm mon^{-1} for Corsican pine and 25 mm mon^{-1} for Douglas fir with 65.3 mm of monthly mean precipitation and ~14 mm mon^{-1} for Norway spruce with 29.8 mm of monthly mean precipitation. At the coniferous forests, the monthly mean E_{WC} constituted 36 to 48% of the monthly mean precipitation.

The measurements of E_{WC} were conducted at a pine forest (a mixture of Scots and Corsican pine; *Pinus sylvestris* L. and *Pinus nigra* var. *Maritima*) in Thetford Forest, England using micrometeorological (i.e., the Bowen ratio) method from March to October in 1972 and 1973 (Stewart, 1977). Transpiration and E_{WC} were differentiated based on wetness conditions determined from six wetness sensors, which were installed within the forest canopy. When A was greater than 20 W m^{-2} and the canopy was completely wet during the study period, E_{WC} was calculated from Eq. 13. The calculated E_{WC} was filtered again using a criterion of g_s (i.e., -10 to 10 s m^{-1}). Annual E_{WC} was 145 mm, which was 25% of the total evapotranspiration (of 566 mm). In addition to the quantification of E_{WC}, Stewart (1977) investigated if the rate of E_{WC} exceeds the input of A. At the pine forest, E_{WC} used 127% of A, which was three times the transpiration rate (of 41% of the available energy) that occurred when the canopy was dry under the same level of A. The excess E_{WC}, compared to A, indicated that additional energy was provided by a downward flux of sensible heat form the air generated from an inversion of temperature over the forest. Measurements of E_{WC} were conducted over maritime pine forest (*Pinus pinaster* Ait.) at Pinhal de Carrasqueira in central Portugal in order to evaluate Rutter model's performance in response to the canopy closure (i.e., complete or incomplete closure) and g_a calculation (Gash *et al*., 1999). The average height of trees was 20 m and the density was 312 stems ha^{-1}. E_{WC} was estimated using two different methods (i.e., the PM method and the energy balance method). H was measured using eddy covariance technique by applying a sonic anemometer (Model 1012R, Gill Instruments, Lymington, UK) and other necessary measurements (e.g., R_N, G, and P_G) were conducted. A power spectra analysis demonstrated that the performance of the anemometer was not affected by rainfall and thus the measurements of H were reliable. Based on criteria on atmospheric saturation (either a 20 min block of eddy correlation data or a 10 min block of eddy correlation overlapping with saturated weather conditions), 34 cases, qualifying by the criteria, were selected to estimate E_{WC}. E_{WC} ranged from 10 to 250 W m^{-2} during the 34 cases. The best agreement between the measured and estimated E_{WC} was observed when a combination of using g_a for momentum flux with incomplete canopy closure. These results assured the usage of g_a for momentum flux and emphasized the importance of canopy structure for accurate estimation of E_{WC}.

Shachnovisch *et al.* (2008) measured E_{WC} in a mature pine forest (*Pinus halepensis*) located in a semi-arid area on the fringes of the Negev desert of Israel. The forest density was 360 trees ha^{-1} with the average tree height of 10 m. Measurements of P_G, P_T, and P_S were made for three years (October 2000 to April 2003) and E_{WC} was calculated using the water balance method. One rain gauge was used to measure P_G, whereas 20 rain gauges were used to measure P_T and then the data of P_T from each rain gauge were averaged for the final P_T value. P_S was monitored on six trees using collectors made from plastic rings sealed with silicone rubber. During the measurement period, P_G varied from 306.0 to 341.5 mm with an average of 308.8 mm. P_T constituted about 94% of P_G, whereas P_S was about 1.4% of P_G. Thus, E_{WC} was about 4.6% of P_G, which was about 14 mm at the pine forest in semi-arid area.

van der Toi *et al.* (2003) conducted the measurements of E_{WC} in a Sitka spruce (*Picea sitchensis*) stand in the Hafren forest Central Wales, UK for six months (March to September, 2000). The height of the trees was about 15 m with the density 2,313 stems ha^{-1} and the canopy cover was close to 100%. H was measured using eddy covariance method with a sonic anemometer (Solent R3, UK) and E_{WC} was calculated as a residual of the energy balance. R_N was measured above the forest at two locations and G was assumed negligible. S was calculated following Herrington (1969) and Thom (1975). E_{WC} was also estimated from the PM equation and vapor pressure was measured from a dry and wet bulb temperature measurements employed above the canopy. g_a was estimated by inversely solving Eq. 9 for g_a. P_G was measured outside the forest on a ground level. The canopy was considered to be wet when the amount of P_G was more than 0.5 mm.

