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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 big error can be made if the water consuming is badly evaluated. The best way to give the ET is to measure it, but often it is estimated. At plot scale, there are two different methods for estimating ET: 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 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 estimation is used (direct, single Kc, dual Kc) 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 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.

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**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). Une grosse 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, 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 sont analysées (directe, single Kc et dual Kc) 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 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 Kc single.

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

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**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:

\[ WUE \text{ (kg m}^{-3}\text{)} = \frac{\text{yield}}{\text{water consumption}} \]
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:

\[
WUE_b \text{ (kg m}^3\text{)} = \frac{\text{biomass}}{\text{water consumption}} \quad (2)
\]

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-meteorological 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, \(ET\) in \(WUE\) and \(WUE_b\) is deduced by models. Generally speaking, there are two different methods for estimating \(ET\): 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 (\(WUE_a\) and the \(WUE_{b,a}\)) 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:

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

(3)

where $A = R_n - G$ is the available energy (W m$^{-2}$), $\rho$ is the air density (kg m$^{-3}$), $\Delta$ is the slope of the saturation pressure deficit versus temperature function (kPa C$^{-1}$), $\gamma$ 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$^{-1}$), $\lambda$ 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:

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

(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 $d = 0.67 h_c$ 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 $z_0 = 0.1 h_c$.

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:

$$\frac{r_c}{r_a} = a \frac{r^*}{r_a} + b$$

(5)

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

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

(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.:

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

(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:

$$ET_{a,i} = K_c ET_0$$

(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):

$$ET_0 = \frac{0.408 \Delta A + \gamma \left( \frac{900}{T + 273} \right) u D}{\Delta + \gamma (1 + 0.34 u)}$$

(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 $ET_{a,i-dual}$.

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 and 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.
In order to evaluate the performances of the three presented model of $ET_a$ ($ET_{a,d}$ direct; $ET_{a,i}$ indirect and $ET_{a,i-dual}$ 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.
Table 1 Statistics of the performances of the ET, 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, is evapotranspiration calculated by direct method, ET, is evapotranspiration calculated by indirect method, ET, dual is evapotranspiration calculated by indirect method with dual Kc).

<table>
<thead>
<tr>
<th>Year</th>
<th>Model</th>
<th>slope</th>
<th>intercept</th>
<th>r²</th>
<th>STDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>ET, d</td>
<td>1.06</td>
<td>0.1</td>
<td>0.86</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>ET, i</td>
<td>0.98</td>
<td>1.9</td>
<td>0.75</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>ET, i-dual</td>
<td>0.99</td>
<td>1.2</td>
<td>0.74</td>
<td>0.71</td>
</tr>
<tr>
<td>2007</td>
<td>ET, d</td>
<td>1.05</td>
<td>0</td>
<td>0.84</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>ET, i</td>
<td>0.94</td>
<td>2.2</td>
<td>0.74</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>ET, i-dual</td>
<td>0.99</td>
<td>1.8</td>
<td>0.79</td>
<td>0.81</td>
</tr>
</tbody>
</table>

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 is i) measured, ii) calculated by direct method, iii) calculated by indirect method with single Kc, iv) calculated by indirect method with dual Kc. From this table it is clear that the values of WUEs closest to that obtained with measured evapotranspiration are those obtained when ET 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 with indirect models: this is linked to Kc 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, direct method, ET, indirect method, ET, dual indirect method with dual Kc.

<table>
<thead>
<tr>
<th>Year</th>
<th>Indicator</th>
<th>ET measured</th>
<th>ET, d</th>
<th>Var.</th>
<th>ET, i</th>
<th>Var.</th>
<th>ET, i-dual</th>
<th>Var.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>WUEa</td>
<td>19.7</td>
<td>19.1</td>
<td>-3.2%</td>
<td>16.2</td>
<td>-17.7%</td>
<td>17.2</td>
<td>-12.9%</td>
</tr>
<tr>
<td></td>
<td>WUEb</td>
<td>33.1</td>
<td>32.0</td>
<td>0.8%</td>
<td>27.2</td>
<td>-17.7%</td>
<td>28.8</td>
<td>-12.9%</td>
</tr>
<tr>
<td>2007</td>
<td>WUEa</td>
<td>15.1</td>
<td>14.5</td>
<td>-3.9%</td>
<td>12.5</td>
<td>-19.5%</td>
<td>12.5</td>
<td>-17.2%</td>
</tr>
<tr>
<td></td>
<td>WUEb</td>
<td>19.8</td>
<td>19.0</td>
<td>0.5%</td>
<td>15.9</td>
<td>-19.5%</td>
<td>16.4</td>
<td>-17.2%</td>
</tr>
</tbody>
</table>

IV – Conclusions

In semi-arid environments the ET, 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 by using data acquired directly in the field (ET, direct method) and data acquired in a reference grass (indirect single Kc and indirect dual Kc models) by using the Kc 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, model is used. The other two ET, models produced big (around 15-20%) errors in the quantification of WUE.
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References


