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Evapotranspiration estimation of crops protected by windbreak in a Mediterranean region

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ABSTRACT

This study is part of a number of studies designed to improve the applicability of the FAO56 model (Irrigation and Drainage Paper by the FAO); the aim of this study is to estimate the crop evapotranspiration (ET_c) protected by windbreaks.

The study was conducted in three steps: (i) We parameterised the effects of the windbreak on the inputs to the FAO56 model. The calibration parameters were obtained from an experimental study performed on two typical crops of the Mediterranean environment, durum wheat and beans. The former is a rain-fed crop, and the latter is an irrigated crop. A new modified version of the FAO56 model, named the FAO56-wb, which takes into account the windbreak effects, is suggested. (ii) We validated the evapotranspiration (ET_{wb}) provided by the FAO56-wb in daily and seasonal scales. The validation was performed using an independent data set of measured soil-water balances that can determine the evapotranspiration (ET) at various distances from the windbreak. The calculated data of the ET_{wb} and the measured data agree, both in the daily and in the seasonal scales, as demonstrated by the Relative Root Mean Square Error test (RRMSE, between 19.9 and 16.3 for durum wheat and between 12.3 and 16.7 for beans) and by the linear regression ($R^2 > 0.8$ for durum wheat and $R^2 > 0.9$ for beans). (iii) We evaluated the simulation of the ET_{wb} for durum wheat and beans using a 25-year series of agro-meteorological data. The FAO56-wb simulates the evapotranspiration as a function of the porosity of the barrier. The simulations demonstrated the windbreak's potential to contain the evapotranspiration of durum wheat and beans in a semi-arid environment, such as the Mediterranean. The effects on ET reduction were more clearly seen with the use of a windbreak with low porosity (20%) and 3 m in height. In this case, a maximum reduction of 31% of the evapotranspiration in a summer crop, such as beans, occurred within a distance from the windbreak equal to 15 times the barrier height.

The results showed that the FAO56-wb is a useful tool to predict the effects of a windbreak even though the model requires only a few agro-environmental inputs.

1. Introduction

The incorporation of windbreaks in agricultural systems is becoming prevalent in many regions of the developed world, where the scarcity of land and water resources has resulted in a need for agriculture to consume less water. In many parts of Europe, hedgerows or low windbreaks are common features of the traditional rural landscapes. Recently, agricultural development has been lead to the establishment of a windbreak system that has been widely diffused in many regions of Australia and New Zealand, the heathlands of Denmark, the Great Plains of North America and the steppes of the former Soviet Union.

In the Mediterranean environment, the limited availability of water implies the need to search for agronomical strategies that can mitigate the consequences of water deficits and increase the efficiency of the irrigation supply.

In dry farming, the use of windbreaks is one of various proposed solutions to reduce evapotranspiration (ET) by modifying the components of the energy balance (Burke, 1998).

ET is the most important variable to know accurately to develop a rational irrigation management plan. The ET is particularly important in environments with long hot, arid periods, such as the Mediterranean region, where the lack of water resources is the main factor limiting agricultural development.

The ET depends on many factors, such as the climate, the soil type and the species being cultivated. The crop evapotranspiration (ET_c) can be estimated by two approaches. In the '*one step*' approach, the ET_c is directly estimated by the environmental conditions and the physical, morphological and physiological features

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of the soil-plant system. The '*two step*' approach considers the ET of a reference crop (ET_0), under known ecophysiological factors, and the crop coefficient (Kc) is used as an aggregation of the physical and physiological differences between the cultivated and reference crops.

At instantaneous time scale, the estimate of ET is performed using the Penman–Monteith equation (Monteith, 1973):

$$\lambda ET = \frac{\Delta(R_n - G) + (\rho Cp(e_a - e_d)/r_a)}{\Delta + \gamma(1 + (r_c/r_a))} \quad (1)$$

where λET is the latent heat flux ($W\,m^{-2}$), Δ the curve slope expressing the saturated vapour tension as a function of the temperature ($kPa\,^\circ C^{-1}$), R_n the net radiation ($W\,m^{-2}$), G the flux density of soil heat ($W\,m^{-2}$), ρ the average air density ($kg\,m^{-3}$), C_p the specific air heat ($MJ\,kg^{-1}\,^\circ C^{-1}$), e_a the saturated vapour pressure at air temperature (kPa), e_d the actual vapour pressure (kPa), r_a the aerodynamic resistance ($s\,m^{-1}$), γ the psychrometric constant ($kPa\,^\circ C^{-1}$), and r_c is the crop canopy resistance to vapour flux ($s\,m^{-1}$).

Some parameters (ρ, C_p, γ) are obtained through the environmental characteristics and are almost constant; others (Δ, R_n, G, e_a, e_d) can be easily measured at agro-meteorological stations. The resistances (r_a and r_c) that reduce the evapotranspiration flow (λET) are difficult to determine because they require specific crop characteristics.

In particular, r_c is mainly a function of the leaf area index (LAI), global radiation (R_g), vapour pressure deficit (VPD), temperature and plant water status whereas r_a requires the calculation of the vegetation roughness (Jarvis, 1976) and the measurement of the wind speed.

Recently, some papers (Shuttleworth, 2006; Shuttleworth and Wallace, 2009; Rana and Katerji, 2009) have suggested alternative approaches to calculate ET by analytical one-step models using operational characteristics. However, the use of two-step models prevails in the calculation of ET for practical purposes. The '*one step*' approach requires that the climatic variables be measured above the crops (Rana et al., 1994) while the '*two step*' approach uses the measurements of variables found in standard meteorological stations.

