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Comment on "Technical Note: On the Matt–Shuttleworth approach to estimate crop water requirements" by Lhomme et al. (2014)

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Abstract

It is clear from Lhomme et al. (2014) that aspects of the explanation of the Matt–Shuttleworth approach can generate confusion. Presumably this is because the description in Shuttleworth (2006) was not sufficiently explicit and simple. This paper explains the logic behind the Matt–Shuttleworth approach clearly, simply and concisely. It shows how the Matt–Shuttleworth can be implemented using a few simple equations and provides access to ancillary calculation resources that can be used for such implementation. If the crop water requirement community decided that it is preferable to use the Penman–Monteith equation to estimate crop water requirements directly for all crops, the United Nations Food and Agriculture Organization could now update Irrigation and Drainage Paper 56 using the Matt–Shuttleworth approach by deriving tabulated values of surface resistance from Table 12 of Allen et al. (1998), with the estimation of crop evaporation then being directly made in a one-step calculation using an equation similar to that already recommended by the United Nations Food and Agriculture Organization for calculating reference crop evaporation.

1 Introduction

It is clear from Lhomme et al. (2014) that aspects of the explanation of the Matt–Shuttleworth approach can generate confusion. Presumably this is because the description in Shuttleworth (2006) was not sufficiently explicit and simple. I welcome the opportunity to redress this and I am grateful to Lhomme et al. (2014) for bringing this need to my attention.

The fundamental premise of the Matt–Shuttleworth approach is that describing evapotranspiration from a crop canopy using the Penman–Montieth Equation (Monteith, 1964) (hereafter referred to as PM) is theoretically superior to describing evapotranspiration using the formula given (for example) as Eq. (1) of Lhomme et al. (2014) (hereafter referred to as FAO). Justifications for this premise are as follows.

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1. It is now widely accepted in advanced models of surface–atmosphere energy exchanges that the control exerted by vegetation can be represented by a plant-dependent surface resistance, r_{sc}, which is broadly equivalent to the canopy average effect of stomatal resistance, and that the control exerted by turbulent transfer can be represented by an aerodynamic resistance, r_{ac}, dependent on wind speed and aerodynamic properties of the canopy. PM merges these two resistances with the surface energy balance. In such advanced models r_{sc} is either assumed fixed or dependent on in-canopy environmental variables and soil moisture if these affect stomatal resistance, but it is never the complex function of weather variables and K_c given as Eq. (10) of Lhomme et al. (2014).

2. The capability of PM to describe crop evapotranspiration is now explicitly accepted as being appropriate by the crop water requirement community because the United Nations Food and Agriculture Organization recommends that reference crop evaporation is calculated from PM (Allen et al., 1998).

2 How is surface resistance calculated in the Matt–Shuttleworth approach?

In the Matt–Shuttleworth approach r_{sc} is a crop-dependent, "effective" value for each day during the crop growth cycle. It may be calculated from the tabulated value of K_c on a particular day in the seasonal cycle (see below), but *not* using weather variables on that day. In fact it is the effective value of $\alpha_a \alpha_s$ in Eq. (7) of Lhomme et al. (2014) on a particular day which should be calculated from r_{sc} and weather data on that day. The surface resistances calculated from Eq. (10) shown in Figs. 2 and 3 of Lhomme et al. (2014) exhibit meteorological dependence only because the dependence that is actually present in $\alpha_a \alpha_s$ is wrongly ascribed to surface resistance when Eq. (7) is inverted to Eq. (10). Moreover, the values of surface resistance labelled M-S in Figs. 2 and 3 are *not* the crop-dependent, effective values given by the Matt–Shuttleworth approach because they are calculated under the authors' mistaken belief that on each day

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the Matt–Shuttleworth approach assumes reference crop evapotranspiration is equal to the value given by the Priestley–Taylor equation (Priestley and Taylor, 1972). Readers should be aware that the Conclusions section of Lhomme et al. (2014) is based on calculations illustrated in these two problematic figures.

