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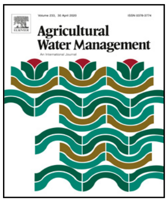

Review

# Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method

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## ABSTRACT

This study reviews the abundant research on FAO56 crop coefficients, published following introduction of the FAO56 paper in 1998. The primary goal was to evaluate, update, and consolidate the mid-season and end-season single ($K_c$) and basal ($K_{cb}$) crop coefficients, tabulated for many field crops in FAO56. The review found that the prevalent approach for estimating crop evapotranspiration ($ET_c$) is the FAO56 $K_c$-$ET_o$ approach, i.e., the product of the $K_c$ and reference evapotranspiration ($ET_o$). The FAO56 $K_c$-$ET_o$ approach requires use of the FAO56 PM-$ET_o$ grass reference equation with appropriate crop-specific $K_c$ and/or $K_{cb}$. Reviewed research provided various approaches to determine $K_c$ and $K_{cb}$ and used a variety of actual crop ET ($ET_{c\ act}$) measurements. Significant attention was placed on accessing the accuracy of the field measurements and models used in these studies. Accuracy requirements, upper limits for $K_c$ values, and related causal errors are discussed. Conceptual approaches relative to $K_c$ transferability requirements are provided with focus on standard crop conditions and use of the FAO56 segmented $K_c$ curve. Papers selected to update $K_c/K_{cb}$ used the FAO56 PM-$ET_o$, provided accurate measurements to determine and partition $ET_{c\ act}$, and satisfied transferability requirements. Selected observed $K_c$ and $K_{cb}$ values were converted to standard, sub-humid climate as adopted in FAO56. Observed values, with respect to tabulated FAO56 $K_c$ and $K_{cb}$, were used in consolidating updated values for crops within general categories of grain legumes, fiber crops, oil crops, sugar crops, small grain cereals, maize and sorghum, and rice. Ancillary data, e.g., maximum root depth and crop height, were also collected from selected literature and tabulated. Results showed good agreement between updated and original tabulated FAO56 $K_c$ and $K_{cb}$, confirming the reliability of the FAO56 values. This indicates change in the $K_c$ ($ET_c/ET_o$ ratio) of crops has not occurred due to climate change during the past ≈sixty years. New $K_c/K_{cb}$ data for crops, not included in FAO56, are also now presented for several oil crops and pseudo-cereals. The approach adopted for rice differs from FAO56 because consideration was given to the numerous rice water management practices currently used and, thus, $K_c/K_{cb}$ values for the initial season of rice were also presented. The review also observed that many research papers did not satisfy the adopted requirements in terms of $ET_o$ method and/or the accuracy of $ET_{c\ act}$ determinations and, therefore, could not be used. Thus, emphasis is placed on adopting improved accuracy and quality control in future research aimed at determining $K_c$ data comparable to presented values. The transferability of standard $K_c$ and $K_{cb}$ has been assured for the values tabulated herein. Improved future applications of the FAO56 $K_c$-$ET_o$ method should consider remote sensing observations when available, particularly in defining crop growth stages at given locations.

## Contents

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## 1. Introduction

In the field-agricultural practice, crop evapotranspiration ($ET_c$) is computed or modeled using weather data and algorithms that describe the aerodynamic characteristics of the vegetation and surface energy driving $ET_c$. One of the most adopted computational procedures is the one proposed in FAO56 (Allen et al., 1998), as recently reviewed by Pereira et al. (2015a) and, relative to the use of models, by Pereira et al. (2020a). The FAO method uses the $K_c$-$ET_o$ approach, where $ET_c$ is the product of a crop coefficient ($K_c$) by the grass reference evapotranspiration ($ET_o$). $ET_o$ represents the primary weather induced effects on the evapotranspiration rate of the grass reference crop, and the crop coefficient ($K_c$) scales the reference $ET_o$ to account for crop-specific influences on $ET_c$ resulting from the differences in aerodynamic and surface resistances between the considered crop and the reference grass crop (Allen et al., 1998; Pereira et al., 1999) during the crop growing season. The $ET_o$ (mm $d^{-1}$) is defined as the evapotranspiration rate of the grass reference crop, which is assumed as a hypothetical grass crop with a height of 0.12 m, a surface resistance of 70 s $m^{-1}$, and an albedo of 0.23, closely resembling an extensive surface of green grass of uniform height, actively growing, adequately watered and completely shading the ground (Allen et al., 1998). Daily $ET_o$ is computed with the PM-$ET_o$ Eq. (1):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where $R_n$-G is the net balance of energy available at the surface (MJ $m^{-2}$ $d^{-1}$), T is the mean daily air temperature (°C) at the reference height of 2 m, ($e_s$ - $e_a$) represents the vapor pressure deficit (VPD) of air (kPa) at 2 m height, $u_2$ is wind speed (m $s^{-1}$) at 2 m height, $\Delta$ is the slope of the saturation vapor pressure–temperature relationship at mean air temperature (kPa $^oC^{-1}$), and $\gamma$ is the psychometric constant (kPa $^oC^{-1}$). The most commonly used time-step in the field practice and related water balance modeling (Pereira et al., 2020a) is daily. Because only vertical fluxes of heat and vapor are considered in the Penman–Monteith combination equation (Monteith, 1965), as parameterized for the grass reference crop to produce the PM-$ET_o$ in Eq. (1), advective heat energy fluxes are not considered in $ET_o$ (Pereira et al., 1999).

Defining $K_c$ as the ratio of $ET_c$ to $ET_o$, and expressing $ET_c$ and $ET_o$ in terms of the Penman–Monteith combination equation (Monteith, 1965), it becomes evident that $K_c$ varies throughout the crop season with the aerodynamic and surface resistance of the crop and the reference crop (Pereira et al., 1999):

$$K_c = \frac{ET_c}{ET_o} = \frac{\dfrac{\Delta_c(R_{n,c} - G_c) + \rho_a c_p(e_s - e_a)_c / r_{a,c}}{\Delta_c + \gamma(1 + r_{s,c}/r_{a,c})}}{\dfrac{\Delta_o(R_{n,o} - G_o) + \rho_a c_p(e_s - e_a)_o / r_{a,o}}{\Delta_o + \gamma(1 + r_{s,o}/r_{a,o})}} \tag{2}$$

where, $R_n$, G, ($e_s$-$e_a$), $\Delta$, and $\gamma$ were defined above, $\rho_a$ is air density, $c_p$ is specific heat of air, $r_a$ is aerodynamic resistance to heat and vapor transport from the surface to $z$ height, and $r_s$ is bulk surface resistance. The subscripts "$c$" and "$o$" are, respectively, for the actual crop vegetation in the numerator and the grass reference crop in the denominator. This ratio (Eq. (2)) allows visualizing that $K_c$ represents an integration of the effects of three primary characteristics that distinguish the crop from the reference: (1) crop height, that affects roughness and aerodynamic resistance; (2) leaf area, fraction of ground covered by the vegetation ($f_c$), leaf age and condition, degree of stomatal control, and soil surface wetness, which determine bulk crop–soil surface resistance $r_s$; and (3) albedo of the crop–soil surface, which influences $R_n$ and depends upon by $f_c$ and soil surface conditions. The derivation of $K_c$ is generally done using empirical approaches that must be consistent relative to the above presented theoretical background. However, this consistency is often not referred to in related crop coefficient literature.

Two $K_c$ approaches are considered in FAO56 (Fig. 1): the time-averaged single $K_c$, which includes multi-day effects of soil evaporation in addition to plant transpiration, and the dual $K_c$, consisting of a basal crop coefficient ($K_{cb}$) and an evaporation coefficient ($K_e$) defined respectively as $K_{cb} = T_c/ET_o$ and $K_e = E_s/ET_o$, with $K_c = K_{cb} + K_e$, where $T_c$ is crop transpiration and $E_s$ is soil evaporation.

Considering Eq. (2), it is evident that $K_c$ varies throughout the crop season since parameters of the crop, in the numerator, will change with the growth of the crop until its maximum development and with crop maturation until harvest, at the end-season. Differently, by definition, the parameters of the reference crop, in the denominator, remain unchanged. FAO24 (Doorenbos and Pruitt, 1977) and, later, FAO56 (Allen et al., 1998) proposed to describe the time variation of $K_c$ using a segmented crop coefficient curve (Fig. 1). It applies to both the single, time-averaged $K_c$ and the basal $K_{cb}$. Because $E_s$ depends upon the fraction of ground cover, on the soil wettings, amount of water in the evaporation layer of the soil, as well as on soil hydrodynamic characteristics, $K_e$ varies with these conditions showing peaks in relation to soil wetting events. The $K_c$ and $K_{cb}$ curves consist of four linear segments representative of the four crop stages identified in Fig. 1: initial, from planting to 10% cover; crop development, up to full development; mid-season, until senescence starts; and late-season until end-season, i.e. harvesting.

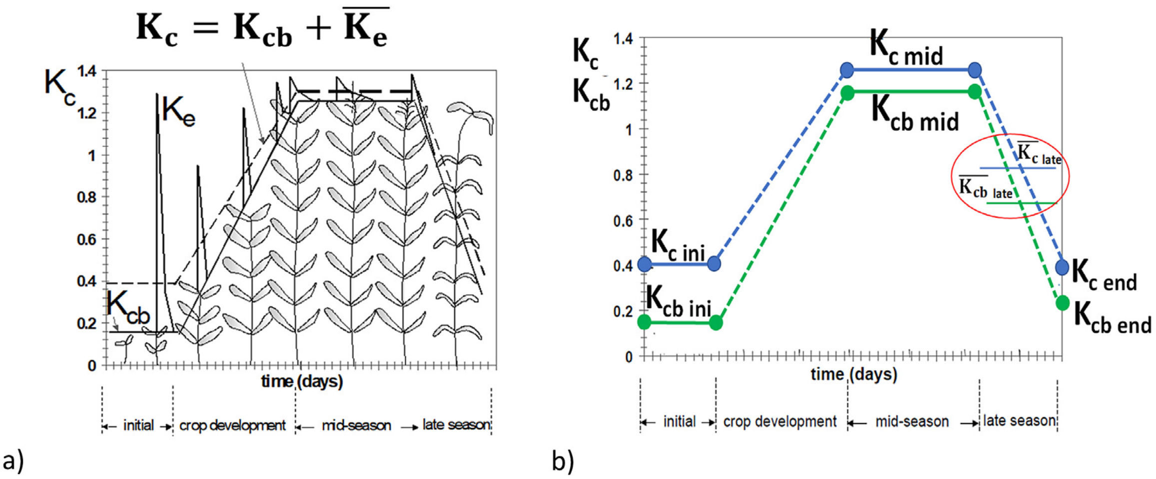


**Fig. 1.** Single and dual crop coefficients curves with identification of the four crop growth stages: (a) curves of the time averaged single crop coefficient ($K_c$), basal crop coefficient ($K_{cb}$), and soil evaporation coefficient ($K_e$); (b) $K_c$ and $K_{cb}$ curves distinguishing the $K_c$ or $K_{cb}$ values required to draw the respective curves ($K_{c\,ini}/K_{cb\ ini}$, $K_{c\,mid}/K_{cb\ mid}$ and $K_{c\,end}/K_{cb\ end}$) that are linearly interpolated over the development and late-season periods (dashed lines); also shown are the late-season averaged $K_c$ and $K_{cb}$ indicating that these values should not be used instead of end-season values.

To draw the segmented curves, it is required to know only the values of $K_c$ at the initial, mid-season and end-season, respectively $K_{c\,ini}$, $K_{c\,mid}$ and $K_{c\,end}$. $K_{c\,ini}$ essentially depends upon $E_s$, since $T_c$ is then very small, and its average may be represented by a horizontal segment. During the mid-season, the ratio $ET_c/ET_o$ has relatively small changes and $K_{c\,mid}$ may also be approximated by a horizontal segment. $K_{c\,end}$ corresponds just to the end of the whole crop cycle, however not exactly that on the harvesting day but an approximate trend value when precipitation occurring just by that end day, or close to it, would increase, disproportionally, the $K_{c\,end}$ value. The $K_{c\,end}$ value should not be confounded with the average $K_c$ for the entire late season stage, because this would largely overestimate $K_{c\,end}$, though mainly when the crop is harvested dry or close to it, as shown in Fig. 1b. Naturally, this guideline refers to both $K_c$ and $K_{cb}$.

The advantage of the segmented $K_c$ curve is that it just requires knowing three values, those at the initial stage ($K_{c\,ini}/K_{cb\,ini}$), at mid-season ($K_{c\,mid}/K_{cb\,mid}$) and at harvesting or end season ($K_{c\,end}/K_{cb\,end}$). $K_c$ values during crop development and late-season stages are then just linearly interpolated (Fig. 1b). However, the FAO $K_c$ curve is not adopted by many researchers, particularly when the objective is obtaining $K_c$ values to be used with the local climate. Alternative usage to the FAO56 curve structure consists of: (a) monthly $K_c$ averages, whose values are tied to the local climate and thus cannot be transferred to other locations; (b) functions relating $K_c$ with time, whose values cannot be transferred because they depend upon the local climate only; (c) functions relating $K_c$ with $f_c$ or a similar indicator as reviewed by Pereira et al. (2020b) relative to assessing $K_c$ from ground cover and height; and (d) in addition to $K_{c\,mid}$, using average values for the crop development stage and the late-season, which then do not allow a means to estimate, respectively, $K_{c\,ini}$ and $K_{c\,end}$ as shown in Fig. 1b. Nevertheless, when graphical representations of cases (a), (b) and/or (c) are produced in papers, a reader may then roughly estimate the values for $K_{c\,ini}$, $K_{c\,mid}$ and $K_{c\,end}$.

To draw the $K_c$ curve (Fig. 1) it is required to know the time durations of the crop stages. Respective indicative values for crops were tabulated in FAO56 (Allen et al., 1998) and in publications by Allen et al. (2007) and Jensen and Allen (2016). However, those tabulated values are just indicative, to be used in first step planning when field observations are not yet available. Those publications refer to the need for observing actual stage durations through field surveys. Thus, users should refrain from using indicative durations, which may deviate much from actual ones, but use actual field observations. Alternatively, for planning purposes, time durations may be replaced by cumulative growing degree-days (CGDD) characterizing the crop growth stages, as earlier reported in many applications in literature, namely as early proposed by Sammis et al. (1985).

When adopting the dual $K_c$ approach, it is essential that partitioning ET into transpiration and soil evaporation be performed accurately. Various methods may be applied as reviewed by Kool et al. (2014). They report on methods that, like FAO56, are based upon the relationship between $E_s$ and $f_c$ (Allen et al., 1998, 2005a,b), as well methods that require the use of specific instrumentation, adopt a double source model, or use isotopes. Modeling plays a main role as in the case of using a soil water balance model like SIMDualKc (Rosa et al., 2012a; Paredes et al., 2014; Pereira et al., 2020a) while the use of remote sensing vegetation indices allows accurate estimation of $K_{cb}$ (Hunsaker et al., 2005a,b, 2007; French et al., 2020; López-Urrea et al., 2020).

$K_c$ and $K_{cb}$ are subject to a large number of influencing factors as summarized in Fig. 2 for $K_c$ at each growth stage. During the initial stage, the variability of $K_{c\,ini}$ relates to soil evaporation and factors controlling it, such as frequency of rainfall and irrigation wettings, use of plastic mulches, plastic tunnels, organic mulching, soil residues management, frequency and depth of irrigation applications, and fraction of soil wetted by irrigation. With such a variety of influencing factors, it is not possible to tabulate values for $K_{c\,ini}$ and it is not possible to derive related values from published papers. FAO56 provided indicative $K_{c\,ini}$ values corresponding to the most common conditions, i.e., when surface irrigation was used, and the soil was maintained bare. However, in many studies, researchers considered indicative $K_{c\,ini}$ as recommended values and thus may have used them erroneously. Therefore, tabulated $K_{c\,ini}$ values are not proposed herein; instead, the $K_{c\,ini}$ computational procedures proposed by Allen et al. (1998 – pg 114–121 -, 2005b) are recommended for users. Simple models can be used for that purpose. For the dual $K_c$ approach, the value $K_{cb\,ini} = 0.15$ is recommended since it averages conditions from bare soil and fraction of ground cover ($f_c$) up to 0.10, and it is assumed to include “diffusive” or residual evaporation from soil for potentially long periods following wetting (Allen et al., 2005a). However, under dry conditions with long periods between wettings, or during the non-growing season, $K_{cb\,ini}$ can be set much lower, even close to 0. Differently, $K_e$ should be computed taking into consideration all the factors affecting soil evaporation as detailed by Allen et al. (1998, 2005a).

FAO56 (Allen et al., 1998) adopted the concept of standard $K_c$ *vs.* actual $K_c$ ($K_{c\,act}$) in correspondence with potential crop ET ($ET_c$) *vs.* actual crop ET ($ET_{c\,act}$). $ET_c$ and $K_c$ refer to optimal, well-watered conditions and pristine cultivated crops, while $ET_{c\,act}$ and $K_{c\,act}$ refer to crop conditions that are often not pristine due to insufficient or non-uniform irrigation, rainfall failures, soil and water salinity, as well as

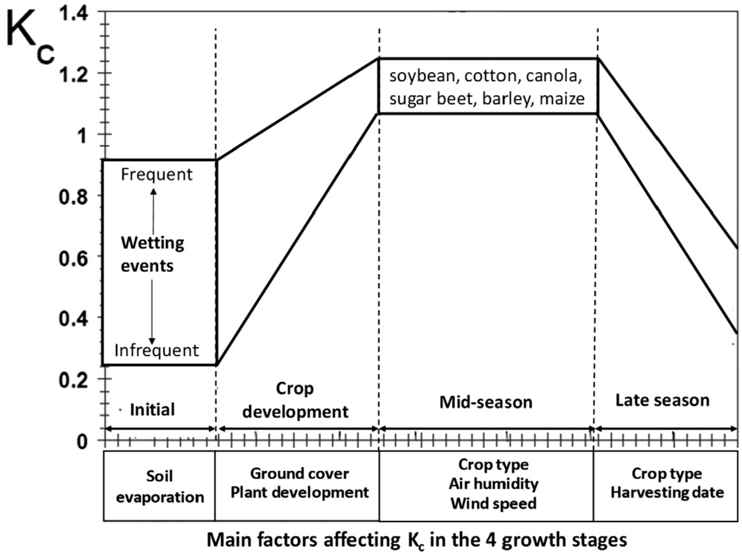


**Fig. 2.** Main factors affecting the actual crop coefficients relative to the four crop growth stages.
*Source:* Adapted from FAO56.

non-optimal soil and agronomic management practices including crop density, planting date, seed quality, and weed and disease control. In addition to these factors, Niaghi et al. (2019) assessed impacts of controlled drainage and related sub-irrigation on $ET_{c\,act}$ and $K_{c\,act}$ of maize; as expected from cultivation with high water table, $K_{c\,act}<K_c$ optimal are reported. Naturally, only standard $K_c$ and $K_{cb}$ values may be transferred to other sites and, therefore, be tabularized as presented in FAO56.

