The crop coefficient (K_c) values of the major crops grown under Mediterranean climate

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Preface

Analyzing accurately the scientific and practical works published on the MELIA web site, it is evident that the most spread method to determine the crop water requirements is the one based on the crop coefficient approach. So, this work has been expressly carried out by the CRA-SCA of Bari (Italy) in order to give a comprehensive state of the art about the values of the crop coefficient of the main crops cultivated in the Mediterranean countries.

Introduction

In Mediterranean region, submitted to arid and semi-arid climate, water is a limiting factor for profitable agriculture, in terms both of overall amount and intermittence and/or irregularity of rainfall events throughout crops' growing season. In this context, irrigation (full or supplementary) of the crops is needed for providing best level of production. However, water is becoming a scarce natural resource and agriculture represents the major water consumption at global scale, thus, proper irrigation scheduling has to be employed by the producers for exploring water saving measures.

The misuse of water due to either low efficiency of irrigation or inadequate irrigation scheduling can lead to loss of water, resulting in higher production costs and negative environmental impacts. Matching water supply and demand are essential for productivity and sustainability in any irrigation scheme. Moreover, knowledge of crop-water requirements is crucial for water resources management and planning in order to improve water-use efficiency (i.a. Hamdy and Lacirignola, 1999; Katerji and Rana, 2008).

Crop-water requirements vary during the growing period, mainly due to variation in crop canopy and climatic conditions, and related to both cropping technique and irrigation methods. About 99% of the water uptake by plants from soil is lost as evapotranspiration (ET), so, it can be stated that the measurement of actual crop evapotranspiration (ET_c) on a daily scale for the whole vegetative cycle is equal to the water requirement of the given crop. Evapotranspiration is defined as the water lost as vapour by an unsaturated vegetative surface and it is the sum of evaporation from soil and transpiration by plants. In order to avoid the underestimation or overestimation of crop water consumption, knowledge of the exact water loss through actual evapotranspiration is necessary for sustainable development and environmentally sound water management in the Mediterranean region. However, overestimation of water consumption is very common practice in this region (Shideed et al., 1995), causing both waste of water and negative impacts on economic, social and environmental levels (Katerji and Rana, 2008). Then, a correct knowledge of ET_c allows improved water management by changing the volume and frequency of irrigation to meet the crop requirements and to adapt to soil characteristics.

ET can be measured or modelled by more or less complex techniques. Usually, for practical purposes at local-field scale the evapotranspiration is estimated by models usable for the same crop in sites at the same region. The most known and used technique to estimate ET is the one based on the K_c approach (Allen et al., 1998) where the ET_c is calculated by using standard agro-meteorological variable and a crop-specific coefficient, the crop coefficient K_c, which should take into account the relationship between atmosphere, crop physiology and agricultural practices.

Since this method is really very used both at research and practical level and since there is a lot of papers (scientific and popular ones) on it, some questions arise: is this method really reliable to accurately determine ET_c? Furthermore: are the K_c values site dependent? Are the K_c values weather dependent?

This work, basically made by studying the huge literature about the K_c, tries to contribute to answer to the above questions. Here, we analyzed the K_c values found in literature for the main crops cultivated in countries submitted to Mediterranean climate. The main objective of this work is to compare the experimental K_c and the values given by the FAO 56 bulletin for the main spread crops in Mediterranean climate.

1. Measurements methods of actual and reference evapotranspiration: a brief summary

Despite of the fact that evapotranspiration is the largest component of hydrologic cycle and soil water balance in the Mediterranean region it is still difficult to accurately it determine.

Evapotranspiration determination includes various measurement techniques and modelling techniques (also direct and indirect), which simulate evapotranspiration as a biophysical process or calculate it using the empirical methods (Rana and Katerji, 2000; Katerji and Rana, 2008).

Accordingly, it is possible to distinguish between crop evapotranspiration under standard condition and crop evapotranspiration under non-standard conditions. In most cases, crop evapotranspiration in the Mediterranean region refers to a non-standard condition due to agricultural water shortages.

There are a great variety of methods for measuring ET; some methods are more suitable than other because of their accuracy or cost or because they are particularly suitable for given space and time scale. These methods are often expansive, demanding in terms of accuracy of measurement and equipment management. Although the methods are inappropriate for routine measurement, they remain important for the evaluation of ET estimates obtained by indirect methods.

The methods of measuring ET should be divided into different categories, since they have been developed to fulfil very different objectives. One set of methods is primarily intended to quantify ET over a long period of time, from weeks to months and to growth season. Another set of methods has been developed to understand the process governing the transfer of energy and matter between the surface and atmosphere. The last set of methods is used to study the water relations of individual plants or parts of plants.

Direct measurement at the plot scale: the weighing lysimeter

Weighing lysimeter (called also “evapotranspirometer”) was developed to provide a direct measurement of ET. A lysimeter is a device, a tank or container, used to define the water movement across a boundary. Actually, only a “weighing lysimeter”, can determine ET directly from the mass balance of the water, as contrasted to a non-weighing lysimeter which indirectly determines ET from the volume balance (Howell et al., 1991).

Thus, weighing lysimeter are usually containers placed in the field with soil cultivated in the same way as the surrounding field. The lysimeter leans on sensor (a balance) capable of measuring the weight variation due to loss of water by the system soil-canopy atmosphere. However, the weighing lysimeter data are not always representative of the conditions of the whole field but, often, they only represent the ET of one point in the field (Grebet and Cuenca, 1991). If the lysimeter surface and area immediately around it are surrounded by drier vegetation or bare soil an oasis effect can occur. Net radiation in excess of latent heat is converted to sensible heat which is transported toward the lysimeter, resulting in a net supply of energy to the lysimeter vegetation. All these defaults cause an increase of ET as compared to the surrounding crop. This overestimation of ET can be particularly important in a high radiation climate such as in the Mediterranean region (Howell et al., 1991; 1995).

The weighing lysimeter, spite of the problems and inconveniences that limited its use, is often considered to be the reference method, and is used in particular for well-watered crops to test the other ET measurement methods.