The performance of the sonic anemometer was acceptable during the wet conditions, satisfying the Monin-Obukov similarity theory (i.e., a linear relationship between the standard deviation of vertical wind, σ_w and u^* in neutral conditionss). The average E_{WC} was 0.123 mm hr^{-1}, whereas the average R_N was equivalent to 0.072 mm hr^{-1}. This indicates that the energy used for E_{WC} was 70% larger than R_N. The average P_G was 2.15 mm hr^{-1}, of which only 6% was used as E_{WC}. E_{WC} calculated with the PM equation was 0.090 mm hr^{-1}, which was 30% lesser than E_{WC} (of 0.123 mm hr^{-1}) with the energy balance method. The difference was due to advection providing additional energy for E_{WC} as calculated with the energy balance method but not being considered in E_{WC} as calculated with the PM equation.

In order to quantify the role of E_{WC}, Kang *et al.* (2011) measured E_{WC} with typical open-path eddy covariance simultaneously with leaf wetness at multiple levels in the canopy at Gwangneung coniferous forest (*Abies* sp.) in Korea from September 2007 to August 2008. The height of the trees was about 23 m with the maximum LAI of ~7.5. They defined wet canopy as the conditions when precipitation is detected and all leaf wetness sensors are wet. Due to the malfunctions of the open-path eddy covariance system, gaps in E_{WC} dataset occurred and a gap-filling method (i.e., a modified-lookup table, MLT) was used to fill these gaps. They employed Variable Infiltration Capacity (VIC) land surface model (LSM) algorithm to simulate E_{WC} and to validate the gap-filled E_{WC} data based on a modified-lookup table (MLT) method during wet canopy conditions. The annual E_{WC} values by the MLT method was 31.9 mm, whereas that by VIC LSM was 85.9 mm. Overall, the annual difference was about 54 mm, i.e. ~10% of the annual ET of 530 mm, suggesting the necessity of a separate gap-filling procedure for wet canopy conditions.

3.2. Deciduous forest

In deciduous hardwood forests, P_G and E_{WC} were observed and compared with the estimated E_{WC} for the periods of 8 to 18 months (Rutter *et al.*, 1975). E_{WC} rate was calculated using the PM equation when the amount of water on the canopy equals or exceeds canopy storage. E_{WC} was also calculated using the water balance method. P_T and P_S were calculated by considering the canopy gap fraction and the proportion of the intercepted by trunks, which were observed over time. The results showed that E_{WC} at deciduous forest was 13 mm mon^{-1} and this magnitude was smaller than that measured simultaneously at coniferous forest (e.g., 23 to 25 mm mon^{-1} for Corsican pine and Douglas fir and ~14 mm mon^{-1} for Norway spruce). E_{WC} constituted 20% of the total precipitation (of 65 mm mon^{-1}).

