Agricultural and Forest Meteorology 214-215 (2015) 402–415

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Rainfall interception and the coupled surface water and energy balance

Albert I.J.M. van Dijk[a,*], John H. Gash[b], Eva van Gorsel[c], Peter D. Blanken[d], Alessandro Cescatti[e], Carmen Emmel[f], Bert Gielen[g], Ian N. Harman[c], Gerard Kiely[h], Lutz Merbold[f], Leonardo Montagnani[i], Eddy Moors[j], Matteo Sottocornola[k], Andrej Varlagin[l], Christopher A. Williams[m], Georg Wohlfahrt[n,o]

[a] Fenner School for Environment & Society, Australian National University, Canberra, Australia
[b] Centre for Ecology and Hydrology, Wallingford, UK
[c] CSIRO Oceans and Atmosphere, Canberra, Australia
[d] Department of Geography, University of Colorado at Boulder, Boulder, USA
[e] European Commission, Joint Research Centre, Institute for Environment and Sustainability, Ispra, Italy
[f] Department of Environmental Systems Science, Institute of Agricultural Sciences, ETH Zurich, Zurich, Switzerland
[g] University of Antwerp, Wilrijk, Belgium
[h] Civil and Environmental Engineering Department, and Environmental Research Institute, University College Cork, Ireland
[i] Faculty of Science and Technology, Free University of Bolzano, and Forest Services, Autonomous Province of Bolzano, Bolzano, Italy
[j] Alterra Wageningen UR, Netherlands
[k] Department of Science, Waterford Institute of Technology, Waterford, Ireland
[l] A.N. Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences, Moscow, Russia
[m] Graduate School of Geography, Clark University, Worcester, USA
[n] Institute of Ecology, University of Innsbruck, Innsbruck, Austria
[o] European Academy of Bolzano, Bolzano, Italy

ARTICLE INFO

Article history:
Received 21 March 2015
Received in revised form 30 July 2015
Accepted 10 September 2015
Available online 29 September 2015

Keywords:
Rainfall interception
Wet canopy evaporation
FLUXNET
Water use
Evapotranspiration
Penman–Monteith theory

ABSTRACT

Evaporation from wet canopies (*E*) can return up to half of incident rainfall back into the atmosphere and is a major cause of the difference in water use between forests and short vegetation. Canopy water budget measurements often suggest values of *E* during rainfall that are several times greater than those predicted from Penman–Monteith theory. Our literature review identified potential issues with both estimation approaches, producing several hypotheses that were tested using micrometeorological observations from 128 FLUXNET sites world-wide. The analysis shows that FLUXNET eddy-covariance measurements tend to provide unreliable measurements of *E* during rainfall. However, the other micrometeorological FLUXNET observations do provide clues as to why conventional Penman–Monteith applications underestimate *E*. Aerodynamic exchange rather than radiation often drives *E* during rainfall, and hence errors in air humidity measurement and aerodynamic conductance calculation have considerable impact. Furthermore, evaporative cooling promotes a downwards heat flux from the air aloft as well as from the biomass and soil; energy sources that are not always considered. Accounting for these factors leads to *E* estimates and modelled interception losses that are considerably higher. On the other hand, canopy water budget measurements can lead to overestimates of *E* due to spatial sampling errors in throughfall and stemflow, underestimation of canopy rainfall storage capacity, and incorrect calculation of rainfall duration. There are remaining questions relating to horizontal advection from nearby dry areas, infrequent large-scale turbulence under stable atmospheric conditions, and the possible mechanical removal of splash droplets by such eddies. These questions have implications for catchment hydrology, rainfall recycling, land surface modelling, and the interpretation of eddy-covariance measurements.

* Corresponding author at: Linnaeus Way, 0200 Canberra, ACT, Australia.
E-mail address: albert.vandijk@anu.edu.au (A.I.J.M. van Dijk).

http://dx.doi.org/10.1016/j.agrformet.2015.09.006

1. Introduction

Rainfall interception is the fraction of rain that falls onto vegetation but never reaches the ground, instead evaporating from the wet canopy. The most direct way to measure rainfall interception evaporation is through the construction of weighing lysimeters, which is a major undertaking for forests (Dunin et al., 1988). Therefore interception loss (the amount of rainfall lost to wet canopy evaporation) has usually been derived as the residual between event gross rainfall measured above the canopy or in a nearby clearing, and net rainfall, the latter calculated as the sum of separately measured throughfall and stemflow below the canopy. In his pioneering paper, Horton (1919) recognised that (i) the fractions of rainfall becoming throughfall and stemflow both vary as a function of storm size and canopy characteristics; (ii) canopy water storage capacity, storm duration and the rate of wet canopy evaporation (E in mm h^{-1}) during rainfall are the important variables determining interception loss; (iii) the interception process can be conceptualised to consist of two components: wet canopy evaporation during rainfall followed by drying of the canopy once rainfall has stopped; (iv) wind can shed water from the canopy, but equally can increase E; and (v) in the absence of snow, the fractional interception loss from evergreen vegetation appears stable throughout the year, suggesting that, at least for Horton's site in New York state, USA, event-average rainfall rate (R in mm h^{-1}) and E both increase in summer in approximate proportion. Research since has generally confirmed and refined these observations (see benchmark papers reprinted in Gash and Shuttleworth, 2007). Law (1957) combined throughfall and stemflow measurements with lysimeter drainage measurements to establish a water budget for spruce and pasture. He concluded that the forests had substantially higher rainfall interception losses and, as a consequence, produced less drainage and streamflow.

