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WUE estimation by using direct and indirect modelling of water losses of sugar beet cropped in a semi-arid environment

R.M. Ferrara, M. Introna, N. Martinelli, G. Rana

CRA - Research Unit for agriculture in dry environments, Bari, Italy

Abstract. Many expressions of water use efficiency (*WUE*) have been proposed in literature, but the most diffuse one is based on the ratio between crop yield and cumulative actual evapotranspiration (ET_a). A big error can be made if the water consuming is badly evaluated. The best way to give the ET_a is to measure it, but often it is estimated. At plot scale, there are two different methods for estimating ET_a: the direct and the indirect method, both based on the Penman-Monteith model. In order to evaluate the errors made on *WUE* due to the ET_a modelling, in this work we evaluate the water use efficiencies in the growth period when *LAI* is greater or equal to 2. Three methods of ET_a estimation is used (direct, single K_c, dual K_c) for a sugar beet crop cultivated in Capitanata Plain (southern Italy) during two experimental field campaigns. The actual evapotranspiration has been measured directly by eddy covariance or by aerodynamic method. All the measurements have been done at hourly scale, but the estimation are presented at daily and seasonal scales. The results show that for *WUE* indicators, the direct method of ET_a calculation gave better performances with respect to the indirect ones, with worst results for the single crop coefficient approach.

Keywords. Actual evapotranspiration – Penman-Monteith – Crop coefficient.

Estimation de l'efficience d'utilisation de l'eau (WUE) par modélisation directe et indirecte des pertes d'eau de la betterave sucrière cultivée en région semi aride.

***Résumé**. Plusieurs expressions de l'efficience d'utilisation de l'eau (WUE) sont disponibles dans la littérature scientifique, mais la plus diffuse est celle basée sur le rapport entre la production d'une culture et l'evapotranspiration réelle cumulée (ET_a). Une grossse erreur peut être commise si la consommation en eau d'une culture n'est pas bien déterminée. La façon la plus correcte pour déterminer la WUE est de la mesurer, mais en tout cas elle peut être estimée. A l'échelle de la parcelle deux méthodes peuvent être considérées: l'une directe et l'autre indirecte ; toutes les deux sont basées sur le modèle de Penman-Monteith. Pour évaluer l'erreur sur la WUE provoquée par la modélisation de l'ET_a, nous calculons dans cet article l'efficience d'utilisation de l'eau dans la période de croissance d'une culture, quand l'indice foliaire (LAI) est égal ou plus grand de 2. Trois méthodes d'estimation de l'ET_a sont analysées (directe, single K_c et dual K_c) pour une culture de betterave à sucre, cultivée en Capitanata (Italie du sud), pendant deux campagnes expérimentales. L'evapotranspiration réelle a été mesurée par deux techniques: eddy covariance et technique aérodynamique. Les mesures ont été faites à l'échelle horaire, tandis que les estimations sont présentées à l'échelle journalière et saisonnière. Les résultats montrent que quand l'ET_a est calculée par la méthode directe, les indicateurs de WUE donnent des valeurs beaucoup plus fiables de celles obtenues en utilisant les méthodes indirectes, surtout pour l'approche du K_c single.*

***Mots-clés.** Evapotranspiration réelle – Penman-Monteith – Coefficient cultural.*

I – Introduction

Since the first studies, different expressions (water use efficiency, crop water productivity) have been proposed and discussed (among others, Feddes, 1985; Pereira *et al.*, 2002; Zwart and Bastiaanssen, 2004). In general, water use efficiency (*WUE*) can be written as following:

$$WUE \text{ (kg m}^{-3}\text{)} = \text{yield / water consumption} \qquad (1)$$

In Eq. (1), if an agronomic approach is chosen (Katerji *et al.*, 2008), the term "yield", can indicate two parameters: i) Global dry matter yield expressed in kg m^{-2}; ii) Marketable crop yield expressed in kg m^{-2}. From applicative point of view, it is worthwhile to mention another important index to estimate the path of water productivity in time, given in term of the dry or fresh biomass per water consuming by evapotranspiration (WUE_b), evaluated during the whole growing season:

$$WUE_b \text{ (kg m}^{-3}\text{)} = \text{biomass / water consumption} \qquad (2)$$

Regarding the water consuming, from the water used by crops during the growing season, 99% is released as water vapour toward the atmosphere. For this reason crop water use is considered approximately equal to actual evapotranspiration (ET_a) in mm or in m^3. This approximation, discussed by Feddes in 1985 is valid only at full crop canopy, thus when leaf area value is over 2 (Katerji and Perrier, 1985). Above this leaf area value, ET_a is nearly similar to crop water use, because evaporation is very low even when soil surface is wet (Ritchie, 1983). On plot scale, ET_a can be determined through different approaches; in particular, ET_a can be measured directly using weighing or drainage lysimeters or can be measured indirectly through micro-metrological methods (Bowen, aerodynamic). These methods result as the most precise to determine ET_a. However, in order to use these methods, precautions are necessary, mainly in the Mediterranean region (Katerji and Rana, 2008).