Indirect measurement at the plot scale: micrometeorological approach

From the energetic point of view, evapotranspiration can be considered as equivalent to the energy employed for transporting water from the inner cells of leaves and plant organs and from the soil to the atmosphere. In this case, it is called “latent heat” and is expressed as energy flux density (Wm^{-2}). Under this form, ET can be measured with the so-called “micrometeorological” methods. These techniques are physically-based and carried out by applying the laws of thermodynamics and of transport of scalars into the atmosphere above the canopy. To apply the micrometeorological methods, it is usually necessary to measure meteorological variables with sensor and suitable equipment placed above canopy.

Micrometeorological methods measure the actual ET with error on the final value of ET around a fraction of mm of water. Thus, they remain very suitable methods for measuring ET in semi-arid and arid environments, where the values of ET are often very low during drought periods (from spring to summer). The only exception is the aerodynamic method, which can be used only below a crop height of 1.5 m.

Another advantage of the micrometeorological technique lies in the fact that they give accurate ET values on different time scales: the hour, the day and, consequently, also the week and the whole season. Therefore, they can be adopted for studying the theoretical aspects of water consumption and the response of the crop to the water supply.

The micrometeorological methods cause small disruptions in the soil-canopy-atmosphere environment, since they require small sensors easy to install, even though good knowledge of electronics and informatics is needed. The micrometeorological methods include the Bowen ratio, the eddy covariance and the aerodynamic one.

Measurement based on the soil water balance

This is an indirect method; in fact, ET is obtained as a residual term in the water balance equation. This latter equation is based on the principle of the conservation of mass in one dimension applied to crop root zone of the soil. Since it is often very difficult to measure accurately all the terms of equation, a number of simplifications make this method unsuitable for precise ET measurements.

Measurement on the plant scale

These methods measure water loss either from a whole single plant or from a small group of plants. They can not directly supply the ET on the plot scale. To achieve this purpose, it is necessary to adopt a specific methodology for each situation, in order to achieve the up scaling from the measurement at the plant level to the ET on the plot scale. These methods include the tracer method, porometry, the sap flow and the chamber system.

The direct estimation of evapotranspiration

Direct crop evapotranspiration measurement methods are expensive and hard work demanding, and the results only apply to the exact conditions in which they were measured. Because direct methods are impractical for permanent use on a large scale, ET is often and commonly estimated, both for practical and research purposes.

The most models diffuse are: Penman equations (1948, 1956), Monteith equations (1963, 1965) and Penman-Monteith (P-M) model (1965). The Penman equation is not relative to the crop. It concerns the evaporation from a given surface when all surface-atmosphere interfaces are wet (saturated). In this model evaporation can be calculated from the available energy and from the convective fluxes. The model has been extended by Penman (1956) to the particular case of a leaf, thanks to the introduction of the concept of “resistance” analogous to Ohm’s law. According to this approach, an energy flux density can be considered as directly proportional to the difference of potential and inversely proportional to the resistance encountered.

The scaling-up of the Penman model (1956) was carried out by Monteith (1965), thanks to the “big leaf surface” concept. According to this hypothesis, the canopy can be thought as a single large leaf, by supposing that the sinks and the source of heat and vapour fluxes can be found at the same layer of the momentum flux sink. Finally, the combination of the three previous equations leads to the general model for estimating the actual crop evapotranspiration, generally known as the “Penman-

Monteith model”. This it is largely accepted by scientific community thanks to its effectiveness. It is an interesting tool for analysis the relationship between ET and environmental factors but it suffers of the huge difficulty to have correct values of canopy resistance (Katerji and Rana, 2006; Todorovic, 1999; Lecina et al., 2003; among many others).

Thus, the best way to calculate ET_c is using a direct mode, without an intermediate calculation for a reference surface. To achieve this aim, the ensemble of biological and physical characteristics of each vegetal surface, involved in the ET_c, must be taken into account: i.e. (i) the albedo, taking into account the reflection of the solar radiation and the architecture of the leaves in the determination of the available energy A, (ii) the height and roughness of the crop which take part of the calculation of the convective exchanges, (iii) the leaf surface and the stomatal conductance which take part of the calculation of the canopy resistance to the transfer of the water between the surface and the atmosphere. It similarly applies a Penman-Monteith type formula. However, in this method the canopy resistance, r_c, is specific for each species, it is not constant but variable in function of climatic characteristics of the atmosphere below the top of the boundary layer above the crop. Its determination is based on modelling works proposed in the scientific literature (see for example Jarvis, 1976; Katerji and Perrier, 1983; Orgaz et al., 2005). These models need also that the determination of the weather variables should be made above the considered crop. For this reason the direct method is considered as not operational. A largely spread direct model to estimate ET_c is well described in detail in Katerji and Rana (2008).

The indirect estimation of evapotranspiration

Due to the aforementioned difficulties in measuring and direct estimating crop actual evapotranspiration, usually, for operational and practical purposes, the water consumption of a crop (ET_c) is evaluated as a fraction of the reference crop evapotranspiration (ET_o): $ET_c = K_c ET_o$, where K_c is the “crop coefficient”, which takes into account the differences existing between a standard crop taken as reference (as grass, alfalfa) and the real crop under study.

The reference evapotranspiration ET_o can be:

a. Directly measured on a reference surface (well-watered grass meadow, free water in a standard pan);
b. Estimated from a semi-empirical formulation based on an analytical approach;
c. Estimated from empirical formulation based on a statistical approach.

In order to render procedures and results comparable worldwide, a well-adapted variety of clipped grass has been chosen to measure ET_o. It must be 8 to 16 cm in height, actively growing and in well-watered conditions, subject to the same weather as the crop for which the water consumption is to be estimated. ET_o can be measured again directly (by means of a weighing lysimeter) or indirectly measured with a micro-meteorological method (Rana et al., 1994; Allen et al., 1996; Steduto et al., 1996; Ventura et al., 1999; Todorovic, 1999; Howell et al., 2000).

The difficulty of measuring directly E_o in a grass meadow led to the use of evaporation pans; some of them were square (Colorado pan), some were placed under the ground, other were circular and placed above the ground surface (class A pan).

It is easy to obtain measurements from those pans. Nevertheless, this kind of measurement has several shortcomings; the main ones can be summarised as the following (Riou, 1984): a) The heat exchange between pan and soil is not negligible; b) The underground pans are very sensitive to the surrounding environment; c) The need to maintain a sufficient edge can cause a wind break effect, which can disturb the evaporation in a way that is difficult to estimate; d) During the night the water usually gets cold on the surface, causing convective flows which can cause the warm water to rise to the surface with consequent possible evaporation.