Herbst *et al.* (2008) estimated E_{WC} using the water balance method and micrometeorological method (i.e., energy balance method and the PM method) in a mixed deciduous forest dominated by oak (*Quercus robur* L.) and birch (*Betula pubescens* L.) in Southern England over a period of 14 months. The average canopy height was 22 m and the maximum LAI was 3.9. In this study, the effect on canopy structure (i.e., leafed or leafless canopy) on E_{WC} was studied. For the energy balance method, H was measured from eddy covariance technique. Estimation of G was conducted from the changes in soil temperature, while that of S was done by calculating change in T and humidity of the canopy air for the energy storage (e.g., Silberstein *et al.*, 2001) and change in T of the biomass for the energy storage in the biomass (e.g., Michiles and Gielow, 2008). The PM equation was applied to estimate E_{WC} using two alternative methods of g_a calculation following Eq. 9 and Eq. 3. For the water balance method, P_G was collected with a funnel on top of the tower and piped down to a tipping bucket rain gauge installed on the ground level. P_T was measured with 30 storage rain gauges employed 4 m apart from each other. In addition, four plastic troughs attached to automatic rain gauges were installed randomly. P_S was collected from three oak and three birch tress from waterproof collars and connected to outlet pipes, which led to tipping bucket rain gauges. Hours with a rainfall rate more than 0.5 mm were considered as wet canopy condition.

The quality of H measurements was assessed from the linear relationship between σ_w and u^* based on the Monin-Obukhov similarity theory. This relationship showed a reliable performance of the eddy covariance method during the wet period. P_G, P_T, and P_S were 773, 564 (73% of P_G), and 17 (2% of P_G) mm, respectively. E_{WC} was 192 mm, which was 25% of P_G. The percentage of total E_{WC} to total P_G (20%) from the leafless canopy was lower than that (29%) from the leafed canopy. However, the average rate of E_{WC} (0.20 mm hr^{-1}) from the leafless canopy was slightly higher than that (0.19 mm hr^{-1}) from the leafed canopy due to stronger wind speed and different aerodynamic properties of the leafless canopy. Unlike van de Tol *et al.* (2003), E_{WC} from the water balance method agreed well with those from the PM equation with two alternative calculations of g_a.

E_{WC} by two deciduous Mediterranean forests of contrasting stature in Slovenia was measured from May 2000 to December 2001 (Sraj *et al.*, 2008). One forest located in the south area (0.31 trees m^{-2}) was denser than the other forest in the north area. The average tree height in the south area was about 8 m, while that in the north area was about 12 m. *LAI* was 6.6 for the south site and 6.9 for the north site. P_G was measured using a tipping bucket and P_T was measured with a combination of fixed (two gutters) and manual roving gauges (10 gauges) to provide representative samples. P_S was made on two individual trees for the two most typical species in each site with a rubber collar fitted around each tree and a tipping bucket connected to the collar measured P_S.

During the measurement period, P_G was 1,319 mm and P_T, P_S, and E_{WC} were 67%, 5%, and 28% of P_G in the south area, respectively. In the north area, P_T, P_S, and E_{WC} were 72%, 3%, and 25% of P_G (1,212 mm), respectively. For both areas, the magnitudes of P_T and E_{WC} were strongly affected by canopy structure and rainfall intensity: P_T was lesser and E_{WC} was greater during the leaf period than the leafless period. High rainfall intensity increased P_T but decreased E_{WC} during the leaf period. Sraj *et al.* (2008) suggested that rainfall intensity is the most influential factor on P_T and E_{WC}. On the contrary, P_S was independent of the canopy structures and rainfall intensity. They also showed that wind speed strongly influenced E_{WC} by shaking branches of trees and reducing the storage capacity of the canopy and thus E_{WC}.

Kang *et al.* (2011) measured E_{WC} at Gwangneung deciduous forest (of *Quercus* sp. and *Carpinus* sp.) in Korea from September 2007 to August 2008 using the same method described above. The height of the trees was ~ 18 m with the maximum LAI of ~4.5. The annual E_{WC} values by the MLT method was 24 mm, whereas that by VIC LSM was 57.8 mm. Overall, the annual difference was ~33.8 mm, i.e. ~10% of the annual *ET* of 367 mm. This magnitude was smaller than that was measured simultaneously at coniferous forest (e.g., 24 mm by the MLT method and 85.9 mm by the VIC LSM).