Moreover, ET_a can be measured through the calculation of soil water balance. This approach is however based on some hypothesis (the capillary rise, runoff and deep percolation are supposed insignificant, rainfall are all efficient). However, some hypotheses are not valid mainly under Mediterranean climatic conditions (Katerji and Rana, 2008).

By model, ET_a can be calculated according to many methods developed in the past decades by different authors (see Katerji and Rana, 2008 for an exhaustive review of the *ET* models).

Finally, in many studies ET_a is not measured, but it is replaced in the Eqs. (1) and (2) by the amount of water supplied by irrigation. The overestimation of water necessary for crops is one of the characteristics of irrigation practice in the Mediterranean region, and this makes difficult the understanding of the obtained *WUE* values (e.g. Shideed *et al.*, 2005).

From the applicative point of view, at plot scale, almost in all the scientific works, ET_a in *WUE* and WUE_b is deduced by models. Generally speaking, there are two different methods for estimating ET_a: the direct and the indirect methods, both based on the Penman-Monteith model. In particular, in the direct approach the measurements of meteorological variables must be done on the crop, while in the indirect one it is enough to measure the meteorological variables on a reference grass (to obtain the reference evapotranspiration, ET_0) and to estimate ET_a as product of ET_0 and a crop coefficient K_c. This latter can be calculated by means of two approaches: the single and the dual crop coefficient approaches.

Considering that an acceptable error of ±20% can be admitted in both numerator and denominator of Eqs. (1) and (2), than a total error of ±40% can be made in the evaluation of *WUE* of a crop with consequent misestimating of irrigation scheduling and programming. For the reasons above described, in this work ET_a is evaluated only when LAI≥2. Thus, here we evaluate the water use efficiency when LAI≥2 (WUE_2 and the WUE_{2b}) using the above mentioned methods of ET_a estimation (direct, single K_c, dual K_c) for a sugar beet crop cultivated in Capitanata Plain, in order to give indications about the best way to evaluate *WUE* at plot scale. The site is submitted to Mediterranean semi-arid climate.

II – Material and methods

1. Theory

The analysis of the crop actual evapotranspiration was made on the basis of the Penman-Monteith (PM) model. In this model, which is theoretically applicable only to the hourly time scale (index "h"), the ET_a is written as:

$$ET_{a,h} = \frac{1}{\lambda}\frac{\Delta A + \rho c_p D/r_a}{\Delta + \gamma\left(1 + r_c/r_a\right)} \tag{3}$$

where $A=R_n\text{-}G$ is the available energy (W m^{-2}), ρ is the air density (kg m^{-3}), Δ is the slope of the saturation pressure deficit versus temperature function (kPa C^{-1}), γ is the psychrometric constant (kPa C^{-1}), c_p is the specific heat of moist air (J kg^{-1} C^{-1}), D the vapour pressure deficit of the air (kPa), r_c is the bulk canopy resistance (s m^{-1}) and r_a is the aerodynamic resistance (s m^{-1}), λ is the latent heat of evaporation (J kg^{-1}). The aerodynamic resistance r_a was calculated between the top of the crop and a reference point z located in the boundary layer above the canopy, following Perrier (1975a; 1975b), as:

$$r_a = \frac{\ln\frac{z-d}{z_0}\ln\frac{z-d}{h_c-d}}{k^2 u} \tag{4}$$

where u (m s^{-1}) is the wind speed measured 2 m above the crop; d (m) is the zero plane displacement estimated as $d=0.67h_c$, with h_c mean height of the crop (m); k is the von Kármán constant and z_0 (m) is the roughness length estimated as $z_0=0.1h_c$.

2. The direct method at hourly and daily scale

For calculating ET_a in the Eq. (3), the canopy resistance r_c has to be previously determined. In the present work, the hourly variation of r_c is simulated starting from a relationship taking into account the associated effects of solar radiation, air vapour pressure deficit and wind speed. Katerji and Perrier (1983) proposed to simulate the resistance r_c by the following relation:

$$\frac{{}_c}{r_a} = a\frac{r^*}{r_a} + b \tag{5}$$

where a and b are empirical calibration coefficients which require experimental determination. r^* (s m^{-1}) is given as:

$$r^* = \frac{\Delta + \gamma}{\Delta\gamma}\frac{\rho c_p D}{A} \tag{6}$$

This resistance r^* can be considered as a "climatic" resistance, because it depends only on weather variables. Moreover, r^* represents a "critical" value for the evaporative process, because it is a threshold between the situation, $r_c < r^*$, for which ET_a increases with increasing wind speed, and the situation, $r_c > r^*$, in which ET_a decreases with wind speed.