Despite these evident flaws, the pan evaporation data routinely measured with simple equipment at meteorological stations can be used to estimate reference E_o, using a simple proportional relationship: $E_o = K_p E_{pan}$, where, K_p is dependent on the type of pan involved and the pan environment in relationship to nearby surfaces and the climate.

Doorenbos and Pruitt (1977) provided detailed guidelines for using pan data to estimate reference E_o. These formulations are generally based on the physical laws concerning the energy balance and the convective exchange on a well-irrigated grass surface. An empirical element is introduced in these formulations to facilitate their calculation, starting from data collected in standard agro-meteorological stations. These stations are usually situated so as to be representative of the catchment, i.e. an area of several kilometres in extension. The main formulas in this case are: 1. Penmans’ formula and its by-product; 2. the Penman-Monteith formula proposed by Allen et al. (1998). The first approach generally is called “corrected Penman” and it includes several formulas. The most commonly used corrected formula is the one proposed by Doorenbos and Pruitt (1977). It was considered in the FAO technical paper n. 24. The second approach was adopted in FAO Bulletin 56, it represent an upgrade of the Doorenbos and Pruitt technique and nowadays it is widely used as the standard approach for estimating reference ET.

The Penman-Monteith approach is a reliable, physically based method and it is a close, simple representation of the physical and physiological factors governing the evapotranspiration process.

Reference evapotranspiration concept had been revised during the last decade resulting in the introduction of the standardized computational procedures two groups of scientists: the FAO Expert Group on the Revision of FAO Methodologies for Crop Water Requirements, which published the FAO Irrigation and Drainage paper 56 (Allen et al., 1994a; Allen et al., 1994b; Allen et al., 1998), and the ASCE-EWRI (American Society of Civil Engineers-Environmental Water Resources Institute) Task Committee on Standardization of Reference Evapotranspiration, which realized a report on standardized reference evapotranspiration (Allen et al., 2005).

But the climate data required in the Penman- Monteith equation are not always available, especially in developing regions. Therefore, many simpler methods have been used and tested in some areas. Blaney- Criddle and Hargreves-Samani are empirical methods that require only temperature data.

2. The Crop coefficient

The concept of K_c was introduced by Jensen (1968) and further developed by the other researchers (Doorenbos and Pruitt, 1975, 1977; Burman et al., 1980a, Burman et al., 1980b; Allen et al., 1998). The crop coefficient is the ratio of the actual crop evapotranspiration (ET_c) to reference crop evapotranspiration (ET_o) and it integrates the effects of characteristics that distinguish field crops from grass, like ground cover, canopy properties and aerodynamic resistance. The estimation of ET_c relies on the so-called two-step approach, where ET_o is determined and ET_c is calculated as the product of ET_o and the K_c for the same day. Reference evapotranspiration is a measure of evaporative demand, while the crop coefficient accounts for crop characteristics and management practices (e.g., frequency of soil wetness). It is specific for each vegetative surface and it evolves in function of the development stage of the crop considered. Evapotranspiration varies in the course of the season because morphological and eco-physiological characteristics of the crop do change over time.

The FAO and WMO (World Meteorological Organization) experts have summarised such evolution in the “crop coefficient curve” to identify the K_c value corresponding to the different crop development and growth stages (initial, middle and late, hence it has $K_{c\ in}$, $K_{c\ mid}$, $K_{c\ end}$) (Tarantino and Spano, 2001). Values of K_c for most agricultural crops increase from a minimum value at planting until maximum K_c is reached at about full canopy cover. The K_c tends to decline at a point after a full cover is reached in the crop season. The declination extent primarily depends on the particular crop growth characteristics (Jensen et al., 1990) and the irrigation management during the late season (Allen et al., 1998). A K_c curve is the seasonal distribution of K_c, often expressed as a smooth continuous function.

For irrigation scheduling purposes, daily values of crop ET_c can be estimated from crop coefficient curves, which reflect the changing rates of crop-water use over the growing season, if the values of daily ET_o are available. FAO paper 56 (Allen et al., 1998) presents a procedure to calculate ET_c using three K_c values that are appropriate for four general growth stages (in days) for a large number of crops. In the single crop coefficient approach, the effect of crop transpiration and soil evaporation are combined into a single K_c coefficient. The coefficient integrates differences in the soil evaporation and crop transpiration rate between the crop and the grass reference surface. As the soil evaporation may fluctuate daily as a result of rainfall or irrigation, the single crop coefficient express only the time-averaged (multy-day) effects of crop evapotranspiration. In the dual crop coefficient approach, the effect of specific wetting events on the value of K_c and ET_c is determined by splitting K_c into two separate coefficients: one for crop transpiration, i.e., the basal crop coefficient (K_{cb}) representing the transpiration of the crop; and another for soil surface evaporation, the soil water evaporation coefficient (K_e). The single K_c coefficient is replaced by $K_c = K_{cb} + K_e$.

The basal crop coefficient, K_{cb}, is defined as the ratio of ET_c and ET_o when soil water evaporation is minimal, but soil water availability remains non-limiting to plant transpiration. As the K_c values include averaged effects of evaporation from the soil surface, the K_{cb} values lie below the K_c values. The soil evaporation coefficient, K_e, describes the evaporation component from the soil surface.

To take account of water stress, K_{cb} or K_c are multiplied by a coefficient K_s which is equal to 1.00 till half the available water is used up and which then declines linearly to zero when all the available water in the rooting zone has been used up. Hence,

$$ET_c = (K_c K_s) ET_o \qquad (1)$$

$$ET_c = (K_{cb} K_s + K_e) ET_o \qquad (2).$$

The terms in brackets in previous equations is called crop coefficient adjusting, $K_{\mathrm{c}\,adj}$. Because the water stress coefficient impacts only crop transpiration, rather than evaporation from the soil, the application using the equation (2) is generally more valid than is application using the equation (1). Allen et al. (1998) reported that in situations where evaporation from soil is not a large component of ETc, use of equation (1) will provide reasonable results.

In the FAO paper 56 are reported the both K_c and K_{cb} values corresponding at the three grown stage for the many crops. These latter values have been obtained by a limited number of experiments carried out in Arizona and Eastern Europe and they should be validated under Mediterranean conditions.