$K_c$ and $K_{c\,act}$, as well as $K_{cb}$ and $K_{cb\,act}$, are related through a stress coefficient ($K_s$) depending upon the sufficiency of available soil water to maintain the crop ET rate at potential. Thus, it results:

$$K_{c\,act} = K_s K_c = K_s K_{cb} + K_e \tag{3}$$

where it is evidenced that when the dual $K_c$ is adopted, $K_s$ only applies to the transpiration coefficient $K_{cb}$. When referring to water insufficiency only, $K_s$ is defined (Allen et al., 1998) as:

$$K_s = \left(\frac{TAW - D_{r,i}}{TAW - RAW}\right) \quad \text{if } D_{r\,i} > RAW \tag{4a}$$

$$K_s = 1 \quad \text{if } D_{r\,i} \le RAW \tag{4b}$$

where TAW and RAW are respectively the total and readily available soil water relative to the rooting depth (mm), with RAW=p TAW (p is the soil water depletion fraction for no water stress), and $D_{ri}$ is the soil water depleted from the root zone at the end of day i (mm). When salinity also affects ET (Allen et al., 1998; Minhas et al., 2020), then:

$$K_s = \left(\frac{TAW - D_{r,i}}{TAW - RAW}\right)\left(1 - \frac{b}{K_y 100}\left(EC_e - EC_{e\,threshold}\right)\right) \tag{5}$$

where $K_y$ is the yield response factor (-) describing the relationship between the relative yield decrease with the relative evapotranspiration deficit (Doorenbos and Kassam, 1979), $EC_{e\,threshold}$ (dS $m^{-1}$) is the soil $EC_e$ value from where crop production starts to be affected by salinity, and b is the percent rate of yield decrease relative to the $EC_e$ excess relative to $EC_{e\,threshold}$ (%/(dS $m^{-1}$)). Indicative values for those parameters are updated and tabularized by Minhas et al. (2020). Eqs. (4) and (5) above make it evident that $K_{c\,act}$ values cannot be transferred when a crop has an ET rate inferior to potential due to crop and water management and/or salinity impacts.

The standard FAO56 tabularized $K_{c\,mid}/K_{cb\,mid}$ and $K_{c\,end}/K_{cb\,end}$ values refer to irrigation management and precipitation frequencies typical of a sub-humid climate where minimum relative humidity and wind speed at 2 m height are, respectively $RH_{min}$ = 45% and $u_2$ = 2 m $s^{-1}$ as defined in FAO56 (Allen et al., 1998). Under humid and calm conditions, the $K_{c\,mid}$ for “full-cover” crops generally exceed 1.0 by only 0.05 to 0.10, approximately, because “full-cover” crops and the reference crop behave similarly regarding absorption of short-wave radiation, the primary energy source for evaporation under humid and calm conditions (Allen et al., 2011b). Differences in ET caused by differences in the aerodynamic resistance $r_a$ between the agricultural and the reference crop are also small because the VPD is then small; thus, the values of $K_c$ are less dependent on differences between the aerodynamic components of $ET_c$ and $ET_o$ (Eq. (2)). On the contrary, under arid conditions, such differences in $r_a$ are more pronounced because the VPD is then large. Hence, $K_c$ will be larger under arid conditions, mainly for tall crops that are more subjected to wind effects in terms of replacing the saturated air close to the leaves with drier air, thus accelerating evaporation fluxes. Then $K_c$ values may not exceed 1.0 by more than about 0.25 as discussed by Allen et al. (2011b,a) and in the companion paper (Pereira et al., 2021) unless advection occurs adding energy for evaporation. $K_c$ obtained under advective influences are much too large and therefore are not transferable.

During the last two decades, much research has been performed to develop and update crop coefficients, however with diverse objectives, and using a variety of field methods and approaches to derive $K_c$ and $K_{cb}$ from research results. It is therefore opportune to assess such research, select recognized advances and results, including when approaches were not in agreement with the FAO56 methodologies. Thus, the objectives of this study consist of evaluating the progress in deriving $K_c$ and $K_{cb}$ values for agricultural field crops, updating standard $K_c$ and $K_{cb}$ values formerly tabulated in FAO56, extending that information to other crops and crop conditions not previously made available such as for rice, as well as update crop characteristics required when formulating a water balance for irrigation planning. However, the analysis will not include changes in $K_c$ due to modification of cropping practices such as the use of mulches, residues cover and intercropping. These aspects are dealt in a recent article that reviews the impacts of diverse management practices on $K_e$ and $K_c$ (Jovanovic et al., 2020). Another important objective of the current article is to provide $K_c$ and $K_{cb}$ information that could be used to determine the upper limit of crop evapotranspiration and, therefore, help establish a target for the amounts of irrigation water use and support developing water saving practices, thus responding to current environment challenges.

The intention of this review is in providing recent and updated information from the literature on $K_c$ and $K_{cb}$ at mid-season and end-of-season for field crops. Defining specific durations of crop stages for the various crops was not applicable to this paper's scope. Growth stage lengths for any crop can vary widely from one location to the next and that is why using local observations including remote sensing data (such as vegetation index, VI) is a forefront in FAO56 application (e.g., Hunsaker et al., 2005a,b). While general recommendations for growth stage lengths were provided in FAO56 for most crops, many times these stage-lengths have been used directly in local studies with resultant claims of poor $ET_c$ agreement with measurements. Thus, caution is needed. Consequently, it is recommended here to refrain from using the indicative stage durations provided in FAO56 but instead use the actual field observations of crop growth stage durations as a function of days past planting or cumulative growing degree days (CGDD).

This Section 1 – Introduction – has presented the main concepts relative to crop coefficients that are the basis of the performed analysis and of the adoption of distinct concepts of standard and actual crop coefficients. Section 2 updates energy limits on ET and $K_c$ values, advection effects, and limitations to transferability of $K_c$ data, focusing on field methods used to determine crop evapotranspiration and, therefore, the $K_c$ and $K_{cb}$ values. In addition, Section 2 updates the required adjustments to standard climate and the procedures and constraints on collecting and handling $K_c$ information from literature. A review of published $K_c$ and $K_{cb}$ for field crops that satisfy the basic requisites for transferability consist of Section 3, with crops grouped as grain legumes, fiber crops, oil crops, sugar crops, small grains, maize and sorghum, and rice. Section 4 presents the tabulated values of the $K_{c\,mid}/K_{c\,end}$ and $K_{cb\,mid}/K_{cb\,end}$ resulting from that review taking consideration of the FAO56 tabulated values. Section 5 aims at presenting the consolidated main ancillary data for the same crops. Finally, conclusions and recommendations are made in Section 6.

## 2. Background for updating the standard single and basal crop coefficients

### 2.1. Limits on maximum values for ET and crop coefficients; advection effects

As previously referred, the availability of energy incident at the surface constrains the potential evaporation rate and forces adherence to the law of conservation of energy. The basic equation of the balance of energy

$$R_n - G = \lambda ET + H \tag{6}$$

shows that the available energy at the surface, $R_n$-G, is the source for both the latent and sensible heat flux, respectively $\lambda$ET and H, all expressed in MJ $m^{-2}$ $d^{-1}$. If $\lambda$ET exceeds $R_n$-G, it means that an additional energy is added via convective transfer through the equilibrium boundary layer of air above the surface (Allen et al., 2011b). That transfer requires the transport by wind of the required *H* to the surface to support the conversion to ET (De Bruin et al., 2005). Thus, there is an upper limit on ET, including under extreme advection, due to limitations on aerodynamic transport and on equilibrium forces above a vegetation canopy (Allen et al., 2011b). That upper limit on $ET_c$ is readily approximated by comparing against $ET_o$ using the crop coefficient.

Values for $K_c$ may approach 1.3 for tall, dense crops under windy arid and semiarid conditions because of the smooth roughness and small LAI of the grass reference crop (cf. Eq. (2)). In humid climates, ET is dominated more by net radiation availability and less by aerodynamics and VPD. Because a grass reference crop has an albedo like that of most crops at full cover and because the primary energy constraint for the ET process is net radiation, the maximum $K_c$ cannot generally exceed 1.2 to 1.3 with added regional advection effects. Following Allen et al. (2011b), "in arid and semiarid climates, differences in aerodynamic and surface conductances, when coupled with potentially strong regional advection, may cause $K_c$ to be as high as 1.2 to exceptionally high values of 1.4 for tall, dense, healthy and well-watered vegetation".

As discussed by Allen et al. (2011b), "when ET is measured from small expanses of vegetation, the internal boundary layer above the vegetation may not be in equilibrium with the surface and may not have developed up to the height of any meteorological or flux instrumentation". Small expanses of vegetation surrounded by shorter or dry cover may cause a "clothesline effect", so ET and $K_c$ may be significantly greater in those conditions than those in large fields. This also happens with lysimeters since the vegetation inside the lysimeter may function as a clothesline (Allen et al., 1991a). If ET estimates are to represent large expanses of vegetation, or small stands of vegetation surrounded by mixtures of other vegetation having similar roughness and soil water conditions, then $K_c$ values must generally be ≤ 1.2–1.4 for grass reference. These aspects are more fully discussed in the companion paper (Pereira et al., 2021).

Measured or reported $K_c$ above 1.2 in sub-humid regions or above about 1.2 to 1.4 in arid regions should cause an intense scrutiny of the ET measurements, the weather data used to compute $ET_o$, and the data collection and handling procedures. That need for scrutiny is supported by the previously referred recommendations formulated by Allen et al. (2011b,a).

### 2.2. Limitations to the transferability of $K_c$ due to experimental and reporting insufficiencies

Research developed in the last 20 years to derive crop coefficients is very abundant. However, objectives of such studies were diverse, used research methods very different, with variable accuracy, often aiming to obtain $K_c$ for local use only. In addition, they are frequently published with insufficient information relative to methods and instrumentation used, weather conditions or about the crops and the cropping practices used. It resulted that much of the published material had serious limitations to transferability and, hence, could not be used in this review due to a variety of reasons:

(1) Adoption of $ET_o$ equations/approaches different than the standard PM-$ET_o$ (Eq. (1)) defined in FAO56. Since a $K_c$ is defined as the ratio $ET_c/ET_o$ (Eq. (2)), if the $ET_o$ equation changes, the $K_c$ also changes by a value corresponding to the ratio between the selected $ET_o$ equation and PM-$ET_o$. A good example is provided by Shankar et al. (2012) who reported disparate $K_c$ values for maize and mustard computed for seven $ET_o$ equations. The transferability of the research results is only possible when that ratio is well known.

(2) Using a $K_c$ curve relationship different from the standard segmented FAO $K_c$ curve, which implies that only approximate estimations of $K_{c\,mid}$ and $K_{c\,end}$ can be made from the reported graphical data, but generally not possible from tabulated information.

(3) Using non-standard cultivation conditions, such as plastic mulches, direct planting into crop residues or mulch, and intercropping, which change crop ET and soil evaporation ($E_s$), thus $K_c$. These field practices are obviously necessary to control $E_s$ and/or to improve infiltration, but their influences on $K_c$ have to be well-documented if transferability is the goal. However, reported changes in $K_c$ are often quite disparate among research papers, with the study by Feng et al. (2019) showing that impacts of plastic mulch on $K_c$ of maize may be relatively small.

(4) When crop management practices deviate from pristine conditions, unless $K_c$ results could be corrected with the use of $K_s$ (Eqs. (3) and (5)), as it can often be done through modeling, $K_c$ values cannot be directly transferred.

Problems for transferability often result from conditions where $K_c$ experiments are developed, managed and data are handled. This is the common case in small size experimental plots, inadequate setting and management of lysimeters, reduced fetch of energy balance instrumentation towers, and the lack of appropriate estimation of soil water fluxes through the boundaries of the control volume affecting the accuracy of the soil water balance (SWB), e.g., the amount of water passing through the bottom boundary, i.e., deep percolation and capillary rise. Another common problem relates to the use of remote sensing when using non-calibrated vegetation indices and when applications are done without distinction of stressed and non-stressed crops. These aspects were reviewed by Allen et al. (2011b), Evett et al. (2012a,c) and in the companion paper (Pereira et al., 2021). In addition, it is often observed that reported descriptions of the experiments are insufficient in terms of both the instrumentation and the approaches used that would provide evidence for the accuracy of measurements, although recommendations by Allen et al. (2011b,a) could be helpful. When the ET measurements described in literature studies had questionable accuracy, they were deemed to be unacceptable for the use and transfer of the reported $K_c$ values presented herein.

The main problems in achieving crop ET accuracy and usable data were found for the following measurement approaches:

(1) Inaccuracies in performing the soil water balance (SWB), as analyzed by Evett et al. (2012b), which include insufficient characterization of the soil hydraulic properties, non-consideration of the full root zone depth, inadequate spacing and/or frequency of measurements, inaccuracies in measuring the soil water content and/or the irrigation applications and rainfall, poor estimation of deep percolation fluxes and/or gains by capillary rise, rough computational approaches and/or using an inadequately calibrated and validated model.

(2) Using lysimeters without respect to related requirements for accuracy (Allen et al., 1991b,a; López-Urrea et al., 2006; Evett et al., 2016), namely having differences in cropping conditions inside and outside of the lysimeter thus affecting vigor and growth of crop vegetation, poor settings of the lysimeter without similar vegetation surrounding it thus causing local advection or clothesline effects, lack of a fetch such that the equilibrium boundary layer of air cannot be fully adjusted above the lysimeter, and/or having a high exposed rim that favors advective effects.

(3) Measuring ET with the Bowen ratio energy balance (BREB) method having inaccuracies (Payero et al., 2003; Allen et al., 2011b) that include insufficient fetch, insufficient elevation of instruments above the canopy, and less representative measurement of $R_n$ and G.

(4) When measurements are performed with eddy covariance (EC) systems, various corrections and precautions are required (Alfieri et al., 2012; Evett et al., 2012c; Burba, 2013; Kutikoff et al., 2019). Problems arise when requirements are not respected, which include a large fetch to establish an equilibrium boundary layer deeper than the instrument height, sufficient elevation of instruments above the canopy, performing appropriate data corrections, including adjustments for the effects of advection, and correcting data for the energy balance closure error ($R_n$-G=$\lambda$E+H), namely caring for the effects of advection.

(5) The use of remote sensing vegetation indices (VIs) to estimate crop coefficients is now well established, mainly with the Normalized Difference Vegetation Index (NDVI Hunsaker et al., 2005a,b; Calera-Belmonte et al., 2017) and the soil adjusted vegetation index (SAVI, Glenn et al., 2011). Linear relationships between the NDVI and $K_c$ or $K_{cb}$ are mentioned in numerous studies, some of which will be referred to later in the paper. However, more recently, other VIs have shown higher correlation with $K_c$ and may be more preferable when using images of the Sentinel-2 satellite (Rozenstein et al., 2018). A main difficulty for deriving $K_c$ or $K_{cb}$ from a VI is improper calibration of the index and also the possibility that VI observations in pixels do not correspond to the crop growing under an approximately pristine condition, as for examples provided by Hunsaker et al. (2005a,b, 2007). Remote sensing energy balance is rarely used to estimate ET for deriving $K_c$ values but would have similar difficulties to those using VI approaches. However, good results on $K_c$ with energy balance have been obtained as reported by Tasumi and Allen (2007).

Reported information and field observations of the crop — plant density, height and vigor, the crop growing stages, and cultivation practices are often incomplete or missing, thus making it impossible, or at least quite difficult, to properly assess the reported $K_c$ values. Moreover, information on the weather variables during the experimental period is often undocumented in papers, particularly so for minimum relative humidity ($RH_{min}$) and wind speed at 2 m height ($u_2$), thus making it difficult to adjust the reported $K_c$ to climate as proposed in FAO56, where it is assumed that $K_c$ refers to a standard semi-humid climate ($RH_{min}$ =45% and $u_2 = 2$ m s$^{-1}$).

When accuracy in measuring crop ET and in computing $ET_o$ is poor, it often results in high $K_c$ values and high $K_c$ x $ET_o$ products occur, which largely exceed the energy available at the surface for evaporation as discussed in Section 2.1. Although very high daily values are possible when advection occurs, values of $K_c$ above 1.3 may be observed for a few occasional days or over short periods but cannot be accepted as averages for large periods, e.g., over a month or the entire mid-season. Researchers should include the control of observed ET through comparing it with the available $R_n$-G. Under advection, H may be negative due to transport of heat into the location under study. Nevertheless, $K_c$ values affected by advection reflect local conditions and are not transferable.

### 2.3. Adjustment to the standard climate

FAO56 (Allen et al., 1998) assumed that the standard, transferable $K_{c\,mid}$ and $K_{c\,end}$ as well as $K_{cb\,mid}$ and $K_{cb\,end}$ values refer to irrigation management and precipitation frequencies typical of a sub-humid climate where $RH_{min}$ = 45% and $u_2$ = 2 m s$^{-1}$. Thus, when local climatic conditions deviate from these values, the observed $K_c$ values, $K_{c\,mid\,(obs)}$ and $K_{c\,end\,(obs)}$, need to be adjusted to become standard $K_c$ values, $K_{c\,mid\,(std)}$ and $K_{c\,end\,(std)}$ as:

$$K_{c\,mid(std)} = K_{c\,mid(obs)} - \left[0.04\left(u_{2\,mid} - 2\right) - 0.004\left(RH_{\min\,mid} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \tag{7a}$$

$$K_{c\,end(std)} = K_{c\,end(obs)} - \left[0.04\left(u_{2\,late} - 2\right) - 0.004\left(RH_{\min\,late} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \tag{7b}$$

where $u_2$ is the average daily wind speed at 2 m height [m s$^{-1}$], $RH_{min}$ is the average daily minimum relative humidity [%], and h is the average plant height [m]. The subscripts mid and late indicate that those averages refer to data observed during the mid- and late-season, respectively. When crops senesce and dry out in the field ($K_{c\,end}$ < 0.45) no adjustment is necessary for $K_{c\,end}$. Crop height should be observed in the field; and tabulated h values often deviate from reality and should not replace field observations. Similar adjustments apply to $K_{cb}$, thus:

$$K_{cb\,mid(std)} = K_{cb\,mid(obs)} - \left[0.04\left(u_{2\,mid} - 2\right) - 0.004\left(RH_{\min\,mid} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \tag{8a}$$

$$K_{cb\,end(std)} = K_{cb\,end(obs)} - \left[0.04\left(u_{2\,late} - 2\right) - 0.004\left(RH_{\min\,late} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \tag{8b}$$

Papers were checked relative to containing the weather information required to perform the above adjustments to the standard climate. Climate descriptions were often insufficient and the papers presenting data on the variables used in Eqs. (7) and (8), i.e., $RH_{min}$, $u_2$, and crop height averages for the mid- and end-season, were very rare. When that information was not available but weather data relative to the experimental location, or a nearby site, could be accessed through websites, then the reported $K_c$ or $K_{cb}$ values were adjusted to the standard climate. It is evident that the approximate average climate values then used did not provide for an accurate adjustment but, otherwise, it would not be possible to perform any approximate adjustment for most of collected information. In addition, most papers also did not provide information on observed crop heights, thus the maximum heights tabulated in FAO56 were used for this purpose.

### 2.4. Procedures for updating $K_c$ and $K_{cb}$

Limitations to transferability, referred before and further analyzed in the companion paper (Pereira et al., 2021), obliged to a careful review of published material to check when derived $K_c$ based upon research performed with adequate accuracy, or reported $K_c$ values were only of local interest and/or representing non-standard experimental conditions. Only $K_c$ relative to recognizable potential evaporative crop conditions resulting from optimal, pristine cropping practices, could be considered. Selected references were checked to ensure that sufficient descriptions of the practices used to measure ET data, crop practices, and related production environment were provided. The reported $K_c$ and $K_{cb}$ obtained under non-standard conditions such as with mulches, crop residues and intercropping are only marginally referred herein. References were also checked to avoid potential computational flaws and shortcomings in data handling and/or in model calibration and validation.

There is a good number of studies on deriving crop coefficients, $K_c$ and $K_{cb}$, for field crops. However, much literature could not be used, mainly when studies:

- Adopted a reference evapotranspiration different of the grass FAO-PM or the grass ASCE-PM ($ET_o$), namely the pan ET, the FAO24 Penman, the alfalfa reference $ET_r$, or any other locally developed or selected ET equation.
- Did not adopt the FAO56 segmented crop coefficient curve, namely when describing $K_c/K_{cb}$ as a non-linear function of time, or $K_c$ were averaged by month or shorter period, in such conditions, mainly without graphical presentation, that it was not possible obtaining values characterizing the mid-season and the end-season.
- Were performed along a single crop season in climates when the variability of environmental characteristics could lead to varied influences on $K_c$ or $K_{cb}$ values.
- Lack of appropriate description of experimental agronomic conditions, thus when it was not possible to assume that derived $K_c$ referred to a non-stressed crop well adapted to the prevailing environmental conditions.