3.3. Rain forest

E_{WC} was estimated from a tropical rain forest at Luquillo Experimental Forest in Puerto Rico through a combination of hydrological and micrometeorological measurements during 1996 and 1997 (Schellekens *et al.*, 2000). The forest height was 20~25 m and the average LAI was between 6 and 7 with the range varying from 2 to 12. In this study, *G* and *S* were assumed negligible and R_N was estimated using a regression equation ($R_N = 0.88R_g - 35$; here R_g is an incoming solar radiation). P_T was recorded continuously using three steel gutters (a 180-L capacity) and from additional 20 randomly placed collectors, P_T was also measured. P_S was regarded as a constant (2.3% of P_G) based on the earlier study at the same site. In the PM method, g_a was obtained by following Thom, (1975; see Eq. 12 in Schellekens *et al.*, 2000).

E_{WC}, evaluated from the hydrological method, was 1,788 mm for 1996 and 1,364 mm for 1997, accounting from 39.2 to 48.5% of P_G (3,687 mm for 1996 and 3,480 mm for 1997). E_{WC} from the PM equation was 221 mm for 1996 (6% of P_G) and 287 mm for 1997 (8% of P_G). The rates of E_{WC} from a wet canopy were 0.93~1.13 mm hr^{-1} for 1996 and 1997. These values far exceeded E_{WC} rates equivalent for the corresponding net radiation inputs (0.1~0.11 mm hr^{-1}), which provided only ~10% of the required energy of E_{WC}. The discrepancy between E_{WC} from these two methods was due to combined effect of energy advection and g_a estimation. Because of unaccounted advection energy portion in R_N, a lower R_N used in the PM equation produced a lesser E_{WC}. In addition, g_a calculated by Thom (1975) was much higher compared to that which was reversely solved from the PM equation, resulting in considerably lower E_{WC}.

Vernimmen *et al.* (2007) conducted the E_{WC} measurements at a lowland evergreen rain forest (LERF) and two heath forests (HF; a tall HF and a stunted HF) in Central Kalimantan, Indonesia for one year (June 2002 to June 2003). Average tree height was about 40 m for LERF, about 20 m for the tall HF and about 15 m for the stunted HF. *LAI* was inferred from biomass estimation (i.e., leaf litterfall and specific leaf area) and canopy gap fraction was assessed from canopy image analysis using photographs vertically taken in July. P_G was recorded above the canopy using a tipping bucket rain gauge. P_T was measured using 20 rain gauges in each HF site and 18 gauges in LERF site and the gauges were relocated randomly to minimize the effect of spatial variability of the measurements. The measurements of P_S was made for more than 20 trees using a stemflow collar consisting of a plastic hose fitted to the stem and the hoses drained into plastic containers. *LAI* was 9.2, 6.0, and 4.8 for the LERF, the tall HF, and the stunted HF, respectively. Canopy gap fraction was similar at three sites, showing 0.13 for the LERF and the tall HF and 0.16 for the stunted HF. During the measurement period, P_G amounted to 2,996 mm, while P_T was 2,481 mm (82.8% of P_G) for the LERF, 2,670 mm (89.1%) for the tall HF, and 2,298 mm (76.7%) for the stunted HF. The amounts of P_T were not matched with the trend of *LAI* and canopy gap fraction of each site. P_S in the LERF, the tall HF and the stunted HF was 0.8%, 1.3%, and 2.0% of P_G, indicating that P_S was almost negligible. E_{WC} derived by subtracting measured P_T and P_S from P_G was 490 mm (16.4% of P_G) for the LERF, 286 mm (9.6%) for the tall HF, and 637 mm (21.3%) for the stunted HF. These variations were attributed by those in P_T rather than P_S.

The values of E_{WC} was much larger than the estimated E_{WC} from the model of Gash *et al.* (1995), which calculated E_{WC} using the PM equation and g_a based on the method of Thom (1975). For example, E_{WC} at the stunted HF was 1.4 mm hr^{-1}, whereas the estimated E_{WC} from the model was 0.06 mm hr^{-1}. Vernimmen *et al.* (2007) suggested that such difference resulted from considerable underestimation of P_T, which was obtained using 20 rain gauges in this study. They emphasized the importance of P_T sampling schemes in tropical forest especially when water balance method was used to estimate E_{WC}.