To make the use of K_c operational, research and experiments have been carried out worldwide, and they have led to determination of the average value that K_c may take in the course of the season over the years (Grattan et al., 1998). It is worth highlighting that the K_c is affected by all the factors that influence soil water status, for instance, the irrigation method and frequency (Doorenbos and Pruitt, 1977; Wright, 1982), the weather factors, the soil characteristics and the agronomic techniques that affect crop growth (Stanghellini et al., 1990; Tarantino and Onofrii, 1991; Cavazza, 1991; Annandale and Stockle, 1994). Consequently, the crop coefficient values reported in the literature can vary even significantly from the actual ones if growing conditions differ from those where the said coefficients were experimentally obtained (Tarantino and Onofrii, 1991).

Ko et al. (2009) and Piccinni et al (2009) observe that K_c values can be different from one region to the other. It is assumed that the different environmental conditions between regions allow variation in variety selection and crop developmental stage which affect K_c (Allen et al., 1998). Elevated air temperatures and water vapour pressure deficit over the growing seasons can cause temporal and transient leaf stomata closure (Baker et al., 2007; Bruce, 1997; Cornic and Massassi, 1996), impeding plants to transpire at its full potential.

The use of K_c developed in other regions with respect those where it is calibrated will not meet accurate crop water requirement and result in either increased production costs due to over-irrigation or reduced profits due to deficit irrigation. However, the development of regionally based K_c could greatly in irrigation management and furthermore provide precise water applications in those areas where high irrigation efficiencies should be achieved.

3. The Review

We started this study by reviewing the literature in order to investigate the variability of crop coefficient values of the more widespread crops in Mediterranean area compared to these reported in the paper FAO 56. This research would highlight all the factors affecting the K_c values, such as cultivar type, agronomics techniques (i.e. fertilizing, pruning, tillage, mulch and greenhouse), measurement or estimating methods of ET_c and ET_o and irrigation methods and management. We consulted the international (and a few national) and recent scientific references relative to areas of the world characterized by Mediterranean climate. This selection assures the reliability of the K_c values, but it limits the number of countries and of crops found. Table 1 and 2 report the crops investigated (24) and the countries involved in the study (10).

Table1. Crops object of the review

N.	Crops		N.	Crops	
1	Alfalfa		13	Melon	*Cucumis melo* L.
2	Broad bean	*Vicia faba* L.	14	Olive	*Olea Europea* L.
3	Cauliflower	*B. oleacea* L. var. botrytis	15	Onion	*Allium cepa* L.
4	Citrus		16	Peach	*Prunus persica* L.
5	Cotton		17	Potato	*Solanum tuberosum* L.
6	Cowpea	*Vigna unguiculata* (L.) Walp.	18	Red Cabbage	*B. oleacea* L. var.rubra
7	Flax	*Linum usitatissimum* L.	19	Sorgum	*Sorghum bicolor* L.
8	Garlic	*Allium sativum* L.	20	Soybean	*Glycine max* L. Merril
9	Grapevine	*Vitis vinifera* L.	21	Sweet pepper	*Capsicum annuum* L.
10	Green bean	*Phaseolus vulgare* L.	22	Tomato	*Lycopersicon esculentum*, Mill.
11	Lettuce	*Lactuca sativa* L.	23	Watermelon	*Citrullus lanatus* L.
12	Maize	*Zea mays* L.	24	Wheat	*Triticum vulgare* L.

Table 2. Countries object of the study on the K_c

Country				
California	Chile	Italy	Jordan	Lebanon
Morocco	Portugal	Spain	Texas	Turkey

The Table 1 shows that the number of crops found is adequate to draw important observations on use of K_c as practical tool for estimating water requirements. Moreover, Citrus, Tomato, Peach, Maize and Melon crops present the major number of variety and cultivars. Furthermore, all crops are representatives of Mediterranean agriculture in terms of dates of transplanting, density and spacing of plantation, cover fraction, fertilization, pest and weed control, maxim height of the crops. Spain (7 works) and Italy and California (5 works) are the countries which have most scientific studies on crop ET and K_c, followed by Texas, Turkey and Portugal (3 works). All the countries are characterized by Mediterranean climate that varies from temperate to semi-arid to arid.

The study shows that for the more important crops in Mediterranean area the more used irrigation methods are drip (surface and subsurface) and sprinkler irrigation methods. This observation reflects the greater sensitivity of the users towards police of saving water, since this irrigation method allows improving irrigation efficiency.

In all examined papers (34), several measure or estimate methods have been used by authors to calculate ET_c, ET_o and hence K_c, such as the temporal scales adopted, obtaining K_c values relative to daily, monthly or seasonal interval for different crops. For this reason, the relationship between the empirical and FAO 56 K_c values is not often easy and immediate, but the same authors provide useful information for the comparison.

The reference evapotranspiration in the most of cases is estimated by FAO 56 Penman-Monteith equation (40% of the cases). Other models of estimation, like those proposed in the FAO Irrigation and Drainage Paper N. 24 (Blaney-Criddle, radiation and modified Penman), CIMIS Penman equation and ASCE Penman-Monteith equation are few used. Often the reference evapotranspiration is measured. The methods more used are Class A pan and weighing lysimeter (40% and 26% of the all cases, respectively), then, other measurement methods occur rarely, like atmometer and evaporimeter. In these methods, when a reference surface is used, a generic grass is considered and the management indicated by FAO Irrigation and Drainage Paper N. 56 (Allen et al., 1998) and following improvement of ASCE Standardized Reference Evapotranspiration Equation (Allen et al., 2005) to distinguish ET_0 for both short and tall reference crop are taken into account.

With regard to actual crop evapotranspiration, it is measured in the majority of cases. The approach more spread is the micrometeorological method eddy covariance (36% of the all cases), followed by both the weighing lysimeter and soil water balance methods (33% and 16% of the all cases). Rarely, other micrometeorological approaches (Bowen ratio), plant physiology approach (sap flow technique) and surface energy balance by data of remote sensing and satellite are reported (e.g. Barbagallo et al., 2009; Er-Raki et al., 2008).

In the majority of the studies, the K_c values are obtained by the single crop coefficient approach, where the effect of crop transpiration and soil evaporation are combined into a single K_c coefficient. Infrequently, the dual crop coefficient approach is used, where the effects of crop transpiration and soil evaporation are determined independently (Lopez-Urrea et al., 2009; Casa et al., 2000; Benli et al., 2006; Er-Raki et al., 2009; Paço et al., 2006). Thus, their discussion will deal with separately (section 4 and 5, respectively).

