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Estimation of transpiration fluxes from rainfed and irrigated sugarcane in South Africa using a canopy resistance and crop coefficient model

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ABSTRACT

The area under sugarcane is rapidly growing worldwide. The consequences of such growth on basin scale water consumption and competing water resources need to be understood. Conventional models for sugarcane evapotranspiration have shown limitations for different environmental conditions. To improve current estimations of sugarcane water consumption, hourly and daily transpiration of rainfed sugarcane in Kwazulu-Natal (South Africa) and daily transpiration for irrigated sugarcane in Mpumalanga (South Africa) were calculated by using the Penman-Monteith equation (T_{PM}) with a variable canopy resistance. Canopy resistance was calculated with the Jarvis-Stewart model from calibrated environmental stress functions. The classic FAO56 crop coefficient approach (T_{FAO56}) was also investigated and crop coefficient values, crop basal coefficient and water stress coefficient were derived. There were differences between derived crop coefficient values and FAO56 weather-adjusted values. Derived crop basal coefficient (K_{cb}) was 0.9 for rainfed and irrigated sugarcane, which was lower than FAO56 weather-adjusted values of 1.19 for rainfed and 1.15 for irrigated at mid-stage. The reduction of the crop basal coefficient with the water stress coefficient resulted in an underestimation of transpiration for rainfed sugarcane. This indicates that water uptake under stress conditions is a complex process, not easy to model as water can be extracted from considerable depths. Daily estimates obtained from T_{PM} outperformed those obtained from T_{FAO56} when compared to Bowen ratio and Surface Renewal system field measurements. For rainfed sugarcane with water-stressed conditions the T_{FAO56} RMSE was 1.55 mm day^{-1} compared to 0.3 mm day^{-1} for T_{PM}. For rainfed sugarcane with water-unstressed conditions the T_{FAO56} RMSE was 0.5 mm day^{-1} and the T_{PM} RMSE was 0.22 mm day^{-1} for T_{PM}. For irrigated sugarcane the T_{PM} RMSE of 0.47 mm day^{-1} was slightly lower than the T_{PM} RMSE of 0.49 mm day^{-1}, and T_{PM} showed better correlation with an R^2 of 0.85 compared to an R^2 of 0.64 for T_{FAO56}. This suggests that calibrated variables of the Jarvis-Stewart model for sugarcane proved to be suitable for both rainfed and irrigated sugarcane in South Africa. More research is needed to verify the validity of the calibrated stressed functions in other regions with high intensity of sugarcane plantations.

1. Introduction

Sugarcane is grown in tropic and sub-tropic zones, where water is often scarce. Due to increasing ethanol and sugar demands, the area under sugarcane is rapidly growing worldwide (Rudorff et al., 2010). Sugarcane water consumption is relatively high. Large scale increases in sugarcane farming compared to other crops may increase overall catchment evapotranspiration (ET) and reduce streamflow. Efficient irrigation systems and good on-farm water management practices are crucial elements to optimize its water consumption. The extent of commercial rainfed and irrigated sugarcane systems in South Africa provides an opportunity to evaluate current methods for computing sugarcane ET (ET_c) over a wide range of conditions, and to derive a general model for this purpose. A valuable data set for evaluation of existing ET_c methodologies

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Nomenclature

List of symbols

c_p	Specific heat at air constant pressure ($\mathrm{J\,kg^{-1}\,{}^\circ C^{-1}}$)
D	Vapor pressure deficit (kPa)
D_r	Root zone depletion (mm)
$D_{0.5}$	Fitting D value for S_D (kPa)
d	Zero plane displacement of reference surface (m)
E	Soil evaporation
E_{FAO56}	E based on ET_0 and K_e ($\mathrm{mm\,day^{-1}}$)
ET_0	Grass reference evapotranspiration ($\mathrm{mm\,hour^{-1}}$) or ($\mathrm{mm\,day^{-1}}$)
ET	Evapotranspiration
ET_c	Sugarcane evapotranspiration
ET_{cane}	Sugarcane reference evapotranspiration
$f(D)$	Vapor pressure stress function
$f(Ta)$	Temperature stress function
$f(Rs)$	Solar radiation stress function
G	Soil heat flux ($\mathrm{W\,m^{-2}}$)
G_c	Canopy conductance ($\mathrm{m\,s^{-1}}$)
$G_{c,max}$	Maximum G_c ($\mathrm{m\,s^{-1}}$)
k	Light extinction coefficient (−)
k_1	Fitting value stress function S_D(−)
k_2	Fitting value stress function S_D (−)
k_3	Fitting value stress function S_r ($\mathrm{W\,m^{-2}}$)
k_4	Fitting value stress function S_m (−)
K	Von Karman's constant
K_c	Crop coefficient (−)
K_{cb}	Crop basal coefficient (−)
K_e	Soil evaporation coefficient (−)
K_s	Water stress coefficient (−)
LAI	Leaf area index ($\mathrm{m^2\,m^{-2}}$)
LAI_{eff}	Effective LAI ($\mathrm{m^2\,m^{-2}}$)
$NDVI$	Normalized difference vegetation index (−)
PM	Penman-Monteith
p	Fraction of TAW
RH	Relative humidity (%)
r_a	Aerodynamic resistance ($\mathrm{s\,m^{-1}}$)
$r_{a,canopy}$	Aerodynamic resistance canopy ($\mathrm{s\,m^{-1}}$)
r_c	Canopy resistance ($\mathrm{s\,m^{-1}}$)
r_s	Surface resistance ($\mathrm{s\,m^{-1}}$)
$r_{s,min}$	Minimum stomatal resistance ($\mathrm{s\,m^{-1}}$)
R_n	Net radiation ($\mathrm{W\,m^{-2}}$)
$R_{n,canopy}$	Net radiation intercepted by the canopy ($\mathrm{W\,m^{-2}}$)
R_s	Solar radiation ($\mathrm{W\,m^{-2}}$)
$R_{s,max}$	Maximum R_s ($\mathrm{W\,m^{-2}}$)
T	Crop transpiration
T_{FAO56}	T based on ET_o and $K_{cb}K_s$ ($\mathrm{mm\,hour^{-1}}$) or ($\mathrm{mm\,day^{-1}}$)
T_{PM}	T based on PM with variable r_c ($\mathrm{W\,m^{-2}}$) or ($\mathrm{mm\,hour^{-1}}$) or ($\mathrm{mm\,day^{-1}}$)
TAW	Total available soil water in the root zone (mm)
Ta	Air temperature (°C)
Ta_{max}	Maximum Ta (°C)
Ta_{min}	Minimum Ta (°C)
Ta_{opt}	Optimal Ta (°C)
u_z	Wind speed at height z ($\mathrm{m\,s^{-1}}$)
z	Height above the ground (m)
z_{oh}	Surface roughness length for sensible heat transfer (m)
z_{om}	Surface roughness length for momentum (m)