The value of r_{sc} in the Matt–Shuttleworth approach for each day would ideally be determined from a seasonal model that has been calibrated by field experiment (in much the same way that the fixed value $70\,\mathrm{s\,m^{-1}}$ was defined for the reference crop). Shuttleworth (2006) recommends this, but then seeks to make interim estimates of r_{sc} from the seasonal models of K_c in the existing literature. Presumably there must be environmental conditions when there is a definable pairing between the effective values of K_c and r_{sc}, specifically the prevailing meteorological conditions when the field experiment to determine K_c was carried out. If these meteorological conditions were known then the same data used to specify the particular value of K_c relevant in these conditions could alternatively be used to specify the equivalent value of r_{sc} used in the Matt–Shuttleworth approach. But unfortunately the meteorological conditions when tabulated values of K_c were defined are not available, hence an assumption is required.

Allen et al. (1998) deem the tabulated values of K_c most reliable in "sub-humid conditions" for wind speed $2\,\mathrm{m\,s^{-1}}$, and provide an empirical formula to correct K_c for crops with different heights exposed to different wind speeds in different atmospheric aridity conditions. (Note that such an empirical correction is not required when using the Matt–Shuttleworth approach because crop-specific aerodynamics rather than reference crop-specific aerodynamics are used.) In the Matt–Shuttleworth approach the preferred wind speed of $2\,\mathrm{m\,s^{-1}}$ is adopted, but specification of "sub-humid" is also required to establish pairing between the tabulated value of K_c on a particular day and required value of r_{sc}. Allen et al. (1998) specify sub-humid conditions as being when average minimum daytime relative humidity is 45 %. However, this specification does not recognize the long established fact that both available energy and vapor pressure deficit control evapotranspiration (Penman, 1948), which suggests that characterizing the influence of atmospheric humidity relative to the influence of available energy is arguably a more appropriate way to define the meaning of sub-humid conditions. For this reason, the climatological resistance, r_{clim}, is adopted as a measure of atmospheric aridity in the Matt–Shuttleworth approach, this being calculated from:

$$r_{\mathrm{clim}} = \frac{\rho c_p D_2}{\Delta A} \qquad \text{or} \qquad r_{\mathrm{clim}} \approx \frac{187\,250 \gamma D_2}{\left(275 + T_2^{\mathrm{c}}\right) \Delta A_{\mathrm{mm}}} \, \mathrm{m\,s^{-1}} \tag{1}$$

where ρ (kg m^{-3}) is the density of air, c_p (J kg^{-1} K^{-1}) is the specific heat of moist air, D_2 (kPa) is the vapor pressure deficit and T_2^{C} (°C) the air temperature both at 2 m, Δ (kPa K^{-1}) is the rate of change of saturated vapor pressure with temperature, γ (kPa K^{-1}) is the psychrometric constant, and A (W m^{-2}) is the available energy which becomes A_{mm} (mm) when expressed as evaporated water equivalent. The pairing between the tabulated value of K_{c} and value of r_{sc} is then defined by specifying r_{clim} in sub-humid conditions when the tabulated value of K_{c} in Eq. (1) of Lhomme et al. (2014) provides its best estimate of crop evapotranspiration.

Shuttleworth (2006) *does not* assume that reference crop evapotranspiration rate, E_{o}, is equal to the Priestley–Taylor estimate of evapotranspiration rate, E_{PT}, every day as Lhomme et al. (2014) wrongly assume. This is obviously not an acceptable assumption because, as shown in Eq. (23.20) of Shuttleworth (2012), the relationship between E_{o} and E_{PT} on a particular day can in fact be expressed as a function of r_{clim} on that day. However, the condition $E_{\mathrm{o}} = E_{\mathrm{PT}}$ is used to specify the value of r_{clim} considered characteristic of sub-humid conditions (i.e., the ratio of $(\rho c_p D_2)$ to (ΔA) in sub-humid conditions). One argument for selecting this condition is the history behind the calculation of reference crop evaporation. The original approach in Doorenbus and Pruit (1977) – who largely defined the tabulation of K_{c} – allowed calculation of reference crop evaporation in several different ways, including as E_{PT}. Later Allen et al. (1998) added the calculation based on PM which is here referred to as E_{o}. If either $K_{\mathrm{c}}E_{\mathrm{o}}$ or $K_{\mathrm{c}}E_{\mathrm{PT}}$ can be used to calculate crop evapotranspiration optimally in sub-humid conditions, then $E_{\mathrm{o}} = E_{\mathrm{PT}}$ can presumably be used to specify the ratio of $(\rho c_p D_2)$ to (ΔA) (i.e.,