4. Comments on the *Kc* values by the single crop coefficient approach

Table 4 reports the experimental crop coefficient values and those presented by FAO 56. In the table the crops are subdivided as within FAO paper 56 (see table 12 of technical paper).

It seem to be clear that the variability of the K_c values principally is related to irrigation methods, mulching practice, growth in greenhouse, indicators of the development of the crops, such as both leaf area (LAI) and ground cover (GC) indexes. To take into account these factors the estimate of K_c is resulted more accurate.

With respect to K_c values by FAO 56 are highlighted both underestimation and overestimation. In particular, the underestimation is clearly observed for cauliflower, red cabbage, lettuce, melon, broad been, wheat and clementine crops, while the overestimation can be rarely noted for garlic, melon cultivar, cowpea, green bean, cotton, grape wine and peach crops. The same K_c values of FAO 56 are reported by authors for few crops or cultivars such as tomato crop grown in both Italy and Chile, mandarin crop grown in Morocco and flax in Italy. Some crops presents the measured K_c values equal to K_c FAO 56 only for a specific grown stage. Ko et al. (2009) and Piccinni et al. (2009), in fact, show as some of the K_c values for cotton, wheat, maize and sorghum crops corresponded and some did not correspond to those from FAO-56. The Authors consider necessary the development of regionally based and growth-stage-specific K_c.

Crop coefficient values different with respect to the theoretical are founds by Rinaldi and Rana (2005) for tomato crop in Southern Italy. The K_c value corresponding to middle growth stage is greater than K_c FAO 56 of 0.13 and 0.03 for two variety of tomato crop. The Authors highlight that single crop coefficient approach underestimates the water use of tomato crops of 58 mm.

The influence on crop water requirement by the irrigation system and use of mulch is underlined by Amayreh and Al-Abed (2005) and Lovelli et al. (2005). The first authors have studied the behaviour of crop coefficient for field-grown tomato under drip irrigation system with black plastic mulch. This study reports measured K_c values far below the FAO values by about 31% and 40% for K_{cmid}

and K_{cend}, respectively. This means that there is a 36% reduction in the crop coefficient over the entire growing season, excluding initial stage, compared to FAO corresponding value. The low determined K_c values reflect the effect of practicing both localized drip irrigation and plastic mulch covering which is the common practice in the Jordan Valley agricultural area. These obtained results are in accordance with the general FAO recommendation of reducing the FAO tabulated K_c values by 10–30% when using plastic mulches (Allen et al., 1998).

Lovelli et al. (2005) check the latest update proposed by the FAO to estimate evapotranspiration in the case of muskmelon crop both with plastic mulches and no mulch. The procedures suggested in FAO Irrigation and Drainage Paper 56 allows an accurate ET_c estimate in the case of muskmelon cultivated without plastic mulch. For the crop under mulch, a good agreement of the estimated K_c values with the measured ones is obtained only at the initial stage of the cycle, while at the stage of maximum canopy development the measured values are underestimated with respect to the FAO crop coefficients.

The work by Ferreira and Carr (2002) is interesting because they show the effects of differential irrigation and fertiliser treatments on the water use of potatoes. Soil evaporation and crop transpiration were the major components of the daily water loss. Drainage was negligible. For well-fertilised, well-irrigated crops, transpiration was dominant, contributing 75-85% of seasonal ET_c. For the unfertilised crops, evaporation from the soil surface was important, representing up to 50% ET_c over the same time period. As result of this mutual compensation, the total ET_c was similar for fertilised and unfertilised crops when irrigated. The season K_c values reported by authors for fully (0.87-0.85) and partially irrigation (0.62-0.69) and unirrigated treatments (0.4-0.3) are lower that FAO 56 ones for two years of the experiment, underlining the important effect of irrigation on daily rates of actual evapotranspiration.

Er-Raki et al., (2009) use the FAO-56 single crop coefficient approaches to estimate actual evapotranspiration over an irrigated citrus orchard under drip and flood irrigations in Marrakech (Morocco). The results shows that, by using crop coefficients suggested in the FAO-56 paper, the performance of both approaches was poor for two irrigation treatments. While, after the determination of the appropriate values of K_c based on ET_c measurements by eddy covariance, the performance of both approaches greatly improved. The obtained K_c values were lower than the FAO-56 values by about 20%. The lower K_c values obtained that K_c FAO reflect the practice of drip irrigation for one field and the low value of cover fraction for the other field. Additionally, the efficiency of the irrigation practices was investigated by comparing the measured K_c for two fields. The results showed that a considerable amount of water was lost by direct soil evaporation from the citrus orchard irrigated by flooding technique.

Many researches were direct to study both the water use and development of the crop coefficients for crops grown in greenhouse. In Mediterranean areas, the seasonal ET of greenhouse horticultural crops is quite low when compared to that of irrigated crops outdoors. This is due, firstly, to a lower evaporative demand inside a plastic greenhouse, which is 30-40% lower than outdoors throughout the entire greenhouse cropping season (Fernandez, 2000). Secondly, greenhouse cultivation in the Mediterranean areas is mostly concentrated in periods of low evaporative demand (autumn, winter and spring), whereas irrigated crops outdoors are often grown during high evaporative demand periods. Orgaz et al. (2005) carried out an investigation on the major horticultural crops (melon, sweet pepper, green bean, watermelon), usually, cultivated in plastic greenhouse in Spain. In this analysis, K_c values results to vary by crop, development stage and management. Thus, for melon and watermelon greenhouse crops, the mid-season K_c values proposed for outdoor crops (Allen et al., 1998) appear reasonable for use. By contrast, mid-season K_c value for vertically supported greenhouse crops (melon, green bean and sweet pepper) was around 1.3. This K_c value is higher than those reported for the same crops in Italy (Rubino et al., 1986) and California (Snyder et al., 1987; Grattan et al., 1998), and those proposed by Allen et al. (1998) for sub-humid climates, all grown outdoors. The higher K_c values of the vertically supported greenhouse crops, usually reaching 1.5–2 m in height, is probably due to greater net radiation with respect to the short crops, because of the morphological features of their canopies.