Table 1. Precipitation (P_G) and wet canopy evaporation (E_{WC}) with plant phenology variables (plant height, plant density, and leaf area index, LAI) of various forest types

Forest Type	Species	Country	Period (month)	Plant height (m)	Plant density (trees ha^{-1})	LAI	P_G (mm yr^{-1})	E_{WC} (mm yr^{-1})	E_{WC}/P_G (%)	Reference
Coniferous forest	Spruce (*Picea sitchensis)*	UK	6	15.0	2,313*	-	2†	0.1†	5	van der Toi *et al*., 2003
	Pine (*Pinus halepensis)*	Israel	36	-		-	309	14	5	Shachnovisch *et al*., 2008
	Pine (*Pinus sylvestris* and *Pinus nigra)*	UK	-	16.0	800	-	566	145	26	Stewart, 1977
	Pine (*Pinus pinaster Ait)*	Portugal	-	-	312	2.7	800	137	17	Valente *et al*., 1997
	Corsican pine (*Pinus nigra)*	UK	18	20	600	5.1	65§	23§	35	Rutter *et al*., 1975
	Douglas fir (*Pseudotsuga menziesii)*	UK	18	24	-	12.0	65§	35§	54	Rutter *et al*., 1975
	Norway Spruce (*Picea abies)*	UK	8	-	-	-	30§	14§	47	Rutter *et al*., 1975
	Douglas fir and Hemlock (*Pseudotsuga menzesii* and *Tsuga heterophylla)*	USA	8 (1999)	65.0	-	8.1	540	103	23	Link *et al*., 2004
	Douglas fir and Hemlock (*Pseudotsuga menzesii* and *Tsuga heterophylla)*	USA	8 (2000)	65.0	-	8.1	619	155	25	Link *et al*., 2004
	Korean fir (Abies sp.)	Korea	12	23	-	7.5	1,476	85.6	6	Kang et al., 2011
Deciduous forest	Hardwood	UK	-	-		-	65§	13§	20	Rutter *et al*., 1975
	Ash and oak (south side)	Slovenia	18	8.0	310	6.6	1,319	369	28	Sraj *et al*., 2008
	Hornbeam and oak (north side)	Slovenia	18	12.3	90	6.9	1,212	303	25	Sraj *et al*., 2008
	Oak and Beech (*Quercus rabur* and *Fagus sylvatica*)	Belgium	12	30	345	-	1,448	305	21	Staelens *et al*., 2008
	Oak (*Quercus* sp. and *Carpinus* sp)	Korea	12	18	-	4.5	1,503	57.8	4	Kang *et al*., 2011
Mixed forest	Oak and birch	UK	14	22.0		3.9	773	192	25	Herbst *et al*., 2008
Rain forest	Rain forest	Puerto Rico	12	20.0-25.0	-	6-7	3,687	1,788	48	Schellekens *et al*., 2000
	Rain forest (a lowland forest)	Indonesia	12	40.0	-	9.2	2,996	490	16	Verminmen *et al*., 2007
	Rain forest (a tall heath forest)	Indonesia	12	20.0	-	6.0	2,996	286	10	Verminmen *et al*., 2007
	Rain forest (a stunted heath forest)	Indonesia	12	15.0	-	4.8	2,996	637	21	Verminmen *et al*., 2007
	Rain forest (an unlogged forest)	Indonesia	6	8.5-48.0	580	-	2,199	251	11	Asdak *et al*., 1998
	Rain forest (a logged forest)	Indonesia	13	6.8-20.0	211-278	-	2,199	219	10	Asdak *et al*., 1998
Other forests	Eucalypt (*Eucalyptus globulus*)	Portugal	-	-	1,010	3.2	800	86	11	Valente *et al*., 1997
	Laurel forest (*Myrica faya* and *Laurus azorica*)	Spanish	12	15.5	1,693	7.8	32§	13§	42	Aboal *et al*., 1999
	Evergreen Oak (*Quercus ilex)*	Portugal	24	6.6	3,5-45	-	1,736	376	22	David *et al*., 2006

*Unit of plant density is in stems ha^{-1}.
†Unit of P_G and E_{WC} is in mm hr^{-1}.
§Unit of P_G and E_{WC} is in mm mon^{-1}.