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the value of r_clim) in these sub-humid conditions. In addition, Shuttleworth (2006) describes modeling studies of feedback interactions between the atmospheric boundary layer and surface exchanges at regional scale which suggest there is a range of surface resistances and atmospheric aridity when the concept of "potential evaporation" applies, and when there is at least approximate equality between E_PT and evapotranspiration calculated from PM for a range of surface resistances typical of pastureland and many agricultural crops, including 70 s m^{-1}.

Specifying sub-humid conditions from $E_\text{o} = E_\text{PT}$ ultimately leads to the result that r_sc should be calculated from K_c for a preferred value of r_clim given by:

$$r_\text{clim}^\text{pref} = 104\left(1.26\frac{\Delta + 1.67\gamma}{\Delta + \gamma} - 1\right)\,\text{m}\,\text{s}^{-1}. \quad (2)$$

To calculate the required value of r_sc Shuttleworth (2006) then simply adopts the definition of $K_\text{c} = \alpha_a \alpha_s$ given (for example) as Eq. (7) of Lhomme et al. (2014) and inverts this to express r_sc as a function of K_c, but with the ratio of ($\rho c_p D_2$) to (ΔA) set equal to the (now defined) value of $r_\text{clim}^\text{pref}$ in sub-humid conditions. However, in order to allow this calculation for crops with height greater than 2 m the interrelationship between r_sc and K_c is first recast to a height of 50 m, and appropriate forms of aerodynamic resistances and vapor pressure used, these being defined using Eq. (24) with $Z = 50$ m, and Eqs. (27) and (29) in Shuttleworth (2006).

However, Eq. (2) means the value of r_clim when r_sc should be calculated is not yet fully specified because Δ it is a function of temperature. Ideally the temperature selected to calculate Δ would be that when K_c was calibrated, but this temperature is generally not known. For this reason Shuttleworth and Wallace (2010) investigated the sensitivity of the calculation of r_sc to temperature and on this basis recommended using 20 °C, which implies r_sc is optimally calculated from K_c when $r_\text{clim}^\text{pref}$ is 55 s m^{-1}. For this value of $r_\text{clim}^\text{pref}$ and a 2 m wind speed of 2 m s^{-1}, the second "advective" term in the numerator of the equation used to calculate E_o is, for example, around 50 % of the first "radiation" term; and for this value of $r_\text{clim}^\text{pref}$ the Allen et al. (1998) criteria that relative humidity is greater than 45 % is met at 20 °C for A_{mm} values in the range zero to 7 mm day^{-1}. By using the preferred values of temperature (20 °C) and wind speed (2 m s^{-1}) and assuming a pressure of 100 kPa in Eqs. (23.34), (23.35) and (23.36) of Shuttleworth (2012) then simplifying, it can be shown that:

$$r_{\mathrm{sc}} = \frac{1.2614 R_{\mathrm{c}}^{50} + 168.66}{K_{\mathrm{c}}} - 1.5881 R_{\mathrm{c}}^{50}\ \mathrm{s\,m^{-1}} \qquad (3)$$

where

$$R_{\mathrm{c}}^{50} = 3.56 \ln\left[\frac{(50-0.67h_{\mathrm{c}})}{0.123h_{\mathrm{c}}}\right] \ln\left[\frac{(50-0.67h_{\mathrm{c}})}{0.0123h_{\mathrm{c}}}\right] \ \text{(no units)} \qquad (4)$$

with h_{c} being the height of the crop. Table 23.5 of Shuttleworth (2012) gives values of r_{sc} calculated from selected values of K_{c} and h_{c} representative of tabulated values during Stage 3 of crop growth.