Assessed papers refer to a variety of approaches to estimate $ET_{c\,act}$. When methods were insufficiently described and did not allow assessing the sufficiency of quality of performed field work and related data analyses were insufficient, papers were discarded. The analysis of data included checking the upper values of $K_c$ as discussed before.

When information on lysimeter setting was not stating the area cropping around it, or the care for limiting micro-scale advection or clothesline effects, or about determining the effective evaporation area, high $K_c$ data were treated as influenced by advection or clothesline effects. If various sources of $K_c$ for the same crop were available data were discarded; if those sources were insufficient, then $K_c$ or $K_{cb}$ values were reduced by 10% as a rule of tomb to correct excess $K_c$ due to less good lysimeter setting and management. If $K_{c\,end} \geq K_{c\,mid}$ data were necessarily discarded. If $K_{c\,mid} > 1.40$ without appropriate explanation, data were discarded, namely when lacking adequate description of procedures used with SWB, BREB, EC or else that could justify those high values. A similar rule of tomb was used to "correct" $K_{c\,mid}$ or $K_{cb\,mid}$ when the reported $K_c$ or $K_{cb}$ adjusted for the standard climate produced season averaged $1.40 \geq K_{c\,mid} > 1.25$ and/or $1.35 \geq K_{cb\,mid} > 1.20$. Naturally, end-season values were reduced proportionally.

In addition to issues dealt above concerning published $K_c$ data, the following limitations relative to the various methods used to estimate $ET_{c\,act}$ are noted:

- Weighing lysimeters (WL): acceptable data refer to WL installed in large fields where it is possible to assume vertical vapor fluxes. However, when lysimeter methods were insufficient or when the average $K_{c\,mid}$ and $K_{c\,end}$ values largely exceeded those observed by other authors and/or tabulated in FAO56, related papers were discarded.
- Drainage or water table lysimeters (DL and WTL): data were used when soil moisture observations were performed complementarily to lysimeter observations and information provided was sufficient to assume that local advection or clothesline effects did not affect results. As for WL, if average $K_{c\,mid}$ and $K_{c\,end}$ were excessive, related papers were also discarded.
- Energy balance from measurements of eddy covariance (EC) and/or Bowen ratio (BREB): data were used when proper location of towers was indicated, corrections were mentioned, and closure error was discussed.
- Soil water balance (SWB): data were selected when there was sufficient information on depth and frequency of observations, deep percolation was considered, and there was some kind of evidence that computed soil moisture dynamics followed that of observations. In addition, data were from plots having a minimum size to avoid local advection or clothesline effects.
- SWB models were selected when evidence of appropriate calibration and validation was given. Models considered included ISAREG (Popova et al., 2006; Cholpankulov et al., 2008; Popova and Pereira, 2011), SALTMED (Silva et al., 2013a; Pulvento et al., 2013, 2015) and SIMDualKc (Rosa et al., 2012b, 2016; Zhao et al., 2013; Paredes et al., 2014). The crop growth-yield model AquaCrop (Giménez et al., 2017) was also considered.
- Data were used when obtained by remote sensing of NDVI or SAVI when at least two years of observations were performed, information allowed an understanding that NDVI or SAVI were obtained for a non-stressed crop, and that the relationships between the crop coefficient and the vegetation index were properly calibrated/tested.

### 2.5. Tabulating collected crop coefficients information

It was considered essential to contribute only the best available information collected, in other words, an adequate identification of the selected studies, the retained crop coefficients, and the retained related ancillary data. For ease in accessing that information, sets of Tables are used. The subscript (obs) is adopted to identify the collected $K_c$ and $K_{cb}$ values reported in literature, which were obtained from field observations of $ET_{c\,act}$. Aiming at transferability, those collected crop coefficients were adjusted to the standard climate using Eqs. (7) and (8) and are identified with the subscript (std), thus indicating that such values are standard single or basal crop coefficients. For all crops, actual $K_{c\,(obs)}$ were more often reported than $K_{cb\,(obs)}$, likely because the derivation of the latter requires detailed partitioning of $ET_{c\,act}$. Performing that partition is quite demanding both in terms of field data collection and in the use of specific computation algorithms, which may be incorporated in simulation models, e.g. the SIMDualKc model.

Collected information are presented in Tables for all groups of crops, including:

- The common English name and the scientific name of the crop;
- The reference of the selected paper;
- The location where field data were collected, which allows a perception of the type of climate;
- The field method used to gather data aimed at estimating $ET_{c\,act}$ (as discussed before);
- Information on the $K_{c\,mid\,(obs)}$ and $K_{c\,end\,(obs)}$, or on the $K_{cb\,mid\,(obs)}$ and $K_{cb\,end\,(obs)}$, reported in literature; and
- Crop coefficient values adjusted to the standard climate, thus $K_{c\,mid\,(std)}$ and $K_{c\,end\,(std)}$, or the $K_{cb\,mid\,(std)}$ and $K_{cb\,end\,(std)}$.

Additional Tables are used to provide the collected field information on main ancillary crop parameters that are often used in water balance studies, namely for irrigation scheduling purposes, and that were consistently proposed in FAO56. These parameters consist of

- Maximum root depth ($Z_{r\,max}$, m);
- Maximum crop height ($h_{max}$, m);
- Maximum leaf area index ($LAI_{max}$, $m^2\ m^{-2}$);
- Maximum fraction of ground cover ($f_{c\,max}$); and
- Soil water depletion fractions for no stress (p) at the initial, mid-season and end-season ($p_{ini}$, $p_{mid}$ and $p_{end}$) assuming $ET_c = 5$ mm $d^{-1}$.

Unfortunately, for many crops, that ancillary information is incomplete or even lacking. Interesting to note that most of ancillary data were provided by studies using a soil water balance approach, or when a dual $K_c$ approach was adopted.

## 3. Review on derived single and basal crop coefficients for field crops

### 3.1. Grain legumes

There is a large number of papers reporting on $K_c$ of grain legume crops, less on $K_{cb}$. It was possible to select a reasonable number of papers that report on the derivation of single and basal crop coefficients for use with the PM-$ET_o$ reference evapotranspiration equation with adequate accuracy. Most studies refer to soybean, the main cropped grain legume. More than one paper refers to dry bean, chickpea, cowpea and fababean, while black gram, groundnut and pea are the object of single papers. Unfortunately, appropriate studies on $K_c$ for green gram and lentil were not available.

The selected papers mostly used sprinkler irrigation, often center-pivot systems, as well as, various surface irrigation methods (Table 1). Selected papers using drip irrigation were found for only two chickpea studies and one soybean study. Therefore, observed $K_c$ mostly refer to irrigation conditions where the soil surface is fully wetted. However, these legume crops generally fully shadow the ground by mid-season, thus limiting the energy available for soil evaporation. There was no evidence of high $E_s$ impacts on observed $K_{c\,mid\,(obs)}$ when comparing to the $K_{c\,mid\,(std)}$, while observed differences in $K_{c\,end\,(std)}$ mostly depended on crop management decisions relative to harvesting.

Difficulties relative to assuming an adequate value for $K_{c\,end\,(std)}$ also stem from the fact that $K_c$ for the end season was often replaced by a $K_c$ value relative to the late season or to maturity, or that daily $K_c$ values were unexpectedly increased due to a rain event occurring near to the end season. Other related problems were described earlier in Section 1. Therefore, it was generally more problematic for researchers to produce a proper interpretation of data in estimating $K_{c\,end\,(obs)}$.

The actual crop evapotranspiration ($ET_{c\,act}$) was field observed through a variety of approaches (Table 1). Drainage lysimeters (DL) associated with a SWB using neutron probes were used by Laike et al. (2006) in their study on dry bean; similarly, Patil and Tiwari (2020) used DL and SWB based on capacitance probes measurements for green gram. Weighing lysimeters (WL) were used by Howell et al. (2006) for soybean and by Bastos et al. (2008) and Cavalcante Junior et al. (2016) for cowpea. However, results reported by Bastos et al. (2008) are likely affected by advection and, consequently, their $K_{c\,mid\,(obs)}$ was empirically reduced by 0.10. Garofalo et al. (2009) and Pandey and Pandey (2011) also used WL but in combination with soil water balances (SWB) performed, respectively, with TDR and gravimetric measurements.

Various studies estimated $ET_{c\,act}$ by performing the SWB, with or without a simulation model. Simple SWB computations were used by DeTar (2009) for cowpea with the soil water content (SWC) observed with neutron probes, Suleiman et al. (2013) for groundnuts with SWC measured with TDR, while Zayton et al. (2014) and Alla Jabow et al. (2015) measured the SWC with a gravimetric approach applied respectively to peanuts and to bean, chickpea and fababean studies. Simulation models calibrated with SWB data were reported by Silva et al. (2013a), Wei et al. (2015), Giménez et al. (2017) and Paredes et al. (2017). Silva et al. (2013a) used the SALTMED model with SWC measured with a capacitance probe, while the others used the dual crop coefficient model, SIMDualKc, with calibration and validation performed with SWC measurements by TDR, neutron probes and capacitance sensors, respectively.

Other approaches used for determining $ET_{c\,act}$ refer to eddy covariance (EC), the Bowen ratio energy balance (BREB) and remote sensing (RS), the latter used by Tasumi and Allen (2007). EC applications are reported by Amayreh and Al-Abed (2003) for fababean, and by both Suyker and Verma (2009) and Payero and Irmak (2013) for soybean. Odhiambo and Irmak (2012) and Irmak et al. (2013) used BREB for the study of soybean.

The partition of $ET_{c\,act}$ for calculating $K_{cb}$ was performed using diverse approaches, most often by adopting the FAO56 dual $K_c$ approach, i.e., estimating $K_e$ from the fraction of ground covered by the crop, $f_c$. When using SIMDualKc or SALTMED models, $f_c$ is used as input and $K_{cb}$ is obtained through model calibration as reported by Silva et al. (2013a) for chickpea, Wei et al. (2015) and Giménez et al. (2017) for soybean, and Paredes et al. (2017) for pea. Direct applications of the dual $K_c$ approach were used by Pandey and Pandey (2011) with a SWB for black gram, and by Odhiambo and Irmak (2012) and Irmak et al. (2013) with BREB applied to soybean.

The example of $K_{cb}$ and $K_c$ derivation for pea (Paredes et al., 2017) illustrates well the usability of models to derive the crop coefficients. Fig. 3 shows the differences between the daily $K_c$ values, which resulted from the sum of the daily estimation of $K_{cb}$ and $K_e$, and the time averaged $K_c$ values as used for irrigation scheduling purposes. The average $K_c$ values do not change along the season because, due to frequent precipitation and irrigation, a high $K_e$ value was observed which maintained $K_c = K_e + K_{cb}$ constant throughout the initial and the vegetative period. Differently, during the mid-season $K_e$ was only residual due to the high fraction of ground covered by the crop ($f_{c\,max} = 0.98$) resulting that $K_c$ and $K_{cb}$ values were quite close. Because pea for industry is to be harvested fresh, when the bottom leaves start to senesce, the $K_{cb\,mid}$ and $K_{cb\,end}$ values are very similar.

To use the SIMDualKc model for estimating the pea crop evapotranspiration and related crop coefficients (Fig. 3), the components of the soil water balance were measured taking into consideration the accuracy recommendations provided by Allen et al. (2011b). Observations included: (a) the precipitation and net irrigation depths measured using rain gauges placed at the soil surface; (b) the soil water content ($\theta$, $cm^3\ cm^{-3}$) measurements performed weekly throughout the crop season using a previously calibrated DIVINER 2000 probe (Sentek Pty Ltd, Australia) from 0.10 m to a depth of 0.90 m. After adequate treatment of collected data, the SWB model SIMDualKc was calibrated and validated using independent $\theta$ data sets i.e., one season was used for calibration while the remaining datasets relative to a different season were used for validation of the model.

In addition to recognizing the approaches used and their potential accuracy, it is also important to note that the selected applications were

**Table 1**
Field observed $K_c$ and $K_{cb}$ for grain legumes and corresponding values adjusted to the standard climate ($RH_{min}$ = 45%, $u_2$ = 2 m $s^{-1}$) with identification of the articles reference, location of the field study, methods used for determination and partition of $ET_{cact}$ and irrigation method.

| Crop | Reference | Location | Method for estimating $ET_{c\,act}$ | Irrigation method | $K_c/K_{cb}$ derived from field observations | | $K_c/K_{cb}$ adjusted to the standard climate | |
|---|---|---|---|---|---|---|---|---|
| **Single crop coefficient** | | | | | $K_{c\,mid\,(obs)}$ | $K_{c\,end\,(obs)}$ | $K_{c\,mid\,(std)}$ | $K_{c\,end\,(std)}$ |
| Bean, dry (*Phaseolus vulgaris*) | Laike et al. (2006) | Melkassa, Ethiopia | DL, SWB-neutron | Surface | 1.03 | 0.54 | 0.98 | 0.49 |
| | Tasumi and Allen (2007) | Magic Valley, ID, USA | RS, METRIC model | Sprinkler & furrow | 1.15 | n/r | 1.12 | n/r |
| | Alla Jabow et al. (2015) | Hudeiba, Sudan | SWB-gravim. | Surface | 1.07 | 0.55 | 1.02 | 0.47 |
| Black and green gram (*Vigna mungo*) | | | | | | | | |
| Black gram (dry) | Pandey and Pandey (2011) | Udaipur, Rajastan, India | WL, SWB-gravim. | Furrow | 1.18 | 0.39 | 1.22 | 0.39 |
| Green gram | Patil and Tiwari (2020) | Kharagpur, West Bengal, India | DL, SWB-capacit. | SDI & furrow | | | | |
| | Plastic mulch | | | | 0.83 | 0.30 | 0.88 | 0.30 |
| | No mulch | | | | 0.89 | 0.40 | 0.94 | 0.40 |
| Chickpea (*Cicer arietinum*) | Garofalo et al. (2009) | Foggia, Italy | WL, SWB-TDR | Drip | 0.97 | 0.29 | 0.95 | 0.29 |
| | Silva et al. (2013a) | Elvas, Portugal | SWB-capacit., SALTMED | Drip | 1.00 | 0.35 | 0.97 | 0.35 |
| | Alla Jabow et al. (2015) | Hudeiba, Sudan | SWB-gravim. | Surface | 1.08 | 0.52 | 1.03 | 0.47 |
| Cowpea (*Vigna unguiculata*) | Bastos et al. (2008) | Alvorada do Gurguéia, Brazil | WL | Sprinkler | 1.25 | 0.30 | 1.23 | 0.30 |
| | DeTar (2009) | Shafter, CA, USA | SWB-neutron | SDI | 1.23 | 0.50 | 1.21 | 0.49 |
| | Cavalcante Junior et al. (2016) | Apodi, Ipanguaçu & Mossoró, Brazil | WL | n/r | 1.09 | 0.52 | 1.11 | 0.55 |
| Fababean (fresh) (*Vicia faba*) | Amayreh and Al-Abed (2003) | Amman, Jordan | EC | Furrow | 1.05 | n/r | 1.03 | n/r |
| | Alla Jabow et al. (2015) | Hudeiba, Sudan | SWB-gravim. | Surface | 1.22 | 0.60 | 1.16 | 0.54 |
| Groundnut, peanut (*Arachis hypogaea*) | Suleiman et al. (2013) | Griffin, GE, USA | SWB-TDR | n/r | 1.17 | 0.60 | 1.18 | 0.61 |
| | Zayton et al. (2014) | El-Bostan, Egypt | SWB-gravim. | Sprinkler | 0.88 | 0.63 | 0.88 | 0.63 |
| Pea, fresh (*Pisum sativum*) | Paredes et al. (2017) | Alpiarça, Portugal | SWB-capacit., SIMDualKc | Sprinkler | 1.20 | 1.13 | 1.21 | 1.16 |
| Soybean (*Glycine max*) | Howell et al. (2006) | Bushland, TX, USA | WL | Sprinkler | 1.10 | 0.20 | 1.02 | 0.20 |
| | Suyker and Verma (2009) | Mead, NE., USA | EC | Sprinkler | 1.00 | 0.32 | 0.99 | 0.32 |
| | Odhiambo and Irmak (2012) | Clay Center, NE., USA | BREB, FAO dual $K_c$ approach | SDI | 1.20 | 0.50 | 1.16 | 0.43 |
| | Payero and Irmak (2013) | North Platte, NE., USA | EC | Sprinkler | 1.08 | 0.50 | 1.12 | 0.44 |
| | Irmak et al. (2013) | Clay Center, NE., USA | BREB, FAO dual $K_c$ approach | SDI | 1.12 | 0.18 | 1.15 | 0.18 |
| | Wei et al. (2015) | Daxing, China | SWB-gravim., SIMDualKc | Basin | 0.96 | 0.45 | 1.06 | 0.45 |
| | Giménez et al. (2017) | Paysandú, Uruguay | SWB-neutron, SIMDualKc | Drip | 1.13 | 0.40 | 1.14 | 0.40 |
| **Basal crop coefficient** | | | | | $K_{cb\,mid\,(obs)}$ | $K_{cb\,end\,(obs)}$ | $K_{cb\,mid\,(std)}$ | $K_{cb\,end\,(std)}$ |
| Black gram (*Vigna mungo*) | Pandey and Pandey (2011) | Udaipur, Rajastan, India | WL–FAO dual $K_c$, SWB-gravim. | Furrow | 1.10 | 0.33 | 1.14 | 0.33 |
| Chickpea (*Cicer arietinum*) | Silva et al. (2013a) | Elvas, Portugal | SWB-capacit., SALTMED | Drip | 0.95 | 0.25 | 0.92 | 0.25 |
| Pea, fresh (*Pisum sativum*) | Paredes et al. (2017) | Alpiarça, Portugal | SWB-capacit., SIMDualKc | Sprinkler | 1.15 | 1.10 | 1.16 | 1.13 |
| Soybean (*Glycine max*) | Odhiambo and Irmak (2012) | Clay Center, NE., USA | BREB, FAO dual $K_c$ approach | SDI | 1.10 | 0.30 | 1.06 | 0.30 |
| | Irmak et al. (2013) | Clay Center, NE., USA | BREB, FAO dual $K_c$ approach | SDI | 1.10 | 0.15 | 1.13 | 0.15 |
| | Wei et al. (2015) | Daxing, China | SWB-TDR, SIMDualKc | Basin | 0.95 | 0.35 | 1.05 | 0.35 |
| | Giménez et al. (2016) | Paysandú, Uruguay | SWB-neutron, SIMDualKc | Drip | 1.10 | 0.35 | 1.11 | 0.35 |

BREB — Bowen ratio energy balance; Capacit. — Capacitance probe; DL — Drainage lysimeter; EC — Eddy Covariance; Gravim. — Gravimetric sampling method; Neutron — neutron probe; RS — Remote sensing; SDI — Subsurface drip irrigation; SWB — Soil water balance; TDR — Time-Domain Reflectometry; WL — Weighing lysimeter; n/r — not reported.

made in a variety of climates and countries in various continents. Studies on soybean were within major world producing areas, including the US central Great Plains, the North China plain, and western Uruguay in South America. The study on fresh pea for industry is from Portugal, while studies focusing on chickpea $K_c$ were also developed in the Mediterranean region (Italy and Portugal) and in Sudan. The research on bean and gram is from Central Brazil, Ethiopia, Sudan, India, and the USA, while that on cowpea is from California, USA, and Northeast

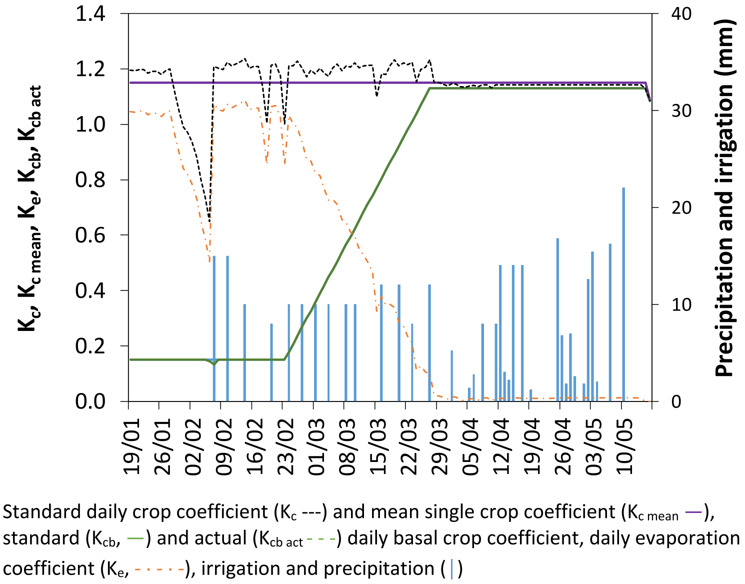


**Fig. 3.** Daily ($K_c$) and mean single ($K_{c\,mean}$) and daily dual crop coefficients ($K_{cb}$, $K_e$) curves derived with the calibrated SIMDualKc model for early harvested green pea. *Source:* Adapted from Paredes et al. (2017).