Asdak *et al.* (1998) conducted the measurement of E_{WC} over rainforests (i.e., a logged forest from November 1993 to April 1994 and an unlogged forest from June 1994 to June 1995) in Central Kalimantan, Indonesia to assess the influence of canopy structure on E_{WC}. The height of the trees in the unlogged forest varied between 8.5 to 48.0 m, while that in the logged forest ranged from 6.8 m to 20.0 m. The density of the forest was about 580 trees ha^{-1} for the unlogged forest and 211~278 trees ha^{-1} for the logged forest. E_{WC} was estimated from the water balance method. P_G was measured using one tipping bucket rain gauge for the unlogged forest and three tipping bucket rain gauges for the logged forest. In order to measure P_T, 50 gauges were equally distributed under the canopy (i.e., a 100 × 40 m plot along with five parallel transects) in the unlogged forest. In the logged forest, 55 gauges were installed according to the proportion of canopy cover and 15 tipping bucket rain gauges were randomly located in fixed positions. P_S was measured on 16 trees in different tree sizes for the unlogged forest and 20 trees for the logged forest.

The estimates of P_T, P_S, and E_{WC} were 1,918 mm (87.2% of P_G, 2,199 mm), 30 mm (1.4%), and 251 mm (11.4%) for the unlogged forest and 3,334 mm (94% of P_G, 3,563 mm), 9.6 mm (0.3%), and 219 mm (6.2%) for the logged forest, respectively. As expected, the closed canopy of the unlogged forest had higher values of P_S and E_{WC} compared to the partially closed canopy of the logged forest, indicating the influence of stand structure on the water budget components. The spatial variability of P_T was statistically significant due to variation in stand structure, resulting in P_T varying from 45 to 105% of P_G. Because there were more trees in the unlogged forest than the logged forest, P_S in the unlogged forest was higher than the logged forest. The difference in stand structure (e.g., canopy closeness) affects the canopy gap faction and canopy storage capacity and aerodynamic properties.

IV. DISCUSSION

4.1. Precipitation, throughfall, and stemflow

E_{WC} is the difference between P_G and P_T and errors in estimation of both can hamper an accurate estimation in E_{WC}. Possible errors relating to P_G measurement is a wind-induced underestimation and/or an overestimation by blow-in rain drops from the nearby higher tree crowns. And spatial variability of P_G can be possible over a short distance during a high-intensity stormy rain period. It is recommended to use a rain gauge with a wind shield to reduce the possible loss in rainfall (Lindorth, 1991) and to conduct precipitation measurement more than one position to have a representative of a measurement site.

Because canopy structure and rainfall intensity affect P_T and P_S (e.g., Sraj *et al.*, 2008), they considerably vary in most forests. Canopy characteristics include crown size, leaf shape and orientation, branch angle, bark type, and canopy gaps whereas rainfall characteristics are continuity, intensity, and the angle of rainfall. In order to overcome high spatial variability of P_T, it has been recommended to use a combination of fixed and randomly roving rain gauges (e.g., Lloyd and Marques, 1988; Sraj *et al.*, 2008). In contrast to the careful measurements of P_T, P_S has received little attention in many studies under a premise that the ratio of P_S to P_G is considerably small (<3% of P_G; Asdak *et al.*, 1998; Schellekens *et al.*, 2000). Asdak *et al.* (1998) reported that P_S was 0.3~1.4% of P_G (see above). However, P_S can be much larger (e.g., 9% of P_G for a coniferous forest, Crockford and Richardson, 1990). The influence of canopy structure on P_S can be negligible (e.g., no variation in P_S at different canopy characteristics in a mixed deciduous forest; Sraj *et al.*, 2008). These results indicate that variation of P_S is site-specific and careful methodological approach is required to make reliable measurement of P_S.