Manuel-Casanova et al. (2009) for lettuce grown in greenhouse conditions in Chile report K_c values lower than those generally adopted for lettuce in field conditions. These differences are due to the complexity of the coefficient which integrates various functions (Katerji et al., 1991; Testi et al., 2004) such as aerodynamic factors linked to crop height, biological factors related to leaf growth and senescence, physical factors linked to soil evaporation, physiological factors of stomata response to the air vapour pressure deficit, and agronomic management factors like distance between rows and irrigation system. Furthermore, in greenhouse conditions, the differences in K_c can also be attributed to the size of the greenhouse and the substrate used.

Many studies highlight the greater accuracy in the compute of the crop coefficient curves as a function of variables more related to crop development: LAI, percent canopy that shades the ground or thermal-based index, expressed as cumulative growing degree days (GDD). This approach, in fact, is considered an improvement compared to guidelines from FAO, that propose to estimate the K_c values as function of the length of the four phenological stages in which crop development is divided. Moreover, it is important the exact estimate of the length of each single growth stage since K_c pattern over time depends on it and, thus, a more accurate estimate of water use is possible (Lovelli et al., 2005). Other alternative approaches have been proposed over the last years to estimate K_c curves for annual crops as a function of time in terms of days after sowing (DAS) or month of the year. This method is easy to implement but, as with the FAO methodology, it does not take into account the influence of environmental and cultural factors on the rate of canopy development.

Relationships linear between K_c and LAI values are reported for green bean and melon by Orgaz et al. (2005); for grapevine by Williams et al. (2003) and for young olive orchard by Testi et al. (2004). In particular, the last author find that the K_c values determined in late autumn, winter and spring is usually high, variable and relatively independent of LAI or ground cover; during the summer the soil evaporation decreases and the K_c is lower, far less variable and LAI-dependent. This K_c values are linearly correlated to LAI or ground cover: the authors proposed a linear model to predict it. This model has shown great robustness despite their empirical nature.

Ayars et al. (2003) find that the K_c was a linear function of the amount of light intercepted by peach (Prunus persica L.) trees. It could be assumed that as leaf area increases so would the amount of solar radiation intercepted and the amount of ET_c.

Martinez-Cob (2007) obtains two crop coefficient equations as function of fraction of GDD for corn crop. The use of grown degree days to estimate K_c curves has the advantage that air temperature data is readily available and there is enough evidence of the influence of such variable on crop development (Ritchie and NeSmith, 1991). In conclusion, for real time irrigation scheduling, the authors advise of avoid the use of the methodology FAO 56 if it is possible to use GDD to estimate K_c as by the FAO methodology the possible variations of corn development due to different climatic conditions for a particular year can not be taken into account.

De Tar (2009) uses a modified soil water balance method with two independent variable (grown degree days, GDD, and days after planting, DAP) to determine the crop coefficients and water use for cowpea grown in California. During the early part of the season the crop coefficients were more closely related to DAP than to GDD, for the full season there was very little difference in the correlation for the various models using DAP vs. GDD.

When the study of the crop water requirement is carried out for many years, a variability over years in both measured K_c and ET_c values at different temporal scale (grown season, daily, monthly) is found by authors (Williams et al., 2003 for grapevine; Martinez-Cob, 2007 for maize; Ferreira and Carr 2002 for potato; Amayreh et al., 2005 for tomato; Testi et al., 2004 for olive orchard). By contrast, Villalobos et al., (2009) does not reported significant differences for the seasonal K_c values relate to two years of measurement for citrus orchard grown in Spain.

De Tar (2009) for cowpea in California estimates the crop coefficient computing ET_o through two methods: P-M equation and Pan evaporation. It find that the crop coefficients calculated using P-M equation for mid-season 2007 were significantly lower than for mid-season 2005, whereas, there was no significant difference with respect to the pan data for the same time periods.

5. Comments on the *Kc* values by the dual crop coefficient approach

Although the studies on dual crop coefficient approach in the Mediterranean area nowadays not are many (Table 5), some important considerations can be made.

The dual crop coefficient consists of two coefficients: a basal crop coefficient K_{cb} and a soil evaporation coefficient K_e. This procedure, using the separate estimates of the plant and soil components of the crop coefficient, would allow an independent observation of both components and the comparison between them (Paço et al., 2006).

A good evaluation of the amount of water lost by direct soil evaporation needs a partitioning of total evapotranspiration into its soil evaporation and plant transpiration components. Therefore, separate and direct measurements of transpiration and soil evaporation are desirable (i.e. through sap flow or isotope measurements) (Williams et al. 2004, Rana et al. 2005). For this reason, the dual crop coefficient is mainly used in research, real-time irrigation scheduling for highly frequent water applications, supplemental irrigation, and detailed soil and hydrologic water balance studies (Allen et al. 1998).

Some studies, carried out in different regions of the world, have compared the results obtained using the approach described by Allen et al. (1998) with those resulting from other methodologies. From this comparison result that some limitations should be expected in the application of the dual crop coefficient FAO 56 approach. For example, Dragoni et al. (2004), which measure actual transpiration in an apple orchard in cool, humid climate (New York, USA), showed a significant overestimation (over 15%) of basal crop coefficients by the FAO 56 method compared to measurements (sap flow).

Also the studies carried out in Mediterranean region showed contrasted results. Casa et al. (2000) and Lopez-Urrea et al. (2009) reported a good agreement. In particular, the second authors found, for onion crop grow under semiarid conditions, that the dual crop coefficient approach is more reliable than the single crop coefficient, since the high values of evaporative component existed during the entire crop cycle.

In contrast, Benli et al. (2006) and Paço et al. (2009) reported basal crop coefficients higher with respect to these tabulated. The first authors assign the different results probably to the difference between the climates. The seconds, for the young peach orchard, indicate a discrepancy with respect the measured values within determine the plant component (overestimation of plant transpiration), would lead to an overestimation of water consumption by 30%. Instead, the soil component estimates in the crop coefficient were similar to measured values.

El-Raki et al. (2009) show the performance of the FAO 56 approach for citrus orchard submitted a two different irrigation methods (drip and flood irrigation). The results suggest that the single crop coefficient approach can be used to derive a good estimate of water consumption of citrus orchards irrigated by the flooding technique with less frequent water applications, while the dual approach can be used for real-time irrigation scheduling with highly frequent water applications, as in the case of the drip irrigated citrus orchards. These results are in agreement with the recommendations suggested in the FAO-56 paper by Allen et al. (1998). In general, the dual crop coefficients approach, however, for incomplete cover and/or drip irrigation, seem to be more suited since it is more flexible.