This model has been used to calculate ET_a for different species (alfalfa, rice, grass, lettuce, sweet sorghum, sunflower, grain sorghum, soybean, clementine orchard, sloping grassland) as reported by Katerji and Rana (2006). It has also been adapted to soil water stress conditions, but this subject will not be discussed here.

The daily values of ET_a were calculated, considering in this direct method (index "d") the sum of hourly values in the time interval between 8 a.m. and 6 p.m.:

$$ET_{a,d} = \sum_{h=8}^{18} ET_a \tag{7}$$

3. The indirect method

From the application point of view, the calculation of the crop ET_a is usually made by the formulation of Allen *et al.* (1998). Actually, this method refers to the maximum evapotranspiration, i.e. when the crop is in well watered conditions, which is the present case. The same methodology has been used by many other authors (i.a. Katerji and Rana, 2006; Testi *et al.*, 2004; Amayreh and Al-Abed, 2005). It is an indirect calculation (index "i"), in fact ET_a is determined by the following relationship:

$$ET_{a,i} = K_c ET_0 \tag{8}$$

In this formulation, ET_0 is the reference evapotranspiration and K_c is the crop coefficient. The recent FAO no. 56 paper (Allen *et al.*, 1998) well defined the concept of ET_0 and adopted the Penman-Monteith equation adapted to a grass crop. Anyway, the authors simplified the procedure to calculate the resistance r_c for the grass. In fact, this was considered constant in all climatic conditions and takes a fixed value in the Penman-Monteith formula. The formula used for the daily values of ET_0 in this work is (all the details in Allen *et al.*, 1998):

$$ET_0 = \frac{0.408\Delta A + \gamma \dfrac{900}{T+273} uD}{\Delta + \gamma (1 + 0.34u)} \tag{9}$$

The accuracy of the ET_a values determined by the Eq. (8) depends on two factors. Firstly, it depends on the accuracy of the determination of ET_0 as carried out by the users in different geographical sites; then, on the accuracy of the K_c values used in Eq. (8). These values were given by Allen *et al.* (1998) for three stages of crop growth cycle (initial, middle and end) for the main cultivated crops. The hypothesis of a constant resistance r_c in the determination of ET_0 for the grass could be a possible source of error. However, some studies showed that this hypothesis gave acceptable estimation of ET_0 in different regions of the world (Smith *et al.*, 1991; Allen *et al.*, 1994a, 1994b). Other studies, mainly carried out in semi-arid and arid regions, showed opposite results: the previously mentioned hypothesis underestimated the values of ET_0 as measured by lysimeters, except for a few cases (see the results obtained by Steduto *et al.*, 1996 in Morocco). The underestimation ranged between 2 and 18% (see Katerji and Rana, 2006 for details). Anyway, since the experimental error of the direct measurement of ET_0 by the lysimeter is about 15% (Rana and Katerji, 2000), the performance of this method seems to be reasonable. Therefore, the approach proposed by Smith *et al.*, (1991) and Allen *et al.*, (1998) merits the attention of researchers.

The second source of possible error concerns the values of K_c, as indicated by Allen *et al.*, (1998). Actually, these values showed more or less important differences with respect to the experimentally determined values of the relationship ET_a/ET_0. Actually, many papers can be found on this subject in the scientific literature. Also if we consider only the more recent literature, it is possible to find differences of ±40% between the K_c values reported by Allen *et al.*, (1998) and the values experimentally obtained, especially during the middle growth cycle (see Katerji and Rana, 2006; 2008). These big differences are mainly due to the complexity of the coefficient K_c, which actually integrates several functions (Testi *et al.*, 2004): aerodynamic factors linked to the height of the crop, biological factors linked to the growth and senescence of the surface leaves, physical factors linked to the evaporation from the soil, physiological factors linked to the response of the stomata to the vapour pressure deficit of the air and agronomical factors linked to the crop management (distance between rows, using mulch, irrigation system, etc.). For this reason, Allen *et al.*, (1998) recommended that the evaluation of K_c values in local climatic conditions by observed data using lysimeters is necessary. Nevertheless, the simple local determination of K_c is not enough if general values of K_c are required. Therefore, it is necessary to search for the relationships between K_c and more or less complex parameters, such as the surface area of the leaves, the humidity of the soil surface and the 3D energy balance (Testi *et al.*, 2004 among many others). This last approach was called "dual K_c" in the FAO56 book. In this case the actual evapotranspiration is called $ET_{a,\text{i-dual}}$.