4.2. Sensible heat flux and heat storage

An attractive aspect of temperature variance method is that temperature measurements from a simple, single-level sensor can provide a reliable estimation of H under the unstable atmospheric conditions (Tillman, 1972; De Bruin *et al.*, 1993). Despite the stable atmospheric conditions during rainy period, Schellenkens *et al.* (2000) applied this method to estimate H (Eq. 14 and 15) and consequently E_{WC} applying the energy balance method (Eq. 12). According to De Bruin and Hartogensis (2005), H can be derived fairly accurately from the variance method under stable atmospheric conditions which are common for most rainy days. They used 2.3 for C_1 and 2.5 for C_2 as the empirical constants in Eq. 14.

Eddy covariance method employs a 3-dimensional sonic anemometer to measure H, whose function is sensitive to water drops. The data during rainfall need to be screened and the performance of the anemometer needs to be verified before the analysis. Kang *et al.* (2010 and 2011) presented the data filtering process collected from the anemometer (e.g., CSAT3, Campbell Sci. USA) by comparing the data from the anemometer, wetness sensors, and precipitation. The performance of the anemometer was relatively independent on rain intensity and quickly recovered after rain stopped. As indicated above, the quality of H measurements can be evaluated from a linear relationship between σ_w and u^* based on the Monin-Obukhov similarity theory (e.g., van der Toi *et al.*, 2003 and Herbst *et al.*, 2008) and from a spectral analysis (e.g., Gash *et al.*, 1999). For an accurate measurement of H, scrutiny on the data prior to the data analysis is strongly recommended.

Estimation of S is one of the challenges in calculating E_{WC} due to the difficulty and the least accuracy, and is often considered insignificant due to its small variability for periods longer than a day compared to other energy components (Oliphant *et al.*, 2004). Finnigan (2006), on the other hand, suggested that the variation in S over short periods such as an hour can be substantial and can cause larger imbalance in energy balance closure. When an attempt is made to determine S, widely varying methods and definitions add more complexity (Oliphant *et al.*, 2004). Based on the previous studies to estimate E_{WC} including S in the energy balance method, S is small because temperature and humidity changes are small and R_N is low when the canopy is wet. Thus, R_N alone is a close approximation to A to estimate E_{WC}. van der Tol *et al.* (2003) reported that E_{WC} was not sensitive to errors induced from S, showing almost no change in E_{WC} regardless of the inclusion of or exclusion of S. However, these results may not be taken as a general case because the magnitudes of S can be site-specific.

4.3. Aerodynamic conductance

Estimation of E_{WC} using the PM equation is sensitive to the value of g_a (Gash *et al.*, 1980 and 1999). In most cases, roughness length for g_a estimation considers only momentum transfer ($z_{0,M}$). A few studies suggest calculating g_a by taking an account of different transfer mechanisms of heat and water vapor ($z_{0,H}$) during rainfall (e.g., Klaassen *et al.*, 1998). According to Gash *et al.* (1999), g_a estimation considering only $z_{0,M}$ had a better result in determining E_{WC} than g_a estimation by considering both $z_{0,M}$ and $z_{0,H}$. Another commonly used method to estimate g_a (Eq. 9) illustrated dissimilar results in calculating E_{WC}. For example, Herbst *et al.* (2008) showed good agreement of E_{WC} from the water balance method with that from the PM equation with g_a obtained by Eq. 9. However, Schellekens *et al.* (2000) showed poor agreement between the measured and estimated E_{WC}. Estimation of E_{WC} may not be as sensitive to g_a as it is suggested by Gash *et al.* (1980 and 1999). E_{WC} can be derived fairly accurately from different methods of g_a estimation.

4.4. Advection of sensible heat

E_{WC} calculated from the PM equation does not include the possible influence of heat advection unlike the energy balance method that encompasses it as presented in sensible heat flux. Stewart (1977) and Schellekens *et al.* (2000) illustrated that excess energy consumed in E_{WC}, compared to net radiation, was due to additional advection energy by sensible heat. Kang *et al.* (2010) presented that consideration of the heat advection in a model performance (e.g., variable infiltration capacity (VIC) land surface model) produced more realistic E_{WC} than a gap-filling method (e.g., a modified look-up table method), resulting in a substantially increased contribution of E_{WC} to the annual ET. Their results suggest that the comparison of E_{WC} estimated from the PM and energy balance methods may not necessarily be equivalent when heat advection occurs, and thus an appropriate method of estimating E_{WC} should be carefully considered to fill the gap of the missing E_{WC} data.