**Table 2**
Observed ancillary crop parameters for grain legumes reported from selected literature.

| Crop | Reference | $Z_{r\,max}$ (m) | $h_{max}$ (m) | $LAI_{max}$ ($m^2$ $m^{-2}$) | $f_{c\,max}$ | $p_{ini}$ | $p_{mid}$ | $p_{end}$ |
|---|---|---|---|---|---|---|---|---|
| Bean, dry (*Phaseolus vulgaris*) | Laike et al. (2006) | 0.90 | 0.66 | 3.7 | n/r | n/r | 0.30 | n/r |
| Black and green gram (*V. mungo*) | | | | | | | | |
| Black gram (dry) | Pandey and Pandey (2011) | 0.60 | 0.40 | n/r | 0.94 | n/r | 0.50 | n/r |
| Green gram | Patil and Tiwari (2020) | 0.40 | n/r | 5.1 | n/r | n/r | n/r | n/r |
| Chickpea (*Cicer arietinum*) | Garofalo et al. (2009) | 0.90 | n/r | 4.0 | 0.97 | n/r | n/r | n/r |
| | Silva et al. (2013a) | 0.80 | 0.41 | 1.9 | 0.80 | n/r | n/r | n/r |
| Cowpea (*Vigna unguiculata*) | DeTar (2009) | 1.50 | n/r | n/r | 0.80 | n/r | 0.20 | n/r |
| Fababean, fresh (*Vicea faba*) | Amayreh and Al-Abed (2003) | n/r | n/r | n/r | 0.85 | n/r | n/r | n/r |
| Groundnut (peanut) (*A. hypogaea*) | Suleiman et al. (2013) | 1.00 | n/r | n/r | 0.90 | n/r | 0.55 | n/r |
| | Zayton et al. (2014) | 0.60 | n/r | n/r | n/r | n/r | n/r | n/r |
| Pea, fresh (*Pisum sativum*) | Paredes et al. (2017) | 0.80 | 0.50 | n/r | 0.98 | 0.40 | 0.40 | 0.40 |
| Soybean (*Glycine max*) | Howell et al. (2006) | 1.40 | 1.05 | 5.4 | n/r | n/r | n/r | n/r |
| | Odhiambo and Irmak (2012) | 1.20 | n/r | 5.5 | n/r | n/r | 0.50 | n/r |
| | Payero and Irmak (2013) | n/r | 0.85 | n/r | n/r | n/r | n/r | n/r |
| | Suyker and Verma (2009) | n/r | n/r | 5.7 | n/r | n/r | n/r | n/r |
| | Wei et al. (2015) | 1.00 | 0.75 | n/r | 0.99 | 0.50 | 0.50 | 0.50 |
| | Giménez et al. (2017) | 1.00 | 0.94 | n/r | 1.00 | 0.50 | 0.50 | 0.50 |

$Z_{r\,max}$ – maximum root depth; $h_{max}$ – maximum crop height; $LAI_{max}$ – maximum leaf area index; $f_{c\,max}$ – maximum fraction of ground cover; $p_{ini}$, $p_{mid}$, $p_{end}$ – soil water depletion fraction for no stress for respectively the initial, mid and end season stages; n/r – not reported.

Brazil. The study on $K_c$ for peanuts comes from Georgia, USA, and those for fababean are from Jordan and Sudan. That variety of research origins helps to assume that the reported applications encompass and represent a large diversity of climates and socio-economic management conditions.

Ancillary data are provided by some of the selected studies (Table 2). However, information is scarce but usable to update related data published in FAO56 tables. Of particular interest is the information relative to the fraction p of soil water depletion without causing stress. Values of reported p indicate that, in general, soil water depletion for many crops can be relatively large before stress occurs, up to 0.50–0.55, which then allows more efficient use of large application depths, as made in surface irrigation and non-mechanized sprinkler systems.

New information on root depths ($Z_{r\,max}$) for crops is somewhat scarce (Table 2). Data on crop height are also scarce. Those providing maximum LAI indicate that the studies were likely without stress, except the chickpea study by Silva et al. (2013a), which may have been under some water stress or had low plant density. The values for $f_{c\,max}$ indicate that related crops covered the ground well except for the above referred case study on chickpea.

### 3.2. Fiber, oil and sugar crops

The review of the literature has shown that a large number of papers relative to deriving $K_c$ for fiber crops have been published in the past 20 years, mainly for cotton. However, many of those papers did not assure the accuracy required, although a good number could be selected. Unfortunately, not a single paper was available for hemp, jute, and sisal. There are studies relative to linseed, however cropped as an oil crop, but none referring this crop for fiber, i.e., it was also not possible to update the flax $K_c$ and $K_{cb}$ tabulated in FAO56. Therefore, the selected papers on fiber crops refer only to cotton.

Table 3 shows the selected cotton papers that were deemed to satisfactorily provide published information on derived cotton $K_c$, as based on PM-$ET_o$, and that included the FAO56 $K_c$ curve and crop stage data. These studies used various irrigation methods, mostly sprinkler and

**Table 3**
Field observed $K_c$ and $K_{cb}$ for fiber, oil and sugar crops and corresponding values adjusted to the standard climate ($RH_{min}$ = 45%, $u_2$ = 2 m $s^{-1}$) with identification of the article reference, location of the field study, methods used for determination and partition of $ET_{c act}$ and irrigation method.

| Crop | Reference | Location | Method for estimating $ET_{c\,act}$ | Irrigation method | $K_c/K_{cb}$ derived from field observations | | $K_c/K_{cb}$ adjusted to the standard climate | |
|---|---|---|---|---|---|---|---|---|
| **Single crop coefficient** | | | | | $K_{c\,mid\,(obs)}$ | $K_{c\,end\,(obs)}$ | $K_{c\,mid\,(std)}$ | $K_{c\,end\,(std)}$ |
| ***Fiber crops*** | | | | | | | | |
| Cotton<br>(*Gossypium hirsutum*) | DeTar (2004) | Shafter, CA, USA | SWB-neutron | SDI | 1.11 | 0.20 | 1.07 | 0.20 |
| | Howell et al. (2006) | Bushland, TX, USA | WL | Sprinkler | 1.18 | 0.20 | 1.10 | 0.20 |
| | Cholpankulov et al. (2008) | Hunger Steppe, Kazakhstan | Energy balance, ISAREG | Furrow | 1.20 | 0.25 | 1.19 | 0.25 |
| | | Fergana Valley, Uzbekistan | SWB-neutron, ISAREG | Furrow | 1.20 | 0.65 | 1.22 | 0.66 |
| | Farahani et al. (2008) | Aleppo, Syria | SWB-neutron | Drip | 1.05 | 0.66 | 0.99 | 0.61 |
| | Ko et al. (2009) | Uvalde, TX, USA | WL | Sprinkler | 1.24 | 0.60 | 1.18 | 0.56 |
| | Bezerra et al. (2012) | Apodi, RN, Brazil | BREB | Sprinkler | 1.09 | 0.80 | 1.03 | 0.75 |
| | Kumar et al. (2015) | St. Joseph, LA, USA | WL | Furrow | 1.25 | 0.40 | 1.22 | 0.40 |
| | Rozenstein et al. (2018) | Gedera, Israel | EC, SR, SF | Drip | 0.90 | 0.30 | 0.88 | 0.30 |
| | Han et al. (2019) | Aksu, Xinjiang, China | DL, SWB-neutron | Drip | | | | |
| | | Plastic mulch | | | 1.00 | 0.28 | 0.90 | 0.28 |
| | | No-mulch | | | 1.02 | 0.35 | 0.92 | 0.35 |
| | Anapalli et al. (2020) | Stoneville, MS, USA | EC | Furrow | 0.95 | 0.70 | 0.93 | 0.68 |
| | Fong et al. (2020) | Manila, AR, USA | EC | Sprinkler | 1.01 | 0.30 | 0.97 | 0.30 |
| ***Oil crops*** | | | | | | | | |
| Camelina<br>(*Camelina sativa*) | Hunsaker et al. (2011) | Maricopa, AZ, USA | SWB-TDR & neutron | Surface | 1.20 | 0.54 | 1.12 | 0.47 |
| Canola<br>(*Brassica napus*) | López-Urrea et al. (2020) | Albacete, Spain | WL | Sprinkler | 1.20 | 0.35 | 1.15 | 0.35 |
| Castorbean<br>(*Ricinus communis*) | Dias et al. (2015) | Barbalha, Brazil | BREB | Sprinkler | 1.10 | 0.82 | 1.09 | 0.82 |
| Linseed<br>(*Linum usitatissimum*) | Casa et al. (2000) | Viterbo, Italy | BREB, SWB-gravim. | n/r | 1.00 | 0.20 | 0.97 | 0.20 |
| | Kar et al. (2007) | Dhenkanal, India | SWB-gravim. | Surface | 0.96 | 0.26 | 0.95 | 0.26 |
| Mustard<br>(*Brassica juncea*) | Kar et al. (2007) | Dhenkanal, India | SWB, gravim. | Surface | 1.18 | 0.38 | 1.17 | 0.38 |
| | Shankar et al. (2012) | Roorkee, India | DL, SWB-resist. | Surface | 1.12 | 0.35 | 1.15 | 0.35 |
| | Gupta et al. (2017) | New Delhi, India | WL, SWB-TDR | Basin | 1.04 | 0.55 | 1.00 | 0.45 |
| Safflower<br>(*Carthamus tinctorius*) | Bassil and Kaffka (2002) | Five Points, CA, USA | SWB-neutron | Furrow | 1.30 | 0.22 | 1.22 | 0.22 |
| | Kar et al. (2007) | Dhenkanal, India | SWB-gravim. | Surface | 1.05 | 0.30 | 1.04 | 0.30 |
| Sesame<br>(*Sesamum indicum*) | Sepaskhah and Andam (2001) | Shiraz, Iran | DL, SWB-neutron | n/r | 1.08 | n/r | 1.00 | n/r |
| Sunflower<br>(*Helianthus annuus*) | Tyagi et al. (2000a) | Karnal, India | WL, SWB-neutron | Surface | 1.29 | 0.25 | 1.20 | 0.25 |
| | Karam et al. (2007) | Bekaa Valley, Lebanon | DL, SWB-TDR | Drip | 1.25 | 0.20 | 1.15 | 0.20 |
| | López-Urrea et al. (2014) | Albacete, Spain | WL | Sprinkler | 1.23 | 0.35 | 1.15 | 0.35 |
| | Howell et al. (2015) | Bushland, TX, USA | WL | Sprinkler | 1.29 | 0.30 | 1.17 | 0.30 |
| | Garofalo and Rinaldi (2015) | Foggia, Italy | WL | Drip | 1.10 | 0.10 | 1.07 | 0.10 |
| | Miao et al. (2016) | Dengkou, Hetao, China | SWB-gravim., SIMDualKc | Basin | 1.19 | 0.35 | 1.20 | 0.36 |
| ***Sugar crops*** | | | | | | | | |
| Sugar beet<br>(*Beta vulgaris*) | Tasumi and Allen (2007) | Magic Valley, ID, USA | RS, METRIC model | Sprinkler, surface | 1.19 | n/r | 1.11 | n/r |
| | Utset et al. (2007) | Valladolid, Spain | SWB-neutron, SWAP | n/r | 1.05 | 0.90 | 0.97 | 0.83 |
| | Wang et al. (2021) | Five Points, CA, USA | WL, EC, RS | Sprinkler, drip | 0.97 | 0.85 | 0.96 | 0.82 |
| Sugar cane<br>(*Saccharum officinarum*) | Inman-Bamber and McGlinchey (2003) | Kalamia, Australia | BREB, APSIM | Furrow | 1.24 | n/r | 1.23 | n/r |
| | | Simunye, Swaziland | BREB | Drip | 1.24 | n/r | 1.23 | n/r |
| | Olivier and Singels (2012) | Pongola, South Africa | WL | Drip | | | | |
| | Planting, bare soil | | | | 1.14 | n/r | 1.13 | n/r |
| | Planting, mulch | | | | 1.09 | n/r | 1.08 | n/r |
| | Ratoon, bare soil | | | | 1.10 | n/r | 1.09 | n/r |
| | Ratoon, mulch | | | | 1.04 | n/r | 1.03 | n/r |
| | Silva et al. (2013b) | Paraiba, Brazil | SWB-reflectometry | Sprinkler | 1.06 | 0.76 | 1.11 | 0.81 |
| | Bastidas-Obando et al. (2017) | Mpumalanga, South Africa | SR, SWB-capacit. | Drip | 1.11 | 0.78 | 1.15 | 0.83 |
| | | KwaZulu, Natal, South Africa | BREB, SWB-capacit. | Rainfed | 1.04 | n/r | 1.05 | n/r |
| | Dingre and Gorantiwar (2020) | Rahuri, India | SWB-gravim. | Drip | 1.20 | 0.56 | 1.20 | 0.56 |

(*continued on next page*)

**Table 3** (*continued*).

| Crop | Reference | Location | Method for estimating $ET_{c\,act}$ | Irrigation method | $K_c/K_{cb}$ derived from field observations | | $K_c/K_{cb}$ adjusted to the standard climate | |
|---|---|---|---|---|---|---|---|---|
| **Basal crop coefficient** | | | | | $K_{cb\,mid\,(obs)}$ | $K_{cb\,end\,(obs)}$ | $K_{cb\,mid\,(std)}$ | $K_{cb\,end\,(std)}$ |
| ***Fiber crops*** | | | | | | | | |
| Cotton<br>(*Gossypium hirsutum*) | Hunsaker (1999) | Maricopa, AZ, USA | SWB-TDR & neutron | Basin | 1.30 | 0.40 | 1.21 | 0.40 |
| | Hunsaker et al. (2003) | Maricopa, AZ, USA | SWB-neutron, RS | SDI | 1.16 | 0.65 | 1.06 | 0.56 |
| | Howell et al. (2004) | Bushland, TX, USA | WL | Sprinkler | 1.10 | 0.15 | 1.02 | 0.15 |
| | Hunsaker et al. (2005a) | Maricopa, AZ, USA | SWB-TDR & neutron, RS | Basin | 1.20 | 0.52 | 1.12 | 0.47 |
| | Rosa et al. (2012b) | Fergana Valley, Uzbekistan | SWB-neutron, SIMDualKc | Furrow | 1.15 | 0.50 | 1.17 | 0.52 |
| | Thorp et al. (2017) | Maricopa, AZ, USA | SWB-neutron | Sprinkler | 1.20 | n/r | 1.12 | n/r |
| ***Oil crops*** | | | | | | | | |
| Camelina<br>(*Camelina sativa*) | Hunsaker et al. (2011) | Maricopa, AZ, USA | SWB-TDR & neutron | Surface | 1.18 | 0.54 | 1.10 | 0.47 |
| | Hunsaker et al. (2013) | Maricopa, AZ, USA | SWB-neutron, RS | Surface | 1.19 | 0.37 | 1.09 | 0.37 |
| Canola<br>(*Brassica napus*) | Zeleke et al. (2011) | Wagga Wagga, Australia | SWB-neutron, AquaCrop | Drip | 0.95 | n/r | 0.94 | n/r |
| | López-Urrea et al. (2020) | Albacete, Spain | WL, FAO dual $K_c$ approach | Sprinkler | 1.16 | 0.20 | 1.11 | 0.20 |
| Linseed<br>(*Linum usitatissimum*) | Casa et al. (2000) | Viterbo, Italy | BREB, SWB-gravim. | n/r | 0.95 | 0.18 | 0.93 | 0.18 |
| Sunflower<br>(*Helianthus annuus*) | López-Urrea et al. (2014) | Albacete, Spain | WL, FAO dual $K_c$ approach | Sprinkler | 1.18 | 0.20 | 1.10 | 0.20 |
| | Howell et al. (2015) | Bushland, TX, USA | WL | Sprinkler | 1.22 | 0.25 | 1.10 | 0.25 |
| | Miao et al. (2016) | Dengkou, Hetao, China | SWB-gravim., SIMDualKc | Basin | 1.15 | 0.25 | 1.16 | 0.25 |
| ***Sugar crops*** | | | | | | | | |
| Sugar beet<br>(*Beta vulgaris*) | González-Dugo and Mateos (2008) | Seville, Spain | RS-NDVI | Sprinkler | 1.15 | n/r | 1.11 | n/r |
| | Hauer et al. (2015) | Göttingen, Germany | SWB-gravim. | Rainfed | 1.08 | n/r | 1.10 | n/r |
| | Wang et al. (2021) | Five Points, CA, USA | WL, EC, RS | Sprinkler, drip | 0.92 | 0.80 | 0.91 | 0.77 |

BREB — Bowen ratio energy balance; Capacit. — Capacitance probe; DL — Drainage lysimeter; EC — Eddy Covariance; Gravim. — Gravimetric sampling method; Neutron — neutron probe; Resist. — Resistance probe; RS — Remote sensing; SF — Sap Flow; SR — Surface Renewal; SDI — Subsurface drip irrigation; SWB — Soil water balance; TDR — Time-Domain Reflectometry; WL — Weighing lysimeter; n/r — not reported.

surface irrigation (basin and furrow), with only two papers reporting on subsurface drip irrigation (SDI). This method is quite expensive but has a large potential to control $E_s$, among other benefits. Several other papers reported using above-ground drip irrigation. Studies on cotton were conducted in several countries — Kazakhstan, Uzbekistan, Brazil, Syria, China, Israel, and in semi-arid and arid areas of USA, thus referring to the primary producing areas of the world.