6. Conclusions and Perspectives

The use of model P-M FAO 56 with single crop coefficient approach is very diffuse in the world. However, it was mainly studied and calculated for herbaceous crop; in fact, only few works was devoted to the Kc for orchard and tall crops. The easy application and the availability of the data request by model now aren't the big problem. However, the comparison with to data measured by different methods showed an acceptable agreement only for specific cases, in many cases corrections is strongly necessary.

Besides, the variability of the K_c values respect to those tabulated isn't negligible. From this study emerges that the K_c is crop and climate specific. The interaction between management practices and climate influence the behavior of K_c curves, such as the three characteristics values (initial, middle and late). The important difference, for example, lies within length of stage of grown of the crop or in the spacing and density of plantation. Further research is necessary to determine K_c corrections when plastic mulches are used, to avoid errors on the water consumptions.

In conclusions, for Mediterranean region determination of regionally based K_c curves for the major crops is needed. The crop coefficient values, in fact, were calculated only in the 10% of the countries of this fundamental agricultural area.

Some authors have observed very important inter-annual variability of K_c values, this aspect is explained by difference conditions climatic over years and different rate grown of the crops (especially for tall crop and trees), hence it requires more improvement. In this context, we consider useful the effort of many scientist of relate the K_c to vegetation indices, such LAI, GC and in particular GDD, that, better than other, capture the crop development due to different climatic conditions for a particular year.

From this review appears that the dual crop coefficient approach results more accurate for estimation of crop water requirements respect to single crop coefficient, such as shows the comparison with dates measured (Er-Raki et al., 2009). But, K_{cb} values reported by FAO 56 are cannot utilize in all regions climatic of the world. Also the basal crop coefficient is affected by variability based on climate conditions and crop's managements. The fact that in this method one can adjust separately the contribution of both the soil and vegetation, improve his performance and accuracy respect to single crop coefficient. But also it requires the measurement or computation of more variables and processes, which restrict their practical and spread application.

Numerous scientists are going along with Lascano (2000). He sustains that, for an irrigated cotton crop, the method could not describe adequately daily ET, showing a certain lack of sensibility to capture the dynamic nature of the evaporation process.

Recently Katerji and Rana (2006) came to the same conclusion on the K_c approach performance by comparison two methods of determining ET_c for six species cultivated in the Mediterranean region. The first one is direct and uses a model of r_c proposed by Katerji and Perrier (1983). The second one is indirect and adopted the approach proposed by Allen et al. (1989) in the bulletin FAO 56. In all the analysed situations the direct method gave more accurate estimation of ET_c. The lower performance of the indirect model was analysed in detail by Katerji and Rana (2006). They found that the accuracy of ET_c values indirectly determined depends on two factors. Firstly, it depends on the accuracy of the determination of ET_o; then, on the accuracy of the K_c values used. On the other hands, the direct evaluation of ET_c uses the one step approach instead of the two steps approach. This one step approach, since it is based on lower number of computation steps and on a lower number of error sources, can provide a more accurate estimation of ET_c. For this reason the recent scientific literature underlines the interest of developing methods permitting the direct calculation of ET_c (Testi et al., 2004; Orgaz et al., 2007).

Therefore, the need of characterising the weather variables above the crop, starting from specific measurements not performed routinely for correctly applying this method is the main obstacle to the use of the direct method in practice.

About this, Rana and Katerji (2009) proposed an operational version of a direct ET model based on its calibration and on the determination of the weather variables measurable in the agro-meteorological stations. This calculation needs only the height of the crop. On the other hands, also the indirect method needs the crop height for choosing the most appropriate crop coefficient during the different growth stages of the crop. Therefore, the operational version of the model can be applied in routine and it can be easily made automatic. Even if this methodology is able to replace the weather variables measured above the crop with those measured in a standard agro-meteorological station, as occur also within all the models based on the Penman-Monteith approach, further researches are necessary to evaluate its performance.

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Table 4. Crop coefficient, K_c, values reported by the bibliographies and K_c FAO values.

Crop	Type-variety	K_c				N. years	Irrigation method	Country		Reference
		Initial	Middle	End	Season					
a. Small vegetable										
Cauliflower	*B. oleacea* L. var. botrytis				0.84	1	Ponding	Turkey	Erzurum	Shin et al., 2009
Red Cabbage	*B. oleacea* L. var.rubra				0.83	1				
FAO-56			1.05	0.95						
Garlic	cv. California Early	0.8	1.2-1.3	0.7		1	Center-pivot	Spain	Guadalquivir V. (Cordoba,Ecja)	Villalobos et al., 2004
	cv. Chinese			0.91-0.94		1				
FAO-56			1	0.7						
Lettuce	var. Capitata cv. XP 6256	0.3			0.6	1	Drip	Chile	Santiago	Manuel-Casanova et al., 2009
FAO-56			1	0.95						
Onion	cv. Granero	0.65	1.2	0.75		1	Sprinkler	Spain	Albacete	Lopez-Urrea et al., 2009
FAO-56			1	0.75						
b. Vegetables – Solanum Family (Solanaceae)										
Tomato		0.6	1.15	0.8		2	Furrow	Chile	Maule region	Ortega-Farias et al., 2006
	cv. Pull	1.1	1.3	0.8		1	Drip	Italy	Puglia	Rinaldi and Rana, 2004
	Ibrido PS 1296	0.8	1.2	0.9		1				
			0.81 0.83	0.44 0.47	0.7	2	Drip with mulch	Jordan	Jordan Valley	Amayreh and Al-Abed, 2005
		0.36	0.77-1.2	0.74			Drip	Algeria	Bechar, Tamanrasset	Hamidat et al., 2002
	Processing Tomato	0.19	0.99-1.08	0.6		4	Drip	California		Hanson and May, 2005
		0.19	0.9-1.15	0.7		2	Drip with mulch	Spain	Ebro Valley	Vazquez et al., 2005
FAO-56			1.15-1.2	0.7-0.9						
Sweet pepper	cv. Drago Lamuyo type	0.2	1.3	0.9		2	Drip	Spain	Almeria	Orgaz et al., 2005
FAO-56			1.05	0.9						
c. Vegetables - Cucumber Family (Cucurbitaceae)										
Melon	cv. Categorìa (supported)	0.2	1.1	1		2	Drip	Spain	Almeria	Orgaz et al., 2005
	cv. Eros Galia type (not supp.)	0.2	1.3	1.1		1				
	var. Inodorus, cv. Nabucco	0.1	0.75	0.5		2	Drip whit mulch	Italy	Basilicata	Lovelli et al., 2005
		0.15	0.85	0.6			Drip whitout mulch			
FAO-56			1.05	0.75						
Watermelon	cv. Reina de Corazones	0.2	1.1	1		1	Drip	Spain	Almeria	Orgaz et al., 2005
FAO-56		0.4	1	0.75						
d. Roots and Tubers										
Potato	cv Desirée class AA1				0.87 0.85	2	Sprinkler	Portugal	Braganca	Ferreira and Carr, 2002
FAO-56			1.15	0.75						
e. Legumes										
Cowpea	California Blackeye N.46		1.28 1.17			2	Subsurface drip	California	San Joaquin Valley	DeTar, 2009
FAO-56		0.4	1.05	0.6-0.35						
Broad bean		0.37	1.05					Jordan	Jordan Valley	Amayreh and Al-Abed, 2003
FAO-56		0.5	1.15	1.1						