V. SUMMARY

In this review, wet canopy evaporation from diverse forest types such as deciduous forest, coniferous forest, mixed forest, and rain forest was summarized. The three most commonly used methods are water balance, energy balance, and the Penman-Monteith methods. An accurate estimation of wet canopy evaporation requires reliable measurements of precipitation, throughfall, and stemflow for water balance method, and of sensible heat flux and heat storage for energy balance method, and of aerodynamic conductance and consideration of sensible heat advection for the Penman-Monteith method. In order to account for each method's shortcomings and obtain accurate estimation of wet canopy evaporation, a combination of different methods is preferable. Because the amount of wet canopy evaporation mostly depends on canopy characteristics and meteorological conditions, it is difficult to draw a general conclusion on wet canopy evaporation from particular forest types and meteorological conditions.

Seasonal and annual wet canopy evaporation in forests can be significant due to an extensive cover of forests and frequent rainfalls under the influence of the Asian monsoon in Korea. The measurements of wet canopy evaporation, however, are in paucity. KoFlux, the Korean regional flux measurement network, has been conducting the measurements of evapotranspiration using the eddy covariance system along with hydrometeorological measurements at major forest types. This allows to assess wet canopy evaporation using the combination of multiple methods and to provide the quality data on wet canopy evaporation. Considering the important contribution of wet canopy evaporation to ET, it is essential to scrutinize the role of wet canopy evaporation in the Korean forests under the monsoon climate. It is strongly recommended not only to conduct the measurements of wet canopy evaporation but also to utilize the existing infrastructure (e.g., KoFlux) accompanied with accumulated data for further analysis to provide insights on the role of wet canopy evaporation on hydrological cycles in Korea.

적 요

산림에서의 차단강수증발(E_{WC})은 증발산과 강수에 중요한 기여를 한다. 따라서, 산림에서의 수문순환을 이해하기 위해서는 정확한 E_{WC}를 산정하는 것이 중요하다. 본 고찰에서는 E_{WC}의 측정방법을 소개하고, 선행연구에서 보고된 산림형태(예를 들면, 활엽수림, 침엽수림, 혼효림, 열대림)에 따른 E_{WC} 값과 측정시 고려해야 할 사항에 대하여 논의하였다. 전형적인 E_{WC} 측정에는 물 수지, 에너지 수지 및 Penman-Monteith 방법이 있다. 전반적으로, E_{WC}는 강수량의 5~54%를 차지하였으며, 같은 산림형태내에서도 E_{WC}의 강수량에 대한 기여도는 큰 변동을 보였다. 이러한 변동에는 강수강도, 기상조건, 군락 구조 특성이 영향을 미치는 것으로 나타났다. 따라서 특정 산림형태에서의 E_{WC}의 강수량에 대한 기여도를 정량화하는 것은 어려울 것으로 판단된다. 관측시 발생하는 오차는 E_{WC} 정량화의 불확실성을 증대 시킨다. 물수지 방법의 경우, 풍속의 영향을 받는 강수 관측과 군락 구조의 공간적 비균질성의 영향을 받는 수관통과우 등의 관측 오차를 들 수 있다. 에너지 수지 방법의 경우에는 현열 플럭스와 열저류항의 관측이 주요 오차의 원인이 되며, Penman-Monteith 방법은 공기전도도와 현열의 이류 추정에서 발생하는 오차에 주의를 기울여야 한다. 각 측정방법의 오차를 최소화하고 신뢰할 수 있는 E_{WC}를 얻기위해서는 수문학적 방법과 미기상학적 방법, 즉 물 수지와 에너지 수지 방법을 함께 사용하는 것이 바람직하다.

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