Various approaches were used to derive $K_c$ from field observations. Kumar et al. (2015) and Ko et al. (2009) derived $K_c$ for well-watered cotton with $ET_{c\,act}$ data obtained in weighing lysimeters. It is notable to point out how similar the $K_c$ data for the mid-season were in these two studies (Table 3). Cholpankulov et al. (2008) used an energy balance approach to measure $ET_{c\,act}$ in a study area of Kazakhstan and performed a SWB to compute $ET_{c\,act}$ for a study area in Fergana, Uzbekistan. For both cases, they derived $K_c$ for optimal conditions through calibration and validation of the ISAREG model. The $K_c$ values reported by Cholpankulov et al. (2008) were similar for both semi-arid areas for $K_{c\,mid}$ but differed highly for $K_{c\,end}$, much lower in the steppe of Kazakhstan and higher in Fergana, likely due to local management practices and high upflow from the shallow water table. Bezerra et al. (2012) determined $ET_{c\,act}$ for a semi-arid area in Brazil using the BREB technique while Anapalli et al. (2020) and Fong et al. (2020) used eddy covariance in cotton studies performed in USA. DeTar (2004), in California, used five seasons of SWB data to derive $ET_{c\,act}$ of cotton under SDI. Farahani et al. (2008) also computed $ET_{c\,act}$ by performing a SWB using neutron probe measurements for drip-irrigated cotton in Syria.

The study by Han et al. (2019) used drainage lysimeters combined with SWB based on neutron probe observations of the SWC and focused on comparing $K_c$ for plastic mulch and non-mulch conditions. The experiments were performed in an oasis and salinity effects on ET were assessed with the water and salinity $K_s$ proposed in FAO56 and analyzed by Minhas et al. (2020). The 3-year average show small differences in $K_c$ between mulch and non-mulch (Table 3). Rozenstein et al. (2018) derived $K_c$ using a combination of field methods – EC, surface renewal, and sap-flow – and various remote sensing vegetation indices. This study provided the lowest cotton $K_{c\,mid}$ values in Table 3; authors affirm that the crop was not water or nutrient stressed, thus low values are most likely due to using drip irrigation.

The derivation of cotton basal crop coefficients ($K_{cb}$) based on the FAO56 dual $K_c$ approach was reported by Hunsaker (1999), who performed a SWB for a sandy loam soil in Arizona, USA. Hunsaker (1999) developed back-calculation procedures and used TDR-measured surface SWC data to separate the soil evaporation and transpiration components from measured $ET_c$ using the dual $K_c$ approach. The derived $K_{cb}$ values - $K_{cb\,ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$ - and the respective $K_{cb}$ curve from that study are shown in Fig. 4 with $K_{cb\ mid}$ and $K_{cb\ end}$ given also in Table 3. Hunsaker et al. (2003, 2005a), using SDI and basin irrigation, respectively, provided additional measured cotton $K_{cb}$ data that were derived by SWB at the same arid location and used to correlate $K_{cb}$ to NDVI data obtained by remote sensing. Similarly, Thorp et al. (2017) derived cotton FAO56 $K_{cb\,mid}$ at a nearby sprinkler location in Arizona using a SWB with neutron probe data. Howell et al. (2004) determined $ET_{c\,act}$ with weighing lysimeters, used the FAO56 dual $K_c$ approach to derive cotton $K_{cb}$, and took advection into consideration at this windy Texas location. Field data used with the SWB model ISAREG (Cholpankulov et al., 2008) were also used by Rosa et al. (2012b) with the SIMDualKc model, which integrates the FAO dual $K_c$ approach, so allowing a derivation of $K_{cb}$ when calibrating the model.

There is a good number of studies reporting accurately on crop coefficients for oil crops, however, much of it is for sunflower. Selected $K_c$ and $K_{cb}$ for oil crops are presented in Table 3 and include a few crops not previously considered in FAO56: camelina, linseed and mustard. Data on $K_c$ are much more abundant than those for $K_{cb}$, likely because the derivation of the latter requires $ET_{c\,act}$ partitioning into $T_c$ and $E_s$.

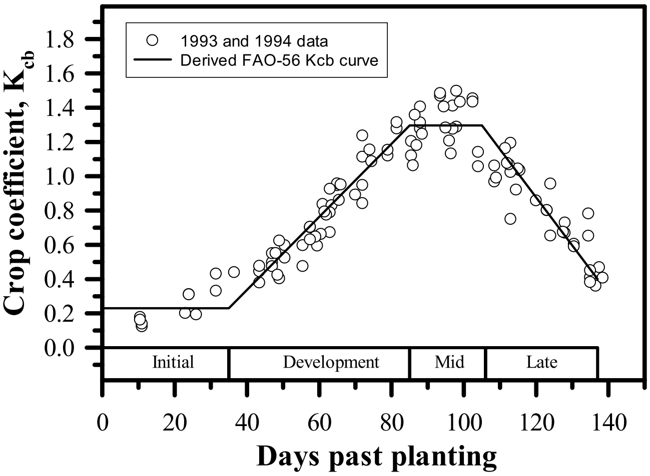


**Fig. 4.** Cotton basal crop coefficients ($K_{cb}$) and fitted FAO56 $K_{cb}$ curve.
*Source:* Adapted from Hunsaker (1999).

Thus, basal crop coefficients are only reported for camelina, canola, linseed and sunflower.

Studies on oil crops refer to diverse environments in various countries: reported studies on camelina were performed in Arizona, USA; for canola in Australia and Spain ; for castorbean in NE Brazil; for linseed in India and Italy; for mustard in India; for safflower in India and the USA; and for sunflower in China, Italy, India, Lebanon, Spain, and the USA. Therefore, the selected studies refer to the various main oil crop producing areas of the world. Most studies were performed using sprinkler and surface irrigation (basin and furrow) and only a couple of studies used drip irrigation.

The most common approach used to determine the actual crop ET of oil crops is the SWB in combination with other methods, DL, WL, RS, and BREB (Table 3). For SWB studies, soil water contents were determined by neutron probe, TDR, resistance, and gravimetric methods were used, either solely or in combination (e.g., Hunsaker et al., 2011; Table 3). Other selected studies for oil crops determined ET strictly by EC or BREB methods.

In addition to the referred studies by Tyagi et al. (2000a) and Gupta et al. (2017), WL were also used by López-Urrea et al. (2020) for canola, and by López-Urrea et al. (2014), Howell et al. (2015), and Garofalo and Rinaldi (2015) for sunflower. Shankar et al. (2012) used drainage lysimeters for deriving $K_c$ for mustard and performed the SWB with Watermark sensors. Remote sensing was used by Hunsaker et al. (2013) to obtain $K_{cb}$ values for camelina supported by SWB.

The partition of $ET_{c\,act}$ and related computation of $K_{cb}$ was performed with the FAO56 dual Kc approach based upon the observation of the fraction of ground covered by the vegetation ($f_c$) in the WL studies reported by López-Urrea et al. (2020) for canola, and López-Urrea et al. (2014) and Howell et al. (2015) for sunflower. The same approach is incorporated in the SIMDualKc model used by Miao et al. (2016) for sunflower, where the $K_{cb}$ values result from the model calibration.

An example for the dynamics of $K_c$, $K_e$ and $K_{cb}$ for sunflower is presented in Fig. 5. Sunflower $ET_{c\,act}$ values were measured with a large weighing lysimeter (López-Urrea et al., 2014). Daily $ET_{c\,act}$ values were calculated as the difference between lysimeter mass losses (from evapotranspiration) and lysimeter mass gains (from precipitation, irrigation or dew) divided by the lysimeter area. No drainage from the lysimeter tank was recorded during the study period. Additionally, the basal crop coefficient ($K_{cb}$) was calculated from the lysimeter $K_c$ values described above minus the estimated evaporation component $K_e$ values calculated with the FAO56 methodology, i.e., based on observed fraction of ground cover, $f_c$. Results in Fig. 5 show that several irrigation and precipitation events occurred along the season which contributed to soil water evaporation, particularly during the crop stages when the $f_c$ was small, i.e. when the energy available at the soil surface was higher.

As observed in Table 3, the reported values for $K_{c\,mid\,(std)}$ results for oil crops were very similar, particularly when considering an individual crop, which also suggests good accuracy in their determination. The values for $K_{c\,end\,(std)}$ have a relatively larger variation, which results from differences in crop management, with harvesting at various maturation conditions.

The current review found 15 published papers presenting field information on sugarcane crop coefficients during the last twenty years. However, only four papers could be selected to provide updated $K_c$ values, but not one was selected for updating $K_{cb}$. Observed and adjusted crop coefficients are presented in Table 3. The methods used for estimating $ET_{c\,act}$ included weighing lysimeters (Olivier and Singels, 2012), surface renewal (Bastidas-Obando et al., 2017), and BREB (Inman-Bamber and McGlinchey, 2003; Bastidas-Obando et al., 2017). A SWB was performed with the SWC sensed with reflectometry probes by Silva et al. (2013b), with capacitance sensors by Bastidas-Obando et al. (2017) and with gravimetric measurements by Dingre and Gorantiwar (2020).

Inman-Bamber and McGlinchey (2003) collected data at one location in Australia and another in Swaziland, however not covering a full crop season. The first location was furrow-irrigated and the second was drip-irrigated, but the respective $K_{c\,mid}$ values were equal, likely because of crop residue mulch-effects on $K_c$. Silva et al. (2013b) reported on a one-year sugarcane study in Sao Francisco Valley, Brazil, where sprinkler irrigation was used. However, Olivier and Singels (2012) developed a study in South Africa comparing the year of planting and the following year, called ratoon, showing that $K_c$ are greater in the planting year relative to ratoon. Moreover, they compared effects of cane residues mulch and bare soil and concluded that $K_c$ are greater by about 0.05 when the crop is cultivated in a bare soil relative to a mulched soil, which relates with the control of $E_s$ by the organic mulch. Drip irrigation was used by Olivier and Singels (2012). Another selected paper is that by Bastidas-Obando et al. (2017) who compared two locations in South Africa, where one was drip-irrigated and the other was rainfed. As expected, the $K_{c\,mid\,(std)}$ was smaller by 7% for the rainfed crop. Observed sugarcane $K_{c\,mid\,(std)}$ were quite coherent, namely decreasing with crop residues mulch and in rainfed conditions, while the two $K_{c\,end\,(std)}$ values reported were quite similar.

Studies on sugar beet $K_c$ are scarce. Selected studies refer to the use of remote sensing with the model METRIC (Tasumi and Allen, 2007) applied in Idaho, USA, to the use of the SWAP model where the SWB was performed with SWC observed with a neutron probe in Northern

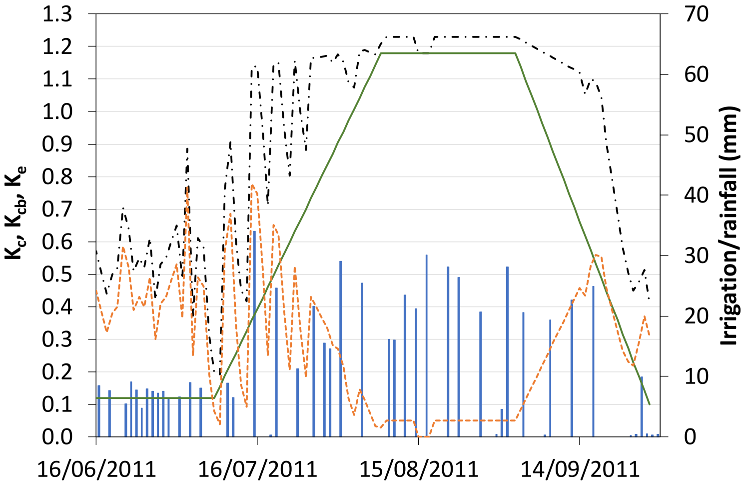


**Fig. 5.** Dynamics of the sunflower basal crop coefficient ($K_{cb}$, ——), single crop coefficient ($K_c$, - • - • -), and soil evaporation coefficient ($K_e$, - - -) derived from weighing lysimeter measurements using the FAO56 dual Kc approach; also depicted daily irrigation and precipitation (vertical bars).
*Source:* Adapted from López-Urrea et al. (2014).

Spain (Utset et al., 2007), and to the recent study by Wang et al. (2021) using weighing lysimeters, eddy covariance and remote sensing. $K_{cb\,mid}$ was observed in two studies using NDVI from RS (González-Dugo and Mateos, 2008; Wang et al., 2021) and in a multi-site SWB study based on gravimetric measurements (Hauer et al., 2015). However, the selected tabulated data from the latter study refers only to the Göttingen site, Germany.

Table 4 provides for ancillary values relative to the crops whose $K_c$ and $K_{cb}$ are presented in Table 3. These values are however limited but are usable for creating tabulated information that will help users to perform a SWB or to parameterize models (e.g., SIMDualKc). The soil water depletion fraction (p) is used in FAO56 procedures to define the allowable soil water depletion for a crop before water stress occurs. The p value is essential for modeling the soil water balance taking into consideration a water stress coefficient ($K_s$, FAO56). However, except for cotton and sunflower, relatively few of the selected papers for other crops provided such values. Moreover, the reported p values varied in a wide range, with small values indicating that water stress was avoided and large ones indicating that water stress could have occurred.

Reported $Z_{r\,max}$ values vary largely. On one hand, these values tend to be larger when the soil is lighter; on the other hand, values depend on the accuracy of observation of the small roots, with many studies referring to the maximum depth as that providing for most water uptake and others reporting on the effectively observed maximum root depth. There is also a large variability of $h_{max}$; measurements may play a role, but crop varieties and crop management certainly are of a great impact. $LAI_{max}$ and $f_{c\,max}$ certainly vary with crop management and cultivation practices. Their values denote good crop development, i.e., do not indicate that experiments were subjected to crop stress. These ancillary parameters were used later in this paper to update related values previously tabulated in FAO56.

### 3.3. Small grain cereals

In addition to small grain cereals, the current review of literature included two pseudo-cereals, amaranth grain and quinoa, not formerly considered in FAO56. Among the small grains, wheat is the most studied crop. Studies relative to oats, rye and millet were not available except as forage crops and, therefore, were not included herein.

The observed actual $K_{c\,mid\,(obs)}$ and $K_{c\,end\,(obs)}$ and the respective values adjusted to the standard climate, $K_{c\,mid\,(std)}$ and $K_{c\,end\,(std)}$ are presented in Table 5. Most selected studies estimated $K_c$ and only a few reported on $K_{cb}$ values, except in wheat. Wheat studies were grouped into winter and spring wheat since the crop cycles and varieties are quite different. In addition, the wheat-crop studies were grouped according to the duration of the late season, shorter when harvesting is performed with high grain moisture, that is to give an opportunity for planting the following summer crop, or longer when the grain is harvested with low moisture. The $K_{c\,end}$ of the latter is generally smaller than at high-harvest grain moisture.

The reported studies most often used basin, furrow, or sprinkler irrigation, thus generally fully wetting the ground. A few studies used drip or SDI, as per the cases of amaranth grain, quinoa, and a few wheat studies. The selected studies are from a large variety of countries and environmental conditions. Amaranth grain was studied in Italy, and barley in Ethiopia, the Czech Republic, and Portugal, the latter country reporting on malt barley for industry. Quinoa studies were in Bolivia and Italy, and the teff study in Ethiopia. Studies for wheat are from China, India, Iran, Syria, North Africa, Northern and southern Europe, and the USA. That vast origin of studies for wheat allows the assumption that most of the main producing areas were accounted for herein.

The $K_c$ and $K_{cb}$ selected studies for small grain cereals used various approaches for measuring actual crop ET. The most common approach is the SWB using assorted methods to measure the SWC, such as gravimetry, neutron probes, TDR, capacitance probes, and FDR.

Pozníková et al. (2014) used the BREB method to estimate $ET_{c\,act}$ and the FAO56 dual $K_c$ approach for its partitioning to then derive $K_{cb}$. EC was used to estimate $ET_{c\,act}$ in various studies, namely Duchemin et al. (2006), Er-Raki et al. (2007), Kjaersgaard et al. (2008), Zhang et al. (2013) and French et al. (2020). Sánchez et al. (2015) used two variations of a simple two-source energy balance (STSEB) approach to estimate $ET_{c\ act}$ and its partitioning on $E_s$ and $T_c$. Weighing lysimeters were used in experiments reported by Garcia et al. (2003) in their studies on quinoa in the Bolivian Altiplan, Tyagi et al. (2000b) focusing on wheat in Punjab, Howell et al. (2006) and Ko et al. (2009) in wheat studies in Texas, USA, and López-Urrea et al. (2009) and Sánchez et al. (2015) for spring wheat in Castilla-la Mancha, Spain.

Remote sensing was used in wheat $K_c$ studies by various authors. Duchemin et al. (2006) and Er-Raki et al. (2007) compared respectively, $K_c$ and $K_{cb}$ values obtained with NDVI with those resulting from EC measurements, while Hunsaker et al. (2005b, 2007) compared $K_{cb}$ obtained with NDVI with $K_{cb}$ obtained by the SWB using neutronic and TDR measurements of SWC. Drerup et al. (2017) also used NDVI-calibrated $K_{cb}$ results in comparison with $K_{cb}$ derived from a SWB with FDR measurements. Differently, Pakparvar et al. (2014) used the energy balance with the remote sensing model SEBS to derive $K_c$ values for wheat. Chattaraj et al. (2013) linked $K_c$ and $K_{cb}$ values based on several