Crop	Type-variety	Kc				N. years	Irrigation method	Country		Reference
		Initial	Middle	End	Season					
Green bean	cv. Helda	0.2	1.4	1.2		2	Drip	Spain	Almeria	Orgaz et al., 2005
FAO-56		0.5	1.05	0.9						
Soybean	cv. Asgrow A-3803	0.62	1	0.66	0.7	2	Sprinkler -Drip	Lebanon	Bekaa Valley	Karam et al., 2005
FAO-56		0.4	1.15	0.5						
g. Fibre Crops										
Flax	cv. Mikael	0.4	0.9	0.2		1		Italy	Viterbo	Casa et al., 2000
FAO-56		0.35	1.1	0.25						
Cotton	DP555	0.4-0.5	1.25	0.6-0.1	0.2-1.5	3	Sprinkler	Texas	Coastier plain	Ko et al., 2009
		0.8	1.13			1		Turkey	Menemen plain	Beyazigul et al., 2000
		0.1-0.9	0.5-1			2	Furrow, drip	Texas	High Plain	Lascano, 2000
FAO-56		0.35	1.15 - 1.2	0.7-0.5						
i. Cereals										
Maize	cv. Juanita				0.88 0.94	2	Sprinkler	Spain	Ebro River Valley	Martinez-Cob , 2007
	cv. Pioneer PR34N43	0.48 0.59	1.28 1.27	0.35 0.35		2				
	32H39, 30G54	0.35	1.2	0.9		2	Sprinkler	Texas	Uvalde	Piccinni et al., 2009
FAO-56		0.3	1.2	0.6-0.35						
Wheat	Ogallala, TAM203	0.53	1.1	0.4		3	Sprinkler	Texas	Coastier plain	Ko et al., 2009
FAO-56		0.7	1.15	0.25-0.4		Winter Wheat (with non-fronzen soils)				
Sorgum	DKS 54	0.4	0.8	0.75		2	Sprinkler	Texas	Coastier plain	Piccinni et al., 2009
FAO-56		0.3	1-1.10	0.55		Sorghum grain				
m. Grapes and Berries										
Grapevine	cv. Tom. Seedless clone 2A	0.2	0.9-1.3			1	Drip	California	S. Joaquin V.	Williams and Ayars, 2005
	cv. Tompson Seedless		0.87 1.08 0.98	0.45		3	Drip	California	S.Joaquin V.	Williams et al., 2003
FAO-56		0.3	0.7	0.45						
n. Fruit tree										
Citrus	Mandarin	0.45	0.6	0.5	0.52		Drip	Morocco	Marrakech	Er-Raki et al., 2009
		0.58	0.55	0.6			Flood			
	Orange tree				0.8	1	Micro-sprayers	Italy	Catania Plain	Barbagallo et al., 2009
	Citrus reticulata Blanco				0.44 0.43	2	Drip	Spain	Mazagon	Villalobos et al., 2009
	Clementine	0.8	1.2	0.8		1	Drip	Italy	Apulia	Rana et al., 2005
FAO-56		0.75	0.7	0.75		70% canopy, with active ground cover				
		0.65	0.6	0.65		50% canopy, no active ground cover				
Peach	(var. Maybelle)				0.6-0.5	1	Sprinkler	Portugal	Aguas de Moura	Ferreira et al., 1996
	cv. Silver King				0.5	2	Drip	Portugal	Atalaia, Montijo	Paço et al., 2006
	cv. O'Henry		0.98-1.06			3	Drip	California	S. Joaquin V.	Ayars et al., 2003
FAO-56		0.55	0.9	0.65						
Olive	cv. Arbequino				0.35-0.45	3	Drip	Spain	Cordoba	Testi et al., 2004
	Agdal	0.65	0.45	0.65		2	Flood	Morocco	Marrakech	Er-Raki et al., 2008
FAO-56		0.65	0.7	0.7						

Table 5. Basal crop coefficient, K_{cb}, values reported in review and K_{cb} values reported in FAO Paper 56

Crop	Type-variety	K_{cb}				N. years	Irr.method	Country		Reference
		Initial	Middle	End	Season					
a. Small vegetable										
Onion	cv. Granero	0.6	1	0.65		1	Sprinkler	Spain	Albacete	Lopez-Urrea et al., 2009
FAO-56			0.95	0.65						
g. Fibre Crops										
Flax	cv. Mikael	0.7	1.1	0.2		1		Italy	Viterbo	Casa et al., 2000
FAO-56			1.05	0.2						
j. Forages										
Alfalfa		0.71	1.78	1.51		3	Sprinkler	Turkey	Plateau Anatolian	Benli et al., 2006
FAO-56		0.3	1.15	1.1						
n. Fruit tree										
Citrus	Mandarin	0.35	0.55	0.45			Drip	Morocco	Marrakech	Er-Raki et al., 2009
		0.3	0.5	0.4			Flood			
FAO-56		0.6	0.55	0.6						
Peach	cv. Silver King		0.7		0.66	2	Drip	Portugal	Atalaia, Montijo	Paco et al., 2006
FAO-56		0.45	0.85	0.6						