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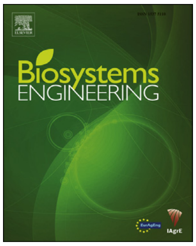

Research Paper

Estimation of wet canopy bulk stomatal resistance from energy flux measurements during sprinkler irrigation

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Bulk stomatal resistance, also known as surface resistance, is typically assumed to be zero during rainfall or other circumstances when a foliage canopy is wet, such as during sprinkler irrigation. However, some recent studies have suggested that resistance does not necessarily fall completely to zero. Although the assumption of zero bulk stomatal resistance for a wet canopy condition may be reasonable, estimation of actual evaporation as well as bulk stomatal resistance during wet conditions via the Penman–Montieth (P–M) equation is still problematic due to the difficulties in measuring the various energy fluxes in the energy balance. It has recently been demonstrated that eddy covariance (ECV) can be used to estimate the actual evapotranspiration during both irrigation and non-irrigation periods. It has also been shown that advection is important in sprinkler irrigation. This paper demonstrates how the same technique can also provide an estimate of the bulk stomatal resistance for a wet crop canopy. It is shown that when all significant energy terms (including advected energy) are taken into account, the bulk stomatal resistance was effectively zero, in contrast to dry canopy values for the same crop of order 30 s m^{-1}, both determined under midday, open sky conditions. The study also shows that ignoring advected energy can lead to an overestimation of bulk stomatal resistance and underestimation of ET when the canopy is wet.

1. Introduction

Wet canopy evaporation (i.e. actual evaporation) during sprinkler irrigation has become an issue of interest in recent years due to the scarcity of water for irrigation. It is also important during rainfall as the 'effectiveness' of rainfall is important in irrigation scheduling. It is generally accepted that evapotranspiration from a wet canopy increases considerably up to the potential evapotranspiration due to the fact that the bulk stomatal resistance, r_s (the resistance of vapour flow through stomatal openings, total leaf area and soil surface) is nearly zero (Hong, Takagi, Ohta, & Kodama, 2012). Rutter, Kershaw, Robins, and Moron (1971), Calder (1979), Gash (1979), and Gash, Valente and David (1999) reported that ET from a forest canopy increases significantly following a

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Nomenclature

CH	crop height, m
C_p	specific capacity of air, J kg^{-1} °C
$CNF(x)$	cumulative flux from upwind direction
d	zero plane displacement
DOY	day of the year
D_H	net sensible heat added horizontally by advection, W m^{-1}
D_V	net latent heat removed horizontally by advection, W m^{-1}
ECV	eddy covariance
ET	evapotranspiration
ET_{act}	actual evapotranspiration
e_a	actual vapour pressure, kPa
e_s	saturation vapour pressure, kPa
e_{uZ}	upwind absolute humidity, kPa
e_{dZ}	downwind absolute humidity, kPa
λE	latent heat flux, W m^{-1}
λE_{adj}	adjusted latent heat flux measured by eddy covariance
$f(x)$	relative contribution of surface flux
G	soil heat flux, W m^{-1}
H	sensible heat flux, W m^{-1}
k	von Karman constant
Q_o	area of flux density
R_n	net radiation, W m^{-1}
r_a	aerodynamic resistance, s m^{-1}
r_s	bulk stomatal resistance, s m^{-1}
T_{uZ}	upwind air temperatures, °C
T_{dZ}	downwind air temperatures, °C
u_*	friction velocity, m s^{-1}
U	average wind speed between the surface and the measurement height Z, m s^{-1}
u	wind speed at reference height, m s^{-1}
X	downwind length, m
γ	psychrometric constant, kPa °C^{-1}
Z	measurement height, m
z	height above the zero plane displacement, m
Z_{om}	momentum roughness length, m
Z_{oh}	vapour and heat roughness length, m
β	Bowen Ratio
ρ_a	density of air, kg m^3
γ	psychometric constant, kPa °C^{-1}
Δ	chord on the saturated vapour pressure curve, kPa °C^{-1}

wetting (rain) period. Murphy and Knoerr (1975), Stewart (1977), Van der Tol, Gash, Grant, McNeil, and Robinson (2003) and Wanqin, Kaiyun, Kellomäki, and Ling (2004) used the Penman–Monteith (P–M) equation with the bulk stomatal resistance (r_s) set to zero to give a similar result. Recent eddy covariance measurements of total evapotranspiration over cotton during sprinkler irrigation by Uddin, Smith, Hancock, and Foley (2013a, 2013b) demonstrated similar results, i.e., a significant increase in ET during and immediately following the irrigation. Nonetheless, Martinez-Cob et al. (2008) and Stambouli, Martınez-Cob, Faci, Howell, and Zapata (2012) attempted to calculate the actual evaporation during irrigation over agricultural crops and suggested that ET decreases significantly (32–55%) during sprinkler irrigation due to the reduced vapour pressure deficit in the atmosphere. Their calculation of ET was undertaken using the FAO Penman–Monteith equation of Allen, Pereira, Raes, and Smith (1998) which does not account for the reduced surface resistance of a wet canopy.

Recently, Hong et al. (2012) and Czikowsky and Fitzjarrald (2009) revealed that the surface resistance did not always fall to zero during and immediately after precipitation events and that this non-negligible surface resistance could be used to determine the proportion of the canopy that was effectively wetted. In both cases, the non-zero value of surface resistance might also have resulted from an underestimation of ET by the eddy covariance measurements. Many authors (Mahrt, 1998; Massman & Clement, 2004; Uddin et al., 2013a) have reported this as a limitation of the ECV method.

Many articles (Abdel-Aziz, Taylor, & Ashcroft, 1964; Rosenberg, 1969; Stewart, 1977; Rosenberg & Verma, 1978; Aase & Siddoway, 1982; McNaughton & Jarvis, 1983; Devitt et al., 1998; Todd, Evett, & Howell, 2000; Tolk, Evett, & Howell, 2006; Hancock, Uddin, Smith, & Foley, 2015) have reported that in wet conditions (irrigation/rain) a strong advection occurs both in forests and agricultural crops especially in arid and semi-arid conditions. This advection increases the wet canopy evaporation substantially, supplying additional energy by a sensible heat flux towards the surface rather than the atmosphere. Abdel-Aziz et al. (1964) tested the Penman formula under semi-arid conditions and drew the conclusion that neither the Penman formula nor any of the modifications adequately accounted for advective energy.

The available literature indicates that most of the past research relating to surface resistance of wet plant canopies has been conducted in forests, and only a limited number of studies have attempted to estimate the wet canopy resistance of agricultural crops. None have included an accurate analysis of advected energy. A recent study by Uddin et al. (2013a, 2013b) and Hancock et al. (2015) demonstrated that a precision energy balance involving eddy covariance measurements is able to provide a measure of the wet canopy evaporation during sprinkler irrigation. It follows that these measurements could also be used to estimate the stomatal resistance during irrigation.

Hence, the objectives of this study are: (i) to estimate the bulk stomatal resistance of a wet canopy agricultural crop (cotton) during sprinkler irrigation, and (ii) to determine the significance of advected energy.

2. Materials and methods

2.1. Study site, experimental description and measurements

The data used in this study were used in earlier studies by the authors to determine the evaporation during sprinkler irrigation of cotton (Uddin et al., 2013a, 2013b) and to quantify the role of advection on evaporation during irrigation (Hancock