**Table 4**
Observed ancillary crop parameters for fiber, oil and sugar crops reported from selected literature.

| | Reference | $Z_{r\,max}$ (m) | $h_{max}$ (m) | $LAI_{max}$ ($m^2\ m^{-2}$) | $f_{c\,max}$ | $p_{ini}$ | $p_{mid}$ | $p_{end}$ |
|---|---|---|---|---|---|---|---|---|
| ***Fiber crops*** | | | | | | | | |
| Cotton | Hunsaker (1999) | 1.70 | 1.05 | 6.6 | n/r | n/r | n/r | n/r |
| (*Gossypium hirsutum*) | Hunsaker et al. (2003) | 1.70 | 1.65 | 4.0 | 0.90 | 0.65 | 0.65 | 0.65 |
| | Howell et al. (2004) | 1.50 | 1.00 | 4.0 | n/r | 0.55 | 0.55 | 0.55 |
| | DeTar (2004) | 1.20 | 1.86 | n/r | 0.81 | n/r | n/r | n/r |
| | Hunsaker et al. (2005a) | 1.70 | 1.20 | n/r | 0.90 | 0.65 | 0.65 | 0.65 |
| | Howell et al. (2006) | 1.40 | 1.03 | 4.0 | n/r | n/r | n/r | n/r |
| | Cholpankulov et al. (2008) | | | | | | | |
| | Hunger Steppe, Kazakhstan | 1.50 | n/r | 4.1 | n/r | 0.60 | 0.70 | 0.75 |
| | Fergana, Uzbekistan | 1.10 | n/r | n/r | n/r | 0.60 | 0.60 | 0.70 |
| | Farahani et al. (2008) | 1.20 | n/r | n/r | n/r | n/r | n/r | n/r |
| | Bezerra et al. (2012) | n/r | 1.25 | 5.3 | n/r | n/r | n/r | n/r |
| | Rosa et al. (2012a,b) | 1.10 | 1.20 | n/r | 0.85 | 0.65 | 0.65 | 0.65 |
| | Kumar et al. (2015) | n/r | 1.20 | n/r | n/r | n/r | n/r | n/r |
| | Thorp et al. (2017) | 1.50 | 1.10 | 5.1 | n/r | n/r | n/r | n/r |
| | Han et al. (2019) | 1.50 | 0.86 | 4.9 | 0.90 | 0.60 | 0.60 | 0.60 |
| ***Oil crops*** | | | | | | | | |
| Camelina | Hunsaker et al. (2011) | 1.50 | 0.65 | n/r | 0.97 | 0.65 | 0.65 | 0.65 |
| (*Camelina sativa*) | Hunsaker et al. (2013) | 1.70 | 0.83 | n/r | 0.96 | 0.60 | 0.60 | 0.60 |
| Canola | Zeleke et al. (2011) | 1.20 | n/r | n/r | 0.80 | n/r | n/r | n/r |
| (*Brassica napus*) | López-Urrea et al. (2020) | 0.40 | 1.00 | n/r | 0.97 | 0.45 | 0.45 | 0.45 |
| Castorbean (*Ricinus communis*) | Dias et al. (2015) | 0.60 | n/r | n/r | n/r | n/r | n/r | n/r |
| Linseed (Flax) (*Linum usitatissimum*) | Kar et al. (2007) | 0.67 | n/r | 3.7 | n/r | n/r | n/r | n/r |
| Mustard | Kar et al. (2007) | 1.17 | n/r | 3.4 | n/r | n/r | n/r | n/r |
| (*Brassica juncea*) | Shankar et al. (2012) | 0.65 | 0.95 | 1.5 | n/r | 0.50 | 0.50 | 0.50 |
| | Gupta et al. (2017) | 0.40 | 1.60 | 4.1 | n/r | n/r | n/r | n/r |
| Safflower | Kar et al. (2007) | 1.66 | n/r | 5.7 | n/r | n/r | n/r | n/r |
| (*Carthamus tinctorius*) | Bassil and Kaffka (2002) | n/r | 1.09 | 2.5 | n/r | n/r | n/r | n/r |
| Sunflower | Tyagi et al. (2000a) | n/r | n/r | 4.3 | n/r | 0.25 | 0.25 | 0.25 |
| (*Helianthus annuus*) | Karam et al. (2007) | 0.90 | n/r | 7.0 | n/r | n/r | n/r | n/r |
| | López-Urrea et al. (2014) | n/r | 1.7 | n/r | 0.88 | 0.44 | 0.44 | 0.44 |
| | Howell et al. (2015) | 2.00 | 1.2 | 5.0–6.0 | n/r | 0.80 | 0.80 | 0.80 |
| | Miao et al. (2016) | 1.00 | 2.0 | n/r | 0.87 | 0.50 | 0.45 | 0.80 |
| ***Sugar crops*** | | | | | | | | |
| Sugar beet | González-Dugo and Mateos (2008) | 1.00 | 0.50 | n/r | 0.80 | 0.55 | 0.55 | 0.55 |
| (*Beta vulgaris*) | Hauer et al. (2015) | n/r | 0.80 | n/r | 0.85 | n/r | n/r | n/r |
| Sugar cane (*Saccharum officinarum*) | Inman-Bamber and McGlinchey (2003) (Australia site) | n/r | 4.0 | n/r | 0.98 | n/r | n/r | n/r |
| | Olivier and Singels (2012) | | | | | | | |
| | Planting year, average | n/r | 2.79 | n/r | 0.97 | n/r | n/r | n/r |
| | Ratoon year, average | n/r | 2.54 | n/r | 0.97 | n/r | n/r | n/r |
| | Silva et al. (2013b) | 0.60 | n/r | 5.6 | n/r | n/r | n/r | n/r |
| | Bastidas-Obando et al. (2017) | | | | | | | |
| | Rainfed | 0.60 | n/r | 4.3 | n/r | n/r | 0.70 | 0.80 |
| | Irrigated | 0.60 | n/r | 7.2 | n/r | n/r | 0.65 | 0.75 |
| | Dingre and Gorantiwar (2020) | 0.75 | n/r | n/r | n/r | 0.65 | 0.65 | 0.65 |

$Z_{r\,max}$ – maximum root depth; $h_{max}$ – maximum crop height; $LAI_{max}$ – maximum leaf area index; $f_{c\,max}$ – maximum fraction of ground cover; $p_{ini}$, $p_{mid}$, $p_{end}$ – soil water depletion fraction for no stress for respectively the initial, mid- and end-season stages; n/r – not reported.

VIs measured with a spectroradiometer to those measured with the SWB using neutron probe for SWC. The recent study by French et al. (2020) compared $K_c$ based on EC observations in commercial durum wheat fields to daily $K_{cb}$ derived by VI using Sentinel 2 and Venus satellites to map the VI time-series for the entire cropping seasons.

A few studies with a SWB approach used models. Under these circumstances, $K_c$ or $K_{cb}$ values are obtained through the calibration of the particular model, which eases the processing of field data when performing a soil water balance. The first SWB model used in this respect was the ISAREG model, where the single $K_c$ approach was used for performing the SWB simulations (e.g., Liu et al., 1998). Later, models adopting the dual $K_c$ approach were developed, thus where derivation of $K_{cb\,mid}$ and $K_{cb\,end}$ are the objects of the calibration. The SALTMED model was used by Pulvento et al. (2013, 2015) for quinoa and the amaranth grain, respectively, while the SIMDualKc model was used for wheat in four papers, and for one barley study. SIMDualKc may use $ET_{c\,act}$ as input, as adopted by Zhang et al. (2013). Data from Zhang et al. (2013) in Fig. 6 shows the results of the calibration of SIMDualKc model using $ET_{c\,act}$ measured with EC equipment in a winter wheat field with frozen soil during the winter months. Large differences between the single daily and time averaged $K_c$ curves occur, particularly during the initial stage, which relates to the high soil water content and related $K_e$ values during the first half of that stage. During the second half of the initial stage, $K_e$ highly decreases while the availability of water in the evaporation layer also decreases. Thus, daily $K_c$ values become closer to $K_{cb}$ values. Differently, during the mid-season $K_e$ is generally low due to fewer wetting events and higher fraction of ground covered by the crop ($f_{c\,max}$ = 0.85), thus $K_c$ and $K_{cb}$ time averaged values become even closer. The $K_{cb\,act}$ curve is below the standard $K_{cb}$ curve for only a few days during the late-season when water stress occurred.

**Table 5**

Field observed $K_c$ and $K_{cb}$ for small grain cereal crops and corresponding values adjusted to the standard climate ($RH_{min}$ = 45%, $u_2$ = 2 m $s^{-1}$) with identification of the article reference, location of the field study, methods used for determination and partition of $ET_{c act}$ and irrigation method.

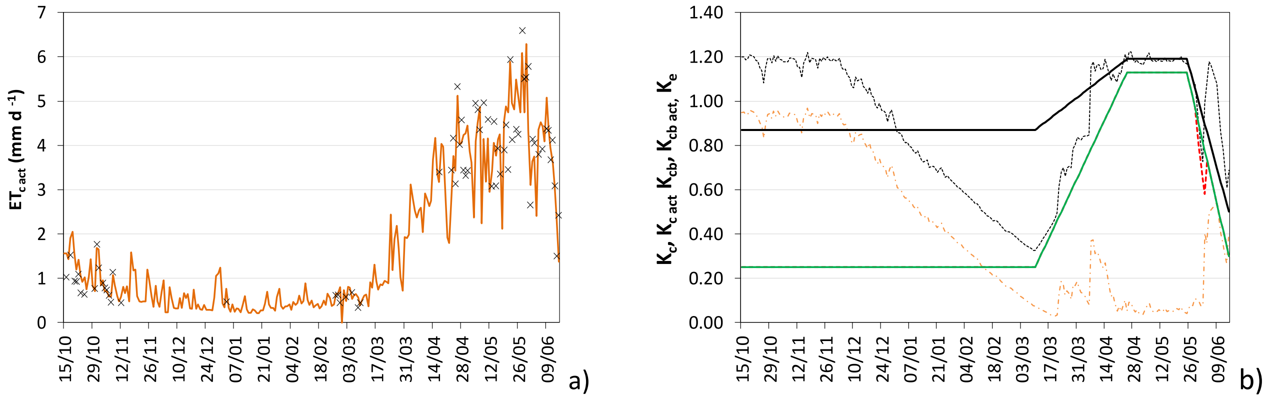
| Crop | Reference | Location | Method for estimating $ET_{c act}$ | Irrigation method | $K_c/K_{cb}$ derived from field observations | | $K_c/K_{cb}$ adjusted to the standard climate | |
|---|---|---|---|---|---|---|---|---|
| **Single crop coefficient** | | | | | $K_{c\,mid\,(obs)}$ | $K_{c\,end\,(obs)}$ | $K_{c\,mid\,(std)}$ | $K_{c\,end\,(std)}$ |
| Amaranth grain (*Amaranthus* sp.) | Pulvento et al. (2015) | Volturno plain, Italy | SWB-gravim., SALTMED | Drip | 1.15 | 0.20 | 1.15 | 0.20 |
| Barley (*Hordeum vulgare*) | Araya et al. (2011a) | Mekelle, Ethiopia | DL, SWB-TDR | Surface | 1.05 | 0.30 | 0.98 | 0.30 |
| | Pereira et al. (2015b) | Alpiarça, Portugal | SWB-capacit., SIMDualKc | Sprinkler | 1.13 | 0.20 | 1.07 | 0.20 |
| Quinoa (*Chenopodium quinoa*) | Garcia et al. (2003) | Patacamaya, Bolivia | WL, SWB-neutron | n/r | 1.00 | 0.70 | 1.01 | 0.67 |
| | Pulvento et al. (2013) | Volturno plain, Italy | SWB-gravim., SALTMED | Drip | 1.15 | 0.40 | 1.15 | 0.40 |
| Teff (*Eragrostis tef*) | Araya et al. (2011b) | Mekelle, Ethiopia | DL, SWB-TDR | Surface | 1.10 | 0.25 | 1.09 | 0.25 |
| Wheat (common) (*Triticum aestivum*) | | | | | | | | |
| Winter wheat | | | | | | | | |
| Low grain moisture | Tyagi et al. (2000b) | Karnal, India | WL, SWB-neutron | n/r | 1.36 | 0.42 | 1.28 | 0.42 |
| | Oweis et al. (2003) | Tel Hadya, Syria | SWB-neutron, ISAREG | Surface | 1.19 | 0.25 | 1.13 | 0.25 |
| | Zairi et al. (2003) | Siliana, Tunisia | SWB-neutron, ISAREG | Furrow | 1.15 | 0.25 | 1.13 | 0.25 |
| | Duchemin et al. (2006) | Marrakesh, Morocco | EC, RS | Flood | 1.00 | 0.20 | 1.03 | 0.20 |
| | Howell et al. (2006) | Bushland, TX, USA | WL | Sprinkler | 1.10 | 0.10 | 1.03 | 0.10 |
| | Kjaersgaard et al. (2008) | Taastrup, Denmark | EC, SWB-TDR | n/r | 1.15 | 0.42 | 1.21 | 0.42 |
| | Gao et al. (2009) | Xinxiang, Henan Province, China | SWB-TDR | Surface | 1.19 | 0.28 | 1.23 | 0.28 |
| | Ko et al. (2009) | Uvalde, TX, USA | WL | Sprinkler | 1.10 | 0.40 | 1.16 | 0.40 |
| | Cai et al. (2009) | Daxing, China | SWB-TDR, ISAREG | Basin | 1.00 | 0.30 | 1.06 | 0.30 |
| | Kharrou et al. (2011) | Marrakech, Morocco | SWB-gravim. | Surface | 1.29 | 0.29 | 1.26 | 0.29 |
| | Chattaraj et al. (2013) | New Delhi, India | SWB-neutron, Hyperspectral data | Basin | | | | |
| | | var. DBW-17 | | | 1.05 | 0.30 | 1.07 | 0.30 |
| | | var. PBW-502 | | | 1.20 | 0.15 | 1.22 | 0.15 |
| | | var. HD-2987 | | | 1.00 | 0.30 | 1.02 | 0.30 |
| | Pakparvar et al. (2014) | Gareh Bygone Plain, Iran | RS-SEBS model | Surface | 1.24 | n/r | 1.16 | n/r |
| High grain moisture | Liu et al. (1998) | Wangdu, Baoding, North China Plain | DL, SWB-neutron & gravim., ISAREG | Surface | 1.00 | 0.60 | 1.06 | 0.64 |
| | Pereira et al. (2003) | Xiongxian, North China Plain | SWB-neutron & TDR, ISAREG | Furrow | 1.13 | 0.60 | 1.19 | 0.64 |
| | Zhao et al. (2013) | Daxing, N. China | SWB-TDR, micro-lys., SIMDualKc | Basin | 1.22 | 0.50 | 1.26 | 0.50 |
| | Zhang et al. (2013) | Daxing, N. China | EC, SIMDualKc | Basin | 1.20 | 0.45 | 1.24 | 0.45 |
| Spring wheat | López-Urrea et al. (2009) | Albacete, Spain | WL | Sprinkler | 1.20 | 0.20 | 1.17 | 0.20 |
| | Sánchez et al. (2015) | Albacete, Spain | STSEB model | Sprinkler | 1.18 | 0.32 | 1.13 | 0.32 |
| | Miao et al. (2016) | Dengkou, Hetao, China | SWB-gravim., SIMDualKc | Basin | 1.18 | 0.30 | 1.11 | 0.30 |
| Wheat (durum) (*Triticum durum*) | | | | | | | | |
| Low grain moisture | French et al. (2020) | Yuma, AZ, USA | EC, RS | Flood | 1.10 | 0.25 | 1.03 | 0.25 |
| **Basal crop coefficient** | | | | | $K_{cb\,mid\,(obs)}$ | $K_{cb\,end\,(obs)}$ | $K_{cb\,mid\,(std)}$ | $K_{cb\,end\,(std)}$ |
| Amaranth grain (*Amaranthus* sp.) | Pulvento et al. (2015) | Volturno plain, Italy | SWB-gravim., SALTMED | Drip | 1.05 | 0.13 | 1.05 | 0.13 |
| Barley (*Hordeum vulgare*) | Pozníková et al. (2014) | Bystřicenad Pernštejnem, Czech Republic | BREB, FAO56 dual $K_c$ approach | n/r | 1.00 | 0.10 | 1.00 | 0.10 |
| | Pereira et al. (2015b) | Alpiarça, Portugal | SWB-capacit., SIMDualKc | Sprinkler | 1.10 | 0.10 | 1.04 | 0.10 |
| Quinoa (*Chenopodium quinoa*) | Pulvento et al. (2013) | Volturno plain, Italy | SWB-gravim., SALTMED | Drip | 1.00 | 0.20 | 1.00 | 0.20 |
| Teff (*Eragrostis tef*) | Araya et al. (2010) | Mekelle, Ethiopia | SWB-TDR, AquaCrop | Surface | 0.95 | n/r | 0.90 | n/r |
| Wheat (common) (*Triticum aestivum*) | | | | | | | | |
| Winter wheat | | | | | | | | |
| Low grain moisture | Hunsaker et al. (2007) | Maricopa, AZ, USA | RS, SWB-neutron, TDR | Basin | 1.18 | 0.28 | 1.11 | 0.28 |
| | Rosa et al. (2012b) | Tel Hadya, Syria | SWB-neutron, SIMDualKc | Surface | 1.05 | 0.25 | 0.99 | 0.25 |
| | Drerup et al. (2017) | Duelmen, Germany | SWB-FDR, RS | Drip | 1.05 | 0.30 | 1.12 | 0.30 |

(*continued on next page*)

**Table 5** (*continued*).

| Crop | Reference | Location | Method for estimating $ET_{cact}$ | Irrigation method | $K_c/K_{cb}$ derived from field observations | | $K_c/K_{cb}$ adjusted to the standard climate | |
|---|---|---|---|---|---|---|---|---|
| **Basal crop coefficient** | | | | | $K_{cb\,mid\,(obs)}$ | $K_{cb\,end\,(obs)}$ | $K_{cb\,mid\,(std)}$ | $K_{cb\,end\,(std)}$ |
| High grain moisture | Pereira et al. (2003) | Xiongxian, North China Plain | SWB-neutron, TDR, ISAREG | Furrow | 1.08 | 0.55 | 1.14 | 0.59 |
| | Chattaraj et al. (2013) | New Delhi, India | SWB-neutron, | Basin | | | | |
| | | var. DBW-17 | spectroradiometer | | 0.95 | 0.25 | 0.97 | 0.25 |
| | | var. PBW-502 | FAO dual $K_c$ | | 1.10 | 0.10 | 1.12 | 0.10 |
| | | var. HD-2987 | | | 0.90 | 0.20 | 0.92 | 0.20 |
| | Zhao et al. (2013) | Daxing, China | SWB-TDR, micro-lys., SIMDualKc | Basin | 1.15 | 0.30 | 1.19 | 0.30 |
| | Zhang et al. (2013) | Daxing, China | EC, SIMDualKc | Basin | 1.15 | 0.30 | 1.19 | 0.30 |
| Spring wheat | Hunsaker et al. (2005b) | Maricopa, AZ, USA | RS, SWB-TDR, FAO dual $K_c$ approach | SDI | 1.15 | 0.35 | 1.12 | 0.35 |
| | López-Urrea et al. (2009) | Albacete, Spain | WL, FAO dual $K_c$ approach | Sprinkler | 1.10 | 0.15 | 1.07 | 0.15 |
| | Sánchez et al. (2015) | Albacete, Spain | STSEB model | Sprinkler | 1.10 | 0.19 | 1.05 | 0.19 |
| | Miao et al. (2016) | Dengkou, Hetao, China | SWB-gravim., SIMDualKc | Basin | 1.15 | 0.25 | 1.15 | 0.25 |
| Wheat (durum) (*Triticum durum*) | | | | | | | | |
| Low grain moisture | Er-Raki et al. (2007) | Haouz, Morocco | EC, RS, FAO dual $K_c$ approach | Flooding | 0.90 | 0.23 | 0.91 | 0.23 |

BREB — Bowen ratio energy balance; Capacit. — Capacitance probe; DL — Drainage lysimeter; EC — Eddy Covariance; FDR — Frequency Domain Reflectometry; Gravim. — Gravimetric sampling method; micro-lys — micro-lysimeter; Neutron — neutron probe; RS — Remote sensing; SDI — Subsurface drip irrigation; STSEB — Simplified version of the two-source energy balance; SWB – Soil water balance; TDR — Time-Domain Reflectometry; WL — Weighing lysimeter; n/r — not reported.



Observed (x) and simulated (—) actual crop evapotranspiration

Standard single Kc (- - -), time averaged Kc (—), standard Kcb (—), actual daily Kcb act (---), evaporation coefficient Ke (-·-·-)

**Fig. 6.** Example of application of the SIMDualKc model to winter wheat with frozen soil during the dormant season: (a) simulated vs. measured $ET_{c\,act}$ by eddy covariance for the calibration of the model, and (b) single and dual crop coefficient curves, and the evaporation coefficient curve, throughout the crop season.
*Source:* Adapted from Zhang et al. (2013).

When a dual $K_c$ simulation model was not used, the partitioning of $ET_{c\,act}$ was performed using the FAO56 dual $K_c$ procedures, thus, the estimated evaporation component is based primarily upon the fraction of ground covered by vegetation ($f_c$) and the soil water characteristics of the surface layer. This was the approach used by Liu and Pereira (2000), Hunsaker et al. (2005b, 2007), Er-Raki et al. (2007), López-Urrea et al. (2009), Chattaraj et al. (2013), Pozníková et al. (2014) and Drerup et al. (2017); however, each author developed different purposefully-applied computational algorithms.

Reported studies offer a variety of approaches that have appropriate computation accuracy, so $K_c$ or $K_{cb}$ values vary from one study to another only in a limited range (Table 5). That variability is usually caused by crop management (e.g., different irrigation methods) and different crop varieties. To illustrate the influence of the varieties, Table 5 includes $K_{cb}$ values for three wheat varieties studied at the same location by Chattaraj et al. (2013).

The ancillary parameters reported in the studies referenced in Table 5 are shown in Table 6. These parameters reflect the management of the cereal crops and may be useful for water balance irrigation scheduling applications. Reported values for spring and winter wheat root depths, $Z_{r\,max}$, varied in a large range, from 0.55 to 1.50 m, while $h_{max}$ ranged from 0.60 to 1.30 m. Both ranges reflect the impact of varieties and crop management but $Z_{r\,max}$ also varies with the soil texture and structure. The same influences occur for other crops but are not apparent due to the limited number of studies. $LAI_{max}$ for wheat varied much, from 3.5 to 7.1 m$^2$ m$^{-2}$ while $f_{c\,max}$ was relatively stable, from 0.85–0.98. The soil water depletion fraction for no stress ranged from 0.45–0.80.