3 How is surface resistance applied in the Matt–Shuttleworth approach?

Because some crops have a crop height greater than 2 m, it is preferable to use the value of r_{sc} in a version of PM which applies for a reference height of 50 m. This version of PM can be written in a form similar to that recommended by the United Nations Food and Agriculture Organization for calculating reference crop evaporation, see Eq. (23.37) of Shuttleworth (2012), thus:

$$\mathrm{ET_c} = \left(\frac{\Delta}{\Delta+\gamma^{**}}\right) A_{\mathrm{mm}} + \left(\frac{\gamma}{\Delta+\gamma^{**}}\right)\left(\frac{187\,250}{275+T_2^{\mathrm{c}}}\right)\left(\frac{D_{50}}{D_2}\right)\frac{u_2 D_2}{R_{\mathrm{c}}^{50}}\ \mathrm{mm} \qquad (5)$$

where u_2 ($\mathrm{m\,s^{-1}}$) and D_2 (kPa) are the wind speed and vapor pressure deficit at 2 m, $\gamma_m^{**} = \gamma(1 + r_{\mathrm{sc}} u_2 / R_{\mathrm{c}}^{50})$, and

$$\left(\frac{D_{50}}{D_2}\right) = \left(\frac{(\Delta+\gamma)302 + 70\gamma u_2}{(\Delta+\gamma)208 + 70\gamma u_2}\right) + \frac{1}{r_{\mathrm{clim}}}\left[\left(\frac{(\Delta+\gamma)302 + 70\gamma u_2}{(\Delta+\gamma)208 + 70\gamma u_2}\right)\left(\frac{208}{u_2}\right) - \frac{302}{u_2}\right] \text{ (no units).} \tag{6}$$

Note that in Eq. (6) r_{clim} is the value calculated by Eq. (1) using measured values of weather variables on the day that $\mathrm{ET_c}$ is calculated, not $r_{\mathrm{clim}}^{\mathrm{pref}}$.

4 Concluding comments

If the crop water requirement community decided that it is preferable to use PM to estimate crop water requirements directly for all crops, the United Nations Food and Agriculture Organization could now update Irrigation and Drainage Paper 56 using the Matt–Shuttleworth approach, i.e., using Eq. (3) to derive tabulated values of r_{sc} from Table 12 of Allen et al. (1998), with a one-step estimate of $\mathrm{ET_c}$ then directly made from Eq. (5).

To facilitate the application of the Matt–Shuttleworth approach I provide two Excel spreadsheets (amongst other files) at http://www.hwr.arizona.edu/~shuttle/Terrestrial_Hydrometeorology/ which are ancillaries to this paper. The first spreadsheet uses Eqs. (3) and (4) to duplicate the calculations of r_{sc} in Table 23.5 of Shuttleworth (2012): it can be modified to make calculations for other combinations of K_{c} and h_{c}. The second spreadsheet is edited from that used to calculate Table 23.6 of Shuttleworth (2012) and makes example calculations of $\mathrm{ET_c}$ using the Matt–Shuttleworth approach, i.e. Eqs. (5) and (6), and also using the traditional FAO method for several example crops (hypothetically) growing at three example sites (Oxford, Tucson, and Manaus) on three example days. It can be modified to make (or test) such calculations with alternative data from alternative sites. It would be interesting if the authors of Lhomme et al. (2014) were to make a numerical exploration for a broad range of atmospheric conditions which compares the calculated values of ET_c using the FAO method and the (correct) Matt–Shuttleworth approach. Based on previous studies of this type (e.g., Shuttleworth and Wallace, 2010) it is likely that the two estimates of ET_c will often be similar but they may differ significantly for taller crops growing in windy conditions and a dry atmosphere.

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