4. Site, crop and measurements

This study was carried out at a site of Southern Italy (Capitanata plain) in 2006 and 2007 during two experimental field campaigns planned for the Italian project AQUATER. The data here presented were acquired in two private farms ("Forte" during 2006 and "De Lucretis" during 2007), on a very large field (5 hectares) of sugar beet (*Beta vulgaris L.*) maintained in well watered conditions; the irrigation was supplied by the "Consorzio di Bonifica della Capitanata (Foggia)", by aspersion method, following the local usage tending to maximize yield. The climate is semi-arid Mediterranean.

The actual evapotranspiration of the crop was measured by the eddy covariance method (EC) (Kaimal e Finnigan, 1994). A three-dimensional sonic anemometer (USA-1, Metek, Germany) was used in these experiments, coupled with an open-path sensor for the fast acquisition of water vapour concentration (LI-7500, Li-Cor, USA). The sensors were connected to an industrial computer and acquired by software (MeteoFlux, Servizi Territorio S.r.l., Cinisello B. (Mi), Italy). In case of failure of the EC technique, the aerodynamic method (Katerji and Rana, 2008) is used for filling the gaps. In this last case wind speed and air temperature at three levels above the crop were measured by commercial sensors after accurate calibration in laboratory. The agrometeorological variables used for the calculation of ET_a were measured directly above the crop, by means of standard commercial meteorological sensors, including net radiometers and soil heat flux plates. The same kinds of sensors were used to measure the meteorological variables for calculating ET_0 by the indirect method: in this case the sensors were placed above a reference grass in an agrometeorological station a few kilometers far from the experimental field. For the micrometeorological measurement of variables and fluxes the fetch in the directions was large enough for being well below the adjusted internal crop boundary layer. The FAO56 tomato K_c was used in this study (1.15 in the mid- season stage).

III – Results and discussion

The calibration of the model, i.e. the calculation of the coefficients *a* and *b* in the Eq. (5) must be made by comparing the ratio r_c/r_a, with r_c deduced by the Eq. (3) once the ET_a is measured in the field above the crop, and the ratio r^*/r_a, with all the variables measured directly above the crop. The result of the calibration (Fig. 1) for the sugar beet has been made by using the data acquired in 2006 and, of course, they were not used for the validation of the model.

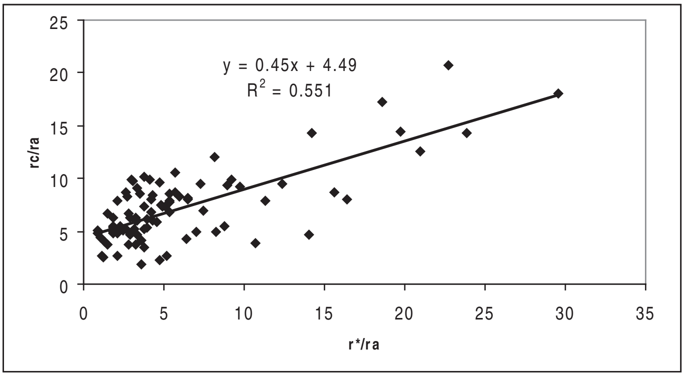

Figure 1. Calibration of the direct model (see text Eq. (5)) for sugar beet using the data acquired in 2006, directly above the crop.

In order to evaluate the performances of the three presented model of ET_a ($ET_{a,d}$ direct; $ET_{a,i}$ indirect and $ET_{a,i\text{-dual}}$ indirect with dual K_c), firstly we compare the daily evapotranspiration values calculated with evapotranspiration measured by eddy covariance method. In Figure 2, the comparison between $ET_{a,d}$ and evapotranspiration measured are presented at daily scale, using the data acquired in 2007. In this figure, 58 daily values of ET_a are reported, these data are relative to the whole crop growth season. The performance of the other two methods are reported in Table 1, by showing the values of the slope and intercept of the linear regression between ET_a measured and calculated together with the determination coefficient (r^2) and the standard error (STDE). From this table can be argued that the direct model had the best performances, both during 2006 and 2007; in fact, this method is accurate having a slope close to 1 and intercept negligible with a regression coefficient very high. Vice versa, the other two methods had bad performances, with high values of the intercept and low r^2. The method based on the dual K_c approach presented better results in both years.