### 3.4. Maize and sorghum

The studies on crop coefficients for maize developed throughout the last decades are very numerous and a large number satisfied the accuracy criteria indicated in Section 2. Reported $K_c$ and $K_{cb}$ values are presented in Table 7, where those relative to sorghum are also shown. A distinction is made for both maize and sorghum in terms of cropping for grain or for silage due to a very different duration of the late-season. Sorghum studies include a third group referring to

**Table 6**
Observed ancillary crop parameters for small grain crops.

| Crop | Reference | $Z_{r\,max}$ (m) | $h_{max}$ (m) | $LAI_{max}$ ($m^2\ m^{-2}$) | $f_{c\,max}$ | $p_{ini}$ | $p_{mid}$ | $p_{end}$ |
|---|---|---|---|---|---|---|---|---|
| Amaranth grain (*Amaranthus* sp.) | Pulvento et al. (2015) | 0.60 | 1.70 | n/r | 0.90 | n/r | n/r | n/r |
| Barley (*Hordeum vulgare*) | Araya et al. (2011a) | 0.60 | n/r | n/r | 0.80 | n/r | n/r | n/r |
| | Pozníková et al. (2014) | 0.65 | n/r | 4.0 | n/r | 0.60 | 0.60 | 0.60 |
| | Pereira et al. (2015b) | 0.90 | 0.80 | n/r | 0.88 | 0.55 | 0.55 | 0.55 |
| Quinoa (*C. quinoa*) | Pulvento et al. (2013) | 0.55 | 1.00 | n/r | 0.60 | n/r | n/r | n/r |
| Teff (*Eragrostis tef*) | Araya et al. (2010) | 1.00 | n/r | n/r | 0.80 | n/r | n/r | n/r |
| Wheat (common) (*Triticum aestivum*) | | | | | | | | |
| Winter wheat | Liu et al. (1998) | 0.80 | n/r | n/r | n/r | 0.52 | 0.70 | 0.74 |
| | Tyagi et al. (2000b) | n/r | n/r | 3.9 | n/r | n/r | n/r | n/r |
| | Oweis et al. (2003) | 1.50 | n/r | n/r | n/r | 0.60 | 0.53 | 0.67 |
| | Zairi et al. (2003) | 1.00 | n/r | n/r | n/r | 0.60 | 0.60 | 0.70 |
| | Pereira et al. (2003) | 1.00 | 0.95 | n/r | n/r | 0.50 | 0.50 | 0.60 |
| | Duchemin et al. (2006) | n/r | n/r | 6.0 | n/r | n/r | n/r | n/r |
| | Howell et al. (2006) | 1.40 | 1.12 | 7.1 | n/r | n/r | n/r | n/r |
| | Hunsaker et al. (2007) | 1.30 | 0.70 | 5.5 | 0.98 | 0.55 | 0.55 | 0.55 |
| | Cai et al. (2009) | 1.00 | n/r | n/r | n/r | 0.60 | 0.50 | 0.60 |
| | Gao et al. (2009) | 1.00 | n/r | 3.5 | n/r | n/r | n/r | n/r |
| | Kharrou et al. (2011) | 0.80 | n/r | 6.0 | n/r | 0.60 | 0.60 | 0.60 |
| | Rosa et al. (2012b) | 1.50 | n/r | n/r | 0.80 | 0.50 | 0.50 | 0.50 |
| | Chattaraj et al. (2013) | 1.00 | n/r | 5.9 | n/r | n/r | n/r | n/r |
| | Zhang et al. (2013) | 1.00 | 0.70 | n/r | 0.85 | 0.60 | 0.60 | 0.60 |
| | Zhao et al. (2013) | 1.00 | 0.60 | n/r | 0.85 | 0.60 | 0.60 | 0.60 |
| | Drerup et al. (2017) | 0.90 | 0.90 | 4.8 | 0.95 | n/r | n/r | n/r |
| Spring wheat | Hunsaker et al. (2005b) | 1.30 | 1.30 | n/r | 0.90 | 0.55 | 0.55 | 0.55 |
| | López-Urrea et al. (2009) | n/r | n/r | n/r | 0.90 | 0.55 | 0.55 | 0.55 |
| | Sánchez et al. (2015) | n/r | 0.68 | n/r | 0.97 | n/r | n/r | n/r |
| | Miao et al. (2016) | 1.00 | 0.82 | n/r | 0.87 | 0.55 | 0.45 | 0.80 |
| Wheat (durum) (*Triticum durum*) | Er-Raki et al. (2007) | 0.55 | n/r | n/r | 0.94 | n/r | n/r | n/r |
| | French et al. (2020) | n/r | 1.05 | n/r | n/r | n/r | n/r | n/r |

$Z_{r\,max}$ – maximum root depth; $h_{max}$ – maximum crop height; $LAI_{max}$ – maximum leaf area index; $f_{c\,max}$ – maximum fraction of ground cover; $p_{ini}$, $p_{mid}$, $p_{end}$ – soil water depletion fraction for no stress for respectively the initial, mid and end season stages; n/r – not reported.

sweet sorghum, cropped for green energy. The main distinction among these distinct groups refers to the $K_c$ or $K_{cb}$ at end season, with $K_{c\,end}$ values for silage near $K_{c\,mid}$ values, since the nutritional value of the crop is higher before senescence develops. Similarly, $K_{c\,end}$ values of sweet sorghum are near the $K_{c\,mid}$ values because the crop energy value decreases when maturation develops. In addition, grain maize studies were grouped according to the grain moisture at harvest: low grain moisture (≅15%) and high grain moisture (>20%), where the latter has a shorter late-season and therefore a larger $K_{c\,end}$ than the former, indicating differences in the time for the crop to dry out in the field. There is also maize produced for human consumption at the table, which have $K_c$ at harvesting close or very close to the $K_{c\,mid}$. However, new literature on this type of maize cropping was not available.

As reported in Table 7, maize studies originate from a very large number of regions and countries, including the more important producing areas of the world. Differently, studies relative to sorghum are more restrictive in terms of their geographical origin, though study locations often coincided with some of the maize study areas.

The majority of reviewed papers reporting on the derivation of $K_c$ and $K_{cb}$ for maize used a SWB approach and most of the selected papers used some form of modeling. The derivation of $K_c$ using SWB was commonly performed with various SWC measurement equipment, namely TDR, FDR, neutron and capacitance probes, as well as, by using gravimetric measurements. Examples of deriving $K_c$ with SWB and not using models are those reported by Cameira et al. (2003), Kar and Verma (2005) and Gao et al. (2009). Hou et al. (2014) reported on $K_{cb}$ derived using a SWB approach combined with transpiration measurements using sap-flow sensors and $E_s$ measurements with micro-lysimeters. Jiang et al. (2014) derived $K_c$ through a study involving SWB, EC and micro-lysimeters.

When SWB models were used, $K_c$ were determined through model calibration with field data, followed by required validation using different data sets. The model reported for $K_c$ derivation was the ISAREG model, and that for $K_{cb}$ determination was the SIMDualKc model (Table 7). These applications were used in different climates in various regions of the world. A complex approach was reported by Ran et al. (2017) on deriving $K_{cb}$ with SIMDualKc, where SWB data were combined with EC data and with microlysimeters measurements of soil evaporation, and sap-flow measurements of transpiration. Differently, Miao et al. (2016) reported on the use of the SIMDualKc model for deriving $K_{cb}$ for maize both grown alone and intercropped with wheat and present a procedure to compute $K_{cb}$ for the intercropped management. Chauhdary et al. (2020) used the SALTMED model calibrated and validated with gravimetric SWC measurements. A single study was selected on deriving $K_{c\,mid}$ with a remote sensing energy balance model (Tasumi and Allen, 2007).

An example on the use of SIMDualKc for deriving maize $K_{cb}$ and $K_c$ through model calibration and validation is given in Fig. 7. It shows that when the model is calibrated, the standard $K_{cb}$ curve (i.e., for optimal conditions, Fig. 7b) does not change when water stress occurs (Fig. 7d), although $K_{cb\,act}$ falls below the curve when water stress occurs. Results from this modeling study (Paredes et al., 2014) determined a p value for non-stress of 0.50 (Table 8). Fig. 7a shows an appropriate calibration of the model and Fig. 7c a validation of the model with another data set.

An earlier study on deriving maize $K_c$ using EC measurements was reported by Suyker and Verma (2009). Zhang et al. (2013) reported on the use of EC measurements to calibrate and validate the model SIMDualKc. Other studies relative to the use of EC data for assessing $K_c$ values are those by Facchi et al. (2013), Alberto et al. (2014), Ding et al. (2015) and Gong et al. (2017), where all but Alberto et al. (2014) using EC measurements associated with SWB observations. Studies using weighing lysimeters include those by Tyagi et al. (2003), Howell et al. (2006, 2008), Piccinni et al. (2009), and Anapalli et al. (2016), combining lysimeter data with soil moisture observations. To better assess the total ET partition, Ding et al. (2013) included a SWB,

**Table 7**

Field observed $K_c$ and $K_{cb}$ for maize and sorghum and corresponding values adjusted to the standard climate ($RH_{min}$ = 45%, $u_2$ = 2 m $s^{-1}$) with identification of the article reference, location of the field study, methods used for determination and partition of $ET_{cact}$ and irrigation method.

| Crop | Reference | Location | Method for estimating $ET_{cact}$ | Irrigation method | $K_c/K_{cb}$ derived from field observations | | $K_c/K_{cb}$ adjusted to standard climate | |
|---|---|---|---|---|---|---|---|---|
| **Single crop coefficient** | | | | | $K_{c\,mid\,(obs)}$ | $K_{c\,end\,(obs)}$ | $K_{c\,mid\,(std)}$ | $K_{c\,end\,(std)}$ |
| Maize, Grain (*Zea mays*) | | | | | | | | |
| Low grain moisture | Liu et al. (1998) | Wangdu, North China Plain | DL, SWB-neutron, gravim., ISAREG | Surface | 0.95 | 0.34 | 1.08 | 0.34 |
| | Cameira et al. (2003) | Coruche, Portugal | SWB-neutron | Sprinkler | 1.10 | 0.20 | 1.10 | 0.20 |
| | Tyagi et al. (2003) | Karnal, India | WL, SWB-neutron | n/r | 1.23 | 0.42 | 1.29 | 0.42 |
| | Howell et al. (2006) | Bushland, TX, USA | WL | Sprinkler | 1.20 | 0.15 | 1.09 | 0.15 |
| | Popova et al. (2006) | Stara Zagora, Bulgaria | SWB-gravim., ISAREG | Furrow | 1.28 | 0.23 | 1.28 | 0.23 |
| | Gao et al. (2009) | Xinxiang, Henan, China | SWB-TDR | Surface | 1.16 | 0.24 | 1.28 | 0.24 |
| | Piccinni et al. (2009) | Uvalde, TX, USA | WL | Sprinkler | 1.20 | 0.30 | 1.10 | 0.30 |
| | Suyker and Verma (2009) | Mead, NE. USA | EC | Sprinkler | 1.09 | 0.34 | 1.05 | 0.34 |
| | Popova and Pereira (2011) | Tsalapitsa, Bulgaria | SWB-gravim., neutron, ISAREG | Furrow | 1.26 | 0.23 | 1.27 | 0.23 |
| | Ding et al. (2013) | Wuwei, Gansu, China | WL, SF, SWB-FDR | Border | 1.20 | 0.60 | 1.18 | 0.56 |
| | Facchi et al. (2013) | Po Valley, Italy | EC, SWB-TDR | Border | 1.00 | 0.43 | 1.04 | 0.43 |
| | Martins et al. (2013) | Santa Maria, Brazil | SWB-FDR, SIMDualKc | Drip | 1.13 | 0.20 | 1.16 | 0.20 |
| | Jiang et al. (2014) | Wuwei, Gansu, China | EC, SWB-FDR | Border | 1.12 | n/r | 1.14 | n/r |
| | Paredes et al. (2014) | Alpiarça, Portugal | SWB-capacit., SIMDualKc | Sprinkler | 1.20 | 0.30 | 1.22 | 0.30 |
| | Ding et al. (2015) | Wuwei, Gansu, China | EC, SWB-FDR | Border | 1.20 | 0.40 | 1.18 | 0.40 |
| | Giménez et al. (2016) | Paysandú, Uruguay | SWB-neutron, SIMDualKc | Drip | 1.15 | 0.42 | 1.12 | 0.42 |
| | Miao et al. (2016) | Dengkou, Hetao, China | SWB-gravim., SIMDualKc | Basin | 1.18 | 0.35 | 1.09 | 0.35 |
| High grain moisture | Pereira et al. (2003) | Xiongxian, North China Plain | SWB-neutron, TDR, ISAREG | Furrow | 1.06 | 0.58 | 1.19 | 0.63 |
| | Kar and Verma (2005) | Dhenkanal, India | SWB-gravim. | Surface | 1.25 | 0.55 | 1.25 | 0.55 |
| | Tasumi and Allen (2007) | Magic Valley, ID, USA | RS, METRIC model | Sprinkler | 1.28 | n/r | 1.23 | n/r |
| | Alberto et al. (2014) | Los Baños, Philipines | EC | Sprinkler | 1.21 | 0.95 | 1.30 | 0.80 |
| | Hou et al. (2014) | Bulang, Shaanxi, China | SF, SWB-TDR | Surface | 1.18 | 0.57 | 1.15 | 0.57 |
| | Zhao et al. (2013) | Daxing, N. China | SWB-TDR, SIMDualKc | Basin | 1.19 | 0.65 | 1.27 | 0.67 |
| | Zhang et al. (2013) | Daxing, N. China | EC, SIMDualKc | Basin | 1.21 | 0.65 | 1.29 | 0.65 |
| | Gong et al. (2017) | Shouyang, Shanxi, China | EC, SWB-FDR | Furrow | 1.12 | 0.60 | 1.20 | 0.64 |
| | Chauhdary et al. (2020) | Faisalabad, Pakistan | SWB-gravimet., SALTMED | Drip | 1.10 | 0.72 | 1.03 | 0.64 |
| Maize, Silage | Cameira et al. (2003) | Coruche, Portugal | SWB-neutron | Sprinkler | 1.00 | 0.95 | 1.01 | 1.01 |
| | Howell et al. (2008) | Bushland, TX, USA | WL, SWB-neutron | Sprinkler | 1.10 | 0.75 | 1.04 | 0.70 |
| | Rosa et al. (2012b) | Coruche, Portugal | SWB-gravim., SIMDualKc | Basin | 1.12 | 0.55 | 1.16 | 0.54 |
| | Facchi et al. (2013) | Po Valley, Italy | EC, SWB-TDR | Border | 1.00 | 0.89 | 1.05 | 0.79 |
| | Martins et al. (2013) | Santa Maria, Brazil | SWB-FDR, SIMDualKc | Sprinkler | 1.15 | 0.80 | 1.21 | 0.87 |
| | Anapalli et al. (2016) | Bushland, TX, USA | WL, SWB-neutron, RZWQM2 | Sprinkler | 1.10 | 0.70 | 1.01 | 0.73 |
| Sorghum, Grain (*Sorghum bicolor*) | Tyagi et al. (2000b) | Karnal, India | WL, SWB-neutron | n/r | 1.24 | 0.85 | 1.25 | 0.76 |
| | Howell et al. (2006) | Bushland, TX, USA | WL | Sprinkler | 1.05 | 0.40 | 0.96 | 0.40 |
| | Bashir et al. (2008) | Gezira, Sudan | RS-SEBAL, SWB-gravim. | – | 1.15 | 0.48 | 1.03 | 0.45 |
| | Shenkut et al. (2013) | Melkassa, Ethiopia | DL, SWB-neutron | n/r | 1.18 | 0.70 | 1.13 | 0.63 |
| Sorghum, Silage | Howell et al. (2008) | Bushland, TX, USA | WL, SWB-neutron | Sprinkler | 0.95 | 0.95 | 0.90 | 0.90 |
| Sorghum, Sweet | Piccinni et al. (2009) | Uvalde, TX, USA | WL | Sprinkler | 1.00 | 0.60 | 0.96 | 0.55 |
| | Martínez-Cruz et al. (2015) | Tucson, AZ, USA | SWB-TDR | Furrow | | | | |
| | | cv A4 | | | 1.15 | n/r | 1.05 | n/r |
| | | cv M81E | | | 1.10 | n/r | 1.00 | n/r |
| | | cv SM | | | 1.10 | n/r | 1.00 | n/r |
| | | cv. ST | | | 1.00 | n/r | 0.90 | n/r |
| | López-Urrea et al. (2016) | Albacete, Spain | WL, FAO dual $K_c$ approach | Sprinkler | 1.19 | n/r | 1.10 | n/r |

(*continued on next page*)

**Table 7** (*continued*).

| Crop | Reference | Location | Method for estimating $ET_{cact}$ | Irrigation method | $K_c/K_{cb}$ derived from field observations | | $K_c/K_{cb}$ adjusted to standard climate | |
|---|---|---|---|---|---|---|---|---|
| **Basal crop coefficient** | | | | | $K_{cb\,mid\,(obs)}$ | $K_{cb\,end\,(obs)}$ | $K_{cb\,mid\,(std)}$ | $K_{cb\,end\,(std)}$ |
| Maize, Grain (*Zea mays*) | | | | | | | | |
| Low grain moisture | Martins et al. (2013) | Santa Maria, Brazil | SWB-FDR, SIMDualKc | Sprinkler | 1.12 | 0.20 | 1.15 | 0.20 |
| | Paredes et al. (2014) | Alpiarça, Portugal | SWB-capacit., SIMDualKc | Sprinkler | 1.15 | 0.30 | 1.17 | 0.30 |
| | Giménez et al. (2016) | Paysandú, Uruguay | SWB-neutron, SIMDualKc | Drip | 1.05 | 0.30 | 1.02 | 0.30 |
| | Miao et al. (2016) | Dengkou, Hetao, China | SWB-gravim., SIMDualKc | Basin | 1.15 | 0.25 | 1.06 | 0.25 |
| | Rosa et al. (2016) | Alvalade, Portugal | SWB-TDR, SIMDualKc | Drip | 1.15 | 0.20 | 1.08 | 0.20 |
| High grain moisture | Pereira et al. (2003) | Xiongxian, North China Plain | SWB-TDR & neutron, ISAREG | Furrow | 1.01 | 0.53 | 1.09 | 0.58 |
| | Zhao et al. (2013) | Daxing, China | SWB-TDR, micro-lys., SIMDualKc | Basin | 1.10 | 0.45 | 1.18 | 0.45 |
| | Zhang et al. (2013) | Daxing, China | EC, SIMDualKc | Basin | 1.15 | 0.45 | 1.23 | 0.45 |
| | Alberto et al. (2014) | Los Baños, Philipines | EC | Sprinkler | 1.13 | 0.64 | 1.22 | 0.77 |
| | Chauhdary et al. (2020) | Faisalabad, Pakistan | SWB-gravim., SALTMED | Drip | 1.00 | 0.55 | 0.93 | 0.47 |
| Maize, Silage | Rosa et al. (2012b) | Coruche, Portugal | SWB-gravim., SIMDualKc | Basin | 1.05 | 0.55 | 1.09 | 0.54 |
| | Martins et al. (2013) | Santa Maria, Brazil | SWB-FDR, SIMDualKc, | Drip | 1.12 | 0.80 | 1.18 | 0.87 |
| Sorghum, Grain (*Sorghum bicolor*) | Kato and Kamichica (2006) | Tottori, Japan | BREB, S-W double source partition | Sprinkler | 0.98 | 0.53 | 0.99 | 0.55 |
| Sorghum, Sweet | López-Urrea et al. (2016) | Albacete, Spain | WL, FAO dual $K_c$ approach | Sprinkler | 1.17 | n/r | 1.08 | n/r |
| | Rosa et al. (2016) | Alvalade, Portugal | SWB-TDR, SIMDualKc | Drip | 1.00 | 0.35 | 0.93 | 0.35 |

BREB — Bowen ratio energy balance; Capacit. — Capacitance probe; DL — Drainage lysimeter; EC — Eddy Covariance; FDR — Frequency Domain Reflectometry; Gravim. — Gravimetric sampling method; micro-lys — micro-lysimeter; Neutron — neutron probe; RS — Remote sensing; SF — Sap Flow; SDI — Subsurface drip irrigation; S–W — Shuttleworth–Wallace method; SWB — Soil water balance; TDR — Time-Domain Reflectometry; WL — Weighing lysimeter; n/r — not reported.