Nearly a century of further water budget measurements have emphasised the role of vegetation type in determining the magnitude of rainfall interception. Forests typically intercept 10–30% (but sometimes up to half) of the rainfall and rapidly return it to the atmosphere, whereas short vegetation intercepts less rainfall (e.g., Crockford and Richardson, 2000; Horton, 1919; Leyton et al., 1967; Roberts, 1999). This difference goes far in explaining why forest establishment is commonly observed to decrease streamflow, at least in small catchment experiments (e.g., Van Dijk et al., 2012). However, the physical processes and atmospheric conditions that allow such a large fraction of rainfall to be returned to the atmosphere are poorly understood. In simulation models, rainfall interception is usually estimated in one of two ways (Muzylo et al., 2009): many conceptual hydrological models assume a fixed ratio between 'net' and 'gross' rainfall, without any attempt to reconcile the evaporation rate implied by the water budget (E_{WB}) with the constraint of balancing the energy budget. Alternatively, more detailed process hydrology and land surface models may include a canopy water balance model following the concepts originally introduced by Rutter et al. (1971). These latter models are coupled to the energy balance if they use evaporation rates based on Penman–Monteith theory (E_{PM}).

Numerous studies have combined field measurements of the canopy water budget with sub-daily or event-based interception modelling. By comparing gross and net rainfall for a series of storm events, one can use graphical or regression approaches to derive an 'effective' $\bar{E}/\bar{R}$ ratio (i.e., of event-average E and R; cf. Gash, 1979) for multiple events and a mean canopy rainfall storage capacity, S (in mm), where S is defined as the minimum depth of water needed to saturate the canopy. Alternatively, these parameters can be found by fitting the interception model against gross and net rainfall measurements per event (Gash et al., 1995) or time step (Rutter et al., 1971). Less commonly, interception has been estimated by comparing rainfall inputs to changes in total water storage in a column of soil with trees (Dunin et al., 1988). More often than not, the different methods produce results that are difficult to explain in terms of the energy balance, in that inferred E exceeds E_{PM} by a factor of two or more (Holwerda et al., 2012; Schellekens et al., 1999). In other words, the observations cannot be reconciled within a coupled water and energy balance.

The objective of this study is to better understand the reasons for the discrepancy between energy and water balance approaches in determining interception loss. This discrepancy is reflected in the uncertainty of flux estimates; in fact, commonly rainfall interception is not even considered as a separate process in the estimation of evapotranspiration by flux tower eddy covariance measurements, remote sensing and modelling methods alike. Better understanding the coupled water and energy balance during rainfall may also have important ramifications for land-use management and water policies, and for our understanding of the role of forests in the climate system (Bonan, 2008). For example, if the rate of vapour return and the rate of energy withdrawal from the boundary layer are greater than current land surface models predict, this may affect the rainfall generation downwind predicted by weather and climate models (Blyth et al., 1994). This in turn would suggest that the implications of vegetation change for rainfall and water resources availability downwind might need to be reconsidered. Conversely, if the true evaporative flux is much lower than estimated from field measurements, it might require a revision of currently held assumptions about the impact of land-cover change on the catchment water balance.

Several hypotheses have been proposed to explain the discrepancy between water budget and energy balance methods, but to the best of our knowledge they have not been systematically assessed or tested. This was the primary motivation for this study.

This article is structured as follows. The theoretical framework to analyse the energy balance theory during rainfall is provided in Section 2. The global FLUXNET 'La Thuile' database (Baldocchi, 2008; Baldocchi et al., 2001) provided unique opportunities to test several of the hypotheses. Details on data selection and the list of 128 sites are provided in Annex A, whereas methodological challenges in measurement and data processing are discussed in Section 3. The proposed causes for the discrepancy in estimated wet canopy evaporation rates are identified in Section 4, and subsequently tested in the following sections. Specifically, issues in applying Penman–Monteith theory are investigated in Section 5, whereas issues in the application of rainfall interception models are examined in Section 6. Finally, we summarise our main conclusions in Section 7. Each hypothesis tested required its own data analysis with a varying level of methodological complexity.

To maintain readability we described the data analysis methods and results together, and relegated some more intricate aspects of the methodology to Appendices B (canopy heat flux estimation) and C (simplified rainfall interception model).

2. Theory

Rutter (1967) was the first to apply the Penman (1952) equation to rainfall interception. With later modifications introduced by Monteith (1981), the Penman–Monteith equation can be used to estimate latent heat flux, λE (W m^{-2}) as:

$$\lambda E_{PM} = \frac{\Delta}{\Delta + \gamma'} A + \frac{\rho c_p}{\Delta + \gamma'} g_a (e_s - e) \tag{1a}$$

with

$$\gamma' = \gamma \left(1 + \frac{g_a}{g_s}\right), \tag{1b}$$