The '*two step*' method proposed by Penman–Monteith in Irrigation and Drainage Paper No. 56 (FAO56 model), which was designed for operating purposes, can be written as ET = Kc ET_0. For practical purposes, Allen et al. (1998) suggested the use of the Penman–Monteith equation in a daily scale; in this case, the energy terms in Eq. (1) are the integral of time in instantaneous values, and the other inputs are the daily mean of the variables.

The ET is estimated by the FAO56 model in nonstandard vegetation conditions (e.g., water stress, use of saline waters, non-pristine vegetation, mulching, intercropping of different species).

Recent scientific research has suggested some changes in the '*two step*' approach to improve the estimate of ET and to generalise it for specific agro-environmental conditions (Ko et al., 2009; Er-Raki et al., 2006; Liu and Luo, 2010).

Among the changes performed to the FAO56 model, those concerning the wind speed and the windbreak effects have not yet been taken into account. The use of windbreaks can reduce the ET because they create an important action on the aerodynamic resistance of the water vapour flow (Burke, 1998).

Windbreaks have been studied all over the world, in Northern China (Zao et al., cited by Brandle et al., 2004), Canada (Kort, 1988), New Zealand (Sturrock, 1984), USA (Brandle et al., 2004), South America (Luis and Bloomberg, 2002), Australia (Nuberg, 1998; Cleugh et al., 2002), and in the Mediterranean region (Ben Salah et al., 1989; Benzarti, 1990; Casa et al., 1994; Campi et al., 2009). However, these studies do not suggest any modelling of the effects of windbreaks on the operating methods to calculate the ET_c using the FAO56 model.

Therefore, the aim of this study was to suggest the functions that need to be introduced into the FAO56 model to calculate ET_c in cases using windbreaks (FAO56-wb model).

After the calibration phase, the validation of the FAO56-wb model is performed by comparing its output (ET_{wb}) in a daily scale with the independent ET measurements that were performed in autumn-spring (durum wheat) and in summer (bean) crops.

Finally, to draw a conclusion from the results, it can be assumed that the FAO56-wb can be used to simulate the benefits provided by the presence of a windbreak on crop water use. For this reason, the ET_{wb} will be simulated over a 25-year period for the two crops, and the FAO56-wb will also be used to develop the appropriate dimensioning of the porosity of the windbreak.

2. Materials and methods

The study is based on the analysis of the microclimate of durum wheat (cv. 'Simeto') and bean (cv. 'Lingua di fuoco') plots, both with a windbreak and without it.

Both crops were cultivated in southern Italy at the experimental farm of the Agricultural Research Council – Research Unit for Cropping Systems in Dry Environments (C.R.A. – S.C.A.) in Rutigliano (lat: 40°59′, long: 17°01′, alt: 147 m a.s.l.). The environment is characterised by an average rain fall of 600 mm, with precipitation mainly concentrated during the autumn period and much more reduced or absent in the spring-summer period. Precipitation is around inadequate to meet the atmosphere's ET requirements; the annual water deficit is 560 mm (Campi et al., 2005). In the location under study, the average annual wind speed is $2.8\,m\,s^{-1}$, which is higher than the average global wind speed ($2.0\,m\,s^{-1}$) (Allen et al., 1998). The prevailing wind direction is north.

The experimental field (100 m × 200 m) has a windbreak barrier of *Cupressus arizonica* L. (3 m high, 20 years old), set perpendicular to the prevailing wind. The porosity is 40%, as calculated according to the approach suggested by Nelmes et al. (2001). This approach for estimating the porosity requires only two wind speed measurements, one located upstream and one located downstream.

The soil has a clay texture with a field water capacity of 30% and a wilting point of 18% (measured through Richards plates on dry soil weight), and its bulk density is $1.15\,g\,m^{-3}$. Because the soil profile is shallow (0.6 m), it has a moderate available soil water capacity (83 mm).

The durum wheat and beans were cultivated following conventional agro-techniques. The irrigation schedule for the beans was performed using the water balance FAO method, where the root development was considered to have a depth up to a maximum of 0.6 m. Irrigation was performed, distributing a total of $2800\,m^3\,ha^{-1}$, using mini-sprinklers uniformly distributed over the field. The irrigation depths were measured using volumetric counters installed in the main irrigation line.

The microclimatic data were measured on the experimental field of durum wheat from 20/10/2004 to 4/06/2005 and then on the nearby bean field from 5/06/2005 to 22/08/2005, using the same microclimatic sensor set (Fig. 1).

The wind speed was measured using cup anemometers (A100R, Vector Instruments, UK; sensitivity threshold: $0.2\,m\,s^{-1}$) installed at the following positions (D/H, where D is the distance from windbreak and H represents the height of the windbreak): 2D/H, 2.7D/H, 3.3D/H, 4.7D/H, 6D/H, 7.3D/H, 10D/H, 12.7D/H, 18D/H and 23.3D/H. The air temperature and relative humidity were measured using thermo-hygrometers (Campbell model cs500; accuracy: ±0.2 °C for air temperature and ±1.5% for RH) installed at the following positions: 2D/H, 2.7D/H, 3.3D/H, 4.7D/H, 12.7D/H and 23.3D/H. The