Greek symbols

γ	Psychrometric constant ($\mathrm{kPa\,{}^\circ C^{-1}}$)
θ	Soil moisture content ($\mathrm{cm^3\,cm^{-3}}$)
θ_e	Effective fraction of available soil moisture (−)
$f(\theta_e)$	Soil moisture stress function
θ_{FC}	Field capacity water content ($\mathrm{cm^3\,cm^{-3}}$)
θ_r	Residual water content ($\mathrm{cm^3\,cm^{-3}}$)
Δ	Slope of vapor pressure curve ($\mathrm{kPa\,{}^\circ C^{-1}}$)
λE	Latent heat flux ($\mathrm{W\,m^{-2}}$) or ($\mathrm{mm\,hour^{-1}}$) or ($\mathrm{mm\,day^{-1}}$)
ρ	Density of air ($\mathrm{kg\,m^{-3}}$)
ψ_{sh}	Stability function for momentum (−)
ψ_{sm}	Stability function for temperature (−)

was derived from two studies in commercial rainfed (Jarmain and Everson, 2002) and irrigated (Jarmain et al., 2014) sugarcane fields in South Africa.

ET_c can be measured by means of a Bowen ratio system (e.g. Grantz and Meinzer, 1991; Inman-Bamber and McGlinchey, 2003; Jarmain and Everson, 2002), eddy covariance (e.g. Cabral et al., 2012; Pakoktom et al., 2013), a Surface Renewal system (Jarmain et al., 2014), weighing lysimeters (Olivier and Singels, 2012) or other systems. Although these methods are inappropriate for routine measurements, they are used for evaluation of indirect ET_c estimates. For example, Inman-Bamber and McGlinchey (2003) compared ET_c measurements from a Bowen ratio system with estimates by the direct Penman Monteith (PM) equation using a constant value for sugarcane surface resistance and fixed crop height for deriving aerodynamic resistances. They indicated that prediction errors of ET_c in a version of the direct PM equation could be rectified by changing the surface resistance. They compared their ET_c measurements with grass reference ET (ET_0) estimates derived from the standardized PM equation by the United Nations Food and Agriculture Organization (FAO56) and the combination of crop coefficient (K_c) for sugarcane as proposed by Allen et al. (1998). They confirmed the K_c values of 0.4 at the initial stage and 1.25 at mid-stage in FAO56 to be correct. The value of 0.7 for the end stage was not supported but they suggested a value of 1.25 for an adequate water supply throughout crop development. Olivier and Singels (2012) evaluated the effect of two crop residue layers and no residue cover on ET_c, measured with weighing lysimeters in South Africa. They calculated K_c values from ET_c measurements and ET_0 estimates. Averaged K_c values for the initial stage were 0.31 for no residue cover (Bare), 0.25 for soil covered by a light layer of cane tops (Tops) and 0.18 for soil covered by a heavy layer of tops and dead leaves (Trash). These values were lower than the K_c value of 0.4 proposed in FAO56. Averaged K_c values for mid-stage were 1.12 for Bare, 1.01 for Tops and 1.13 for Trash, which were lower than the FAO56 K_c value of 1.25. Averaged K_c values for the end stage were 1.1 for Bare, 0.8 for Tops and 0.78 for Trash, which were higher than the K_c value of 0.7 proposed in FAO56. Thus, in the absence of locally measured K_c coefficients, generic values for K_c are often used in hydrological studies and water management (ignoring the specific environmental conditions to which the generic K_c applies).

Estimation of ET_c may be improved by decoupling the transpiration component (T) from the soil evaporation (E) component, as transpiration is disconnected from the soil physical conditions related to E. Allen et al. (1998) in their standard FAO56 approach also provide a procedure based on a two-layer crop coefficient model, which incorporates a crop basal coefficient (K_{cb}) and a coefficient for soil evaporation (K_e). This method is limited to well-watered conditions, and measurement of T for crops under water stress conditions (including rainfed) are likely to be overestimated.