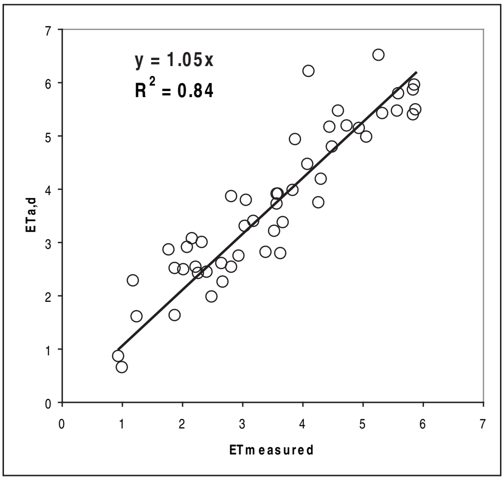

Figure 2. Comparison between daily values of ET_a modelled by the direct method and ET_a directly measured in the field by eddy covariance or aerodynamic method on sugar beet during 2007, when LAI≥2.

Table 1 Statistics of the performances of the ET_a presented model, calculated by the regression between measured and modelled values for the two years of experiment on sugar beet (STDE is the standard error; $ET_{a,d}$ is evapotranspiration calculated by direct method, $ET_{a,i}$ is evapotranspiration calculated by indirect method, $ET_{a,i\text{-}dual}$ is evapotranspiration calculated by indirect method with dual K_c).

Year	Model	slope	intercept	r^2	STDE
2006	$ET_{a,d}$	1.06	0.1	0.86	0.57
	$ET_{a,i}$	0.98	1.9	0.75	0.72
	$ET_{a,i\text{-}dual}$	0.99	1.2	0.74	0.71
2007	$ET_{a,d}$	1.05	0	0.84	0.58
	$ET_{a,i}$	0.94	2.2	0.74	0.89
	$ET_{a,i\text{-}dual}$	0.99	1.8	0.79	0.81

In Table 2 the values of the *WUE* in all the analysed cases is presented for the crop growth season when the sugar beet had a value of LAI≥2. In particular we presented the *WUEs* (both with yield and fresh biomass as numerator) obtained when ET_a is i) measured, ii) calculated by direct method, iii) calculated by indirect method with single K_c, iv) calculated by indirect method with dual K_c. From this table it is clear that the values of *WUEs* closest to that obtained with measured evapotranspiration are those obtained when ET_a is calculated by the direct method. In all other cases, the *WUEs* are underestimated from -12.9% to -19.5%.

Since the two *WUEs* had different values for the two years of the experiments, an attempt of normalising them, dividing by the water vapour deficit, has been carried out in order to establish a suitable univocal relationship between the crop production and the water losses. The results of this normalization gave ambiguous not clear results, maybe due to the particular structure of this crop (big roots and small epigeous parts), thus they are not presented here. Another comment can be made about the underestimation of ET_a with indirect models: this is linked to K_c values used for the estimation, which is lower than the one obtained with local calibration (data not shown).

Table 2. Summary of the *WUE* (Eqs. (1) and (2) in the text) calculated in the growth season when LAI≥2 up to the harvest of sugar beet (i.e. between 13 April and 28 June 2006; between 1 April and 14 April 2007). Var. is the variation in percentage of the *WUE* calculated with the cumulated evapotranspiration following the three methods described in the text: $ET_{a,d}$ direct method, $ET_{a,i}$ indirect method, $ET_{a,i\text{-}dual}$ indirect method with dual K_c.

Year	Indicator	$ET_{measured}$	$ET_{a,d}$	Var.	$ET_{a,i}$	Var.	$ET_{a,i\text{-}dual}$	Var.
2006	WUE^2	19.7	19.1	-3.2%	16.2	-17.7%	17.2	-12.9%
	WUE^2_b	33.1	32.0		27.2		28.8	
2007	WUE^2	15.1	14.5	-3.9%	12.5	-19.5%	12.5	-17.2%
	WUE^2_b	19.8	19.0		15.9		16.4	

IV – Conclusions

In semi-arid environments the ET_a evaluation poses big problems (Katerji and Rana, 2008) that can be reflected in the evaluation of *WUE* at plot scale. In this work, we analysed the performances of three methods to calculate ET_a by using data acquired directly in the field (ET_a direct model) and data acquired in a reference grass (indirect single K_c and indirect dual K_c models) by using the K_c approach as tabulated in the Allen et al (1998) FAO56 book for sugar beet. The results showed that a very small error is found in the calculation of *WUEs* (both when marketable yield and fresh biomass is used) when the direct ET_a model is used. The other two ET_a models produced big (around 15-20%) errors in the quantification of *WUE*.

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