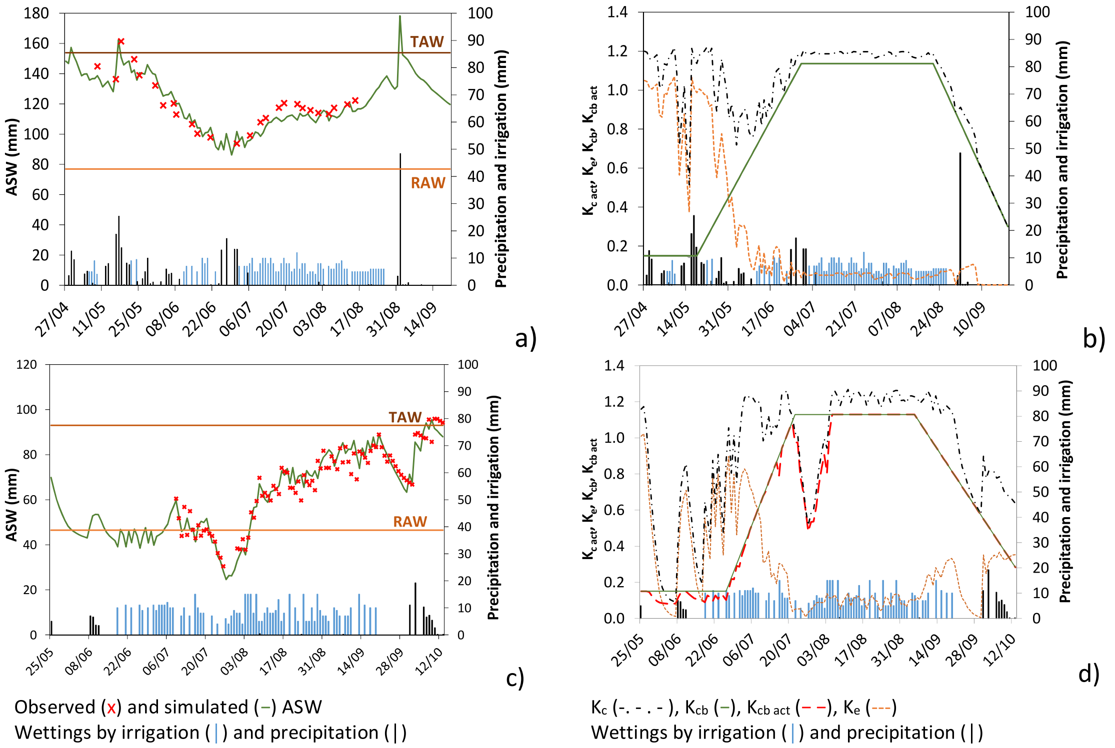


**Fig. 7.** Example of using the SIMDualKc model for deriving $K_{cb}$ and $K_c$ values for maize: dynamics of available soil water, ASW (a and c), and single and basal crop coefficients curves comparing the actual and standard $K_{cb}$ and soil evaporation coefficient $K_e$ without and with water stress (b and d) for maize cropped in Alpiarça, Central Portugal. *Source:* Adapted from Paredes et al. (2014).

**Table 8**
Observed ancillary crop parameters for maize and sorghum.

| Crop | Reference | $Z_{r\ max}$ (m) | $h_{max}$ (m) | $LAI_{max}$ ($m^2\ m^{-2}$) | $f_{c\ max}$ | $p_{ini}$ | $p_{mid}$ | $p_{end}$ |
|---|---|---|---|---|---|---|---|---|
| Maize, Grain (*Zea mays* L.) | Liu et al. (1998) | 0.80 | n/r | n/r | n/r | 0.40 | 0.60 | 0.80 |
| | Cameira et al. (2003) | 0.80 | 2.50 | 7.0 | n/r | n/r | n/r | n/r |
| | Pereira et al. (2003) | 1.00 | 2.98 | n/r | n/r | 0.55 | 0.40 | 0.60 |
| | Tyagi et al. (2003) | 1.50 | n/r | 5.5 | n/r | n/r | n/r | n/r |
| | Kar and Verma (2005) | 0.97 | n/r | 5.1 | n/r | n/r | n/r | n/r |
| | Howell et al. (2006) | 1.40 | 2.77 | 5.5 | n/r | n/r | n/r | n/r |
| | Popova et al. (2006) | 1.30 | n/r | n/r | n/r | 0.45 | 0.60 | 0.78 |
| | Gao et al. (2009) | 1.00 | n/r | 4.0 | n/r | n/r | n/r | n/r |
| | Suyker and Verma (2009) | n/r | n/r | 6.4 | n/r | n/r | n/r | n/r |
| | Popova and Pereira (2011) | 1.30 | n/r | n/r | n/r | 0.80 | 0.66 | 0.80 |
| | Ding et al. (2013) | 1.00 | 2.70 | 5.9 | 0.99 | 0.55 | 0.45 | n/r |
| | Facchi et al. (2013) | 0.70 | 3.40 | 5.7 | 0.96 | 0.55 | 0.55 | 0.55 |
| | Martins et al. (2013) | 0.90 | 2.30 | n/r | 0.90 | 0.50 | 0.50 | 0.50 |
| | Zhao et al. (2013) | 1.00 | 2.50 | n/r | 0.80 | 0.55 | 0.55 | 0.55 |
| | Zhang et al. (2013) | 1.00 | 2.50 | n/r | 0.80 | 0.55 | 0.55 | 0.55 |
| | Alberto et al. (2014) | 1.00 | 2.54 | 4.8 | n/r | n/r | n/r | n/r |
| | Hou et al. (2014) | 0.90 | 2.90 | 5.0 | n/r | 0.50 | 0.50 | 0.50 |
| | Jiang et al. (2014) | 1.00 | 1.60 | 4.8 | n/r | n/r | n/r | n/r |
| | Paredes et al. (2014) | 0.90 | 2.52 | n/r | 0.95 | 0.50 | 0.50 | 0.50 |
| | Ding et al. (2015) | 1.00 | n/r | 5.5 | 0.95 | 0.50 | 0.50 | 0.50 |
| | Wu et al. (2015) | 0.70 | 1.95 | n/r | 0.80 | 0.50 | 0.50 | 0.50 |
| | Giménez et al. (2016) | 0.75 | 2.00 | n/r | 0.95 | 0.55 | 0.50 | 0.75 |
| | Rosa et al. (2016) | 0.60 | 2.24 | 5.7 | 0.94 | 0.55 | 0.55 | 0.80 |
| | Miao et al. (2016) | 1.00 | 2.05 | n/r | 0.93 | 0.55 | 0.45 | 0.80 |
| | Gong et al. (2017) | 1.00 | n/r | 5.5 | n/r | n/r | n/r | n/r |
| | Ran et al. (2017) | 1.00 | n/r | n/r | 0.95 | 0.55 | 0.55 | 0.55 |
| | Chauhdary et al. (2020) | 0.60 | 2.23 | 7.4 | 0.92 | n/r | n/r | n/r |
| Maize, Silage | Cameira et al. (2003) | 0.60 | 2.10 | 4.5 | n/r | n/r | n/r | n/r |
| | Howell et al. (2008) | 1.40 | 3.00 | 5.7 | n/r | n/r | n/r | n/r |
| | Rosa et al. (2012b) | 1.10 | 2.00 | n/r | 0.80 | 0.65 | 0.65 | 0.65 |
| | Facchi et al. (2013) | 0.70 | 3.00 | 4.2 | 0.85 | n/r | n/r | n/r |
| | Martins et al. (2013) | 0.90 | 2.40 | n/r | 0.90 | 0.50 | 0.50 | 0.50 |
| | Anapalli et al. (2016) | 1.40 | 3.00 | 5.1 | n/r | 0.50 | 0.50 | 0.50 |
| Sorghum, Grain (*Sorghum bicolor*) | Tyagi et al. (2000b) | n/r | n/r | 3.9 | n/r | n/r | n/r | n/r |
| | Howell et al. (2006) | 1.40 | 1.48 | 5.3 | n/r | n/r | n/r | n/r |
| | Kato and Kamichica (2006) | n/r | 1.50 | 1.6 | n/r | n/r | n/r | n/r |
| | Bashir et al. (2008) | 1.00 | n/r | 3.2 | n/r | n/r | n/r | n/r |
| | Shenkut et al. (2013) | 1.05 | 1.89 | 4.9 | n/r | 0.55 | 0.55 | 0.55 |
| Sorghum, Silage | Howell et al. (2008) | 1.40 | 3.00 | 5.6 | n/r | n/r | n/r | n/r |
| Sorghum, Sweet | Martínez-Cruz et al. (2015) | 1.80 | n/r | n/r | n/r | 0.50 | 0.50 | 0.50 |
| | López-Urrea et al. (2016) | n/r | 4.60 | n/r | 1.0 | n/r | n/r | n/r |
| | Rosa et al. (2016) | 0.65 | 2.46 | 4.6 | 0.87 | 0.50 | 0.50 | 0.80 |

$Z_{r\ max}$ – maximum root depth; $h_{max}$ – maximum crop height; $LAI_{max}$ – maximum leaf area index; $f_{c\ max}$ – maximum fraction of ground cover; $p_{ini}$, $p_{mid}$, $p_{end}$ – soil water depletion fraction for no stress for respectively the initial, mid and end season stages; n/r – not reported.

sap-flow measurements for transpiration, and ET data from weighing lysimeter observations.

Studies on sorghum grain include those by Tyagi et al. (2000b) and Howell et al. (2008) using weighing-type lysimeters in combination with SWB based on neutron probe measurements. Kato and Kamichica (2006) studied the $K_{cb}$ and the $K_e$ curves in the sorghum grain using the two-compartment model of Shuttleworth and Wallace (S–W model). Bashir et al. (2008) estimated ET of sorghum through remotely sensed data. Sweet sorghum crop coefficients were studied by Piccinni et al. (2009) using a WL and a similar approach with a WL was used by Howell et al. (2008) and López-Urrea et al. (2016). Differently, Shenkut et al. (2013) used a DL performing the SWB using neutron probe data. Martínez-Cruz et al. (2015) studied four varieties of sweet sorghum using SWB with TDR measurements. Rosa et al. (2016) used SWC observations with TDR to calibrate and validate the SIMDualKc model when the experiment with sorghum (and with maize silage) was developed using saline irrigation and the water and salinity stress coefficients were tested (see Minhas et al., 2020).

When studies reported on a range of $K_{c\ mid\ (std)}$ and/or $K_{c\ end\ (std)}$, i.e., when authors did not select the most appropriate values for growth stages and causes for their variability were not identified, average $K_{c\ mid\ (std)}$ and $K_{c\ end\ (std)}$ were estimated. In addition, derived $K_{cb}$ data were used to estimate the $K_c$ values in a few cases following the guidelines indicated in Section 2.5. Results for sorghum show a range of $K_{c\ mid\ (std)}$ values wider than for $K_{cb\ mid\ (std)}$, which likely are due to the effects of rainfall and irrigation on soil evaporation.

Ancillary parameters characterizing both the maize and sorghum crops, which are commonly used in related ET-soil water balance studies, are given in Table 8. $Z_{r\ max}$ vary in a relatively large range for grain maize, 0.6 to 1.5 m, and a similar range for maize silage; however, there are no evident reasons for the extreme variations in values. Most commonly, reported $Z_{r\ max}$ values for maize fall within 0.70 to 1.00 m, which compares to 1.0–1.70 m in the FAO56 tables for maize grain. Sorghum $Z_{r\ max}$ (Table 8) were more consistent than maize, except for the lower depth for sweet sorghum. Reported $h_{max}$ for maize also vary widely, which may be related to different crop varieties and water management practices. More common reported maize values range from 2.50 to 3.00 m, while more extreme height variation primarily depending upon crop varieties and cropping practices. These and other factors could also explain the rather large differences in maximum height found for sorghum. $LAI_{max}$ generally varies from 5.0 to 7.0 $m^2\ m^{-2}$, which may indicate that maize crops were not stressed, whereas two low $LAI_{max}$ values for sorghum, may indicate the opposite. Most frequent $f_{c\ max}$ values varied from 0.80 to 0.95, which also indicate non-stressed sparse crops. However, these values may be influenced by the measurement procedure. The soil water depletion fraction for no stress are mostly around 0.45–0.55 for the mid-season but much higher values for $p_{end}$ are reported in a few papers that probably refer to late season crop management issues.

## 3.5. Rice

### 3.5.1. Rice irrigation water management practices

Rice (*Oryza sativa* L.) is a main staple food crop cultivated everywhere in the world when the climate provides for a warm, hot crop season of about 4 to 5 months and where water availability is sufficiently abundant. Typically, it is cultivated in flooded paddies, but it is cropped in a variety of conditions, from deep water with floating rice to aerobic sprinkler irrigation conditions. That diversity of rice water management results from the wide range of environmental conditions where rice may be cropped and implies numerous different crop varieties able to respond to the unique environmental requirements and related water management issues.

A long review of literature is the basis of the current section. Most of literature on rice crop coefficients are for flooded paddies but $K_c$ for a variety of other conditions has been documented. An exception is for deep floating rice. Water management issues considered refer to:

(a) *Permanent flooded paddies*, which may vary in terms of management of the depth of water in the paddies. For saving water, and because precise land leveling is often applied, that water depth may be reduced from about 0.10 m to less than 0.05 m. However, that reduction also concerns the effects of paddy water in avoiding low temperature impacts on the crop, thus, its proper use depends upon the climate in addition to the ability of the irrigators. That variability of water depths has little impact on crop ET but has great effects on the amount of deep percolation through the root zone bottom and on seepage through the borders of the paddies, particularly into the surface drainage system.

(b) *Flooded paddies with dry seeding*. This is a water saving practice aimed at reducing irrigation during the initial, early stages of the crop, which leads to reducing the initial crop ET, thus smaller $K_{c\,ini}$; however, this does not impact (lessen) ET for the remainder of the crop season. The adoption of this practice can increase mechanization options for the farm operations, since seeding often is performed using an airplane in large farms.

(c) *Flooded paddies with anticipated cutoff*. Greatly reduces irrigation during the late season, a water-saving practice that also reduces crop ET during that stage, which generally leads to a low $K_{c\,end}$. Unfortunately, very few references to this practice were available, and none referred to an appropriate estimation of $K_{c\,end}$.

(d) *Intermittent irrigation of the paddies*, where flooded basin irrigation is applied intermittently to the paddies to keep the soil water content close to saturation. This is a water saving practice developed in South China, where ponded water is not required for temperature control. This practice aims at controlling deep percolation and seepage by avoiding standing water in the paddies except during times when they are flooded. Since the soil water is maintained close to saturation, impacts on ET compared to permanent flooding are generally quite small except for the late season because the intermittent paddies dry easier, which may lead to a reduced $K_{c\,end}$.

(e) *Aerobic rice*, where rice is cropped like any other grain cereal, such as wheat or barley, but irrigation is practiced adopting a smaller management allowed depletion (MAD), thus requiring more frequent irrigation applications. However, rice yields with this practice can be reduced compared to other methods. The climate must be such that the temperature is warm enough to not affect growth. Therefore, $K_{c\,ini}$, $K_{c\,mid}$ and $K_{c\,end}$ values approach those for grain crops but can vary depending on the frequency of irrigation events for rice; generally higher when sprinkler irrigation is practiced. When surface irrigation is used, soil and water management practices differ for level vs. sloping fields, which also influence $K_c$ values.

(f) *Rainfed rice*, where rice is generally cropped in paddy basins, which are essential to store all rainfall water and provide its infiltration into the cropped soil, so it can be productively used by the rice crop. That practice is typical of monsoon climates. $K_c$ values may be high as for flooded paddies when rainfall helps to keep soil water above the field capacity, and $K_c$ values become smaller when time intervals between rain wettings are large.

### 3.5.2. Review on applications

References to rice crop coefficient studies are quite numerous but only few studies respond to the exigencies for accuracy defined for this study earlier in this paper or in the companion paper by Pereira et al. (2021).

The review focused on $K_c$-$ET_o$ applications where the PM-$ET_o$ equation is used. Unfortunately, many applications to rice use FAO24 $ET_o$ equations (Doorenbos and Pruitt, 1977) or pan evaporation $ET_o$ without assessing their relationships with the PM-$ET_o$. In addition, several studies did not adopt the four segments $K_c$ curve adopted in FAO56 and preferred a non-linear description of $K_c$ as a function of time after planting. Moreover, when the FAO $K_c$ curve was adopted some authors reported, either numerically or graphically, on a range of values for $K_{c\,ini}$, $K_{c\,mid}$ and $K_{c\,end}$. However, if these studies were otherwise sound, we were obliged to evaluate the data values, interpreting at our best appropriately reported $K_c$ values.

We noticed that advection was rarely considered, contrarily with studies developed 20 years ago. Two classical studies considering the influence of advection in paddies ET are those by Lourence and Pruitt (1971) and Peterschmitt and Perrier (1991). The first paper refers to an application of the Bowen ratio energy balance (BREB) to flooded paddies in California as well as to a weighing lysimeter at Davis, California. The second concerns the application of an energy balance approach to a paddy field at Pondicherry, India. However, they are rarely quoted in literature, despite that they could be of much interest for more recent studies using BREB or eddy covariance observations. An earlier review on rice ET by Tomar and O'Toole (1979) also referred to impacts of advection. These mentioned studies are among the few focusing on crop coefficients where advection effects were considered. However, these studies were developed prior to FAO56, do not refer to the PM-$ET_o$ and, their approach to $K_c$ follows different concepts. Therefore, the reported $K_c$ values were not compared with those in the current literature review. More recently, a study by Tsai et al. (2007) on the energy balance of rice paddies in Central Taiwan reports that corrections of eddy covariance measurements should include a correction for advection and proposed the required procedure. Alberto et al. (2011) suggested possible impacts of advection in flooded rice but their reported $K_c$ values are relatively small and do not denote large advection impacts for the Los Baños area in the Philippines.

Likely due to various field observation or data handling flaws, many published studies reported $K_c$ values of about 1.50 or greater, thus largely exceeding the expected values when only vertical heat and vapor fluxes occur. Such large values are likely due to horizontal advective transport of heat at local or regional scale, so sensible heat fluxes H are converted into latent heat fluxes LE. These conditions can lead to several days with quite high crop ET but unlikely to an average ET where $K_c$ is above 1.40, a reasonable $K_c$ upper threshold for hot and windy climates as discussed by Allen et al. (2011b). Localized advective impacts also occur when lysimeters or small experimental plots are not well integrated in a vast equally cropped area, or when the crop in the study plots develops more than that surrounding cropped area. Nevertheless, increased LE or ET due to advection is not reported to make $K_c$ 1.50 or larger in the referred studies (Lourence and Pruitt, 1971; Peterschmitt and Perrier, 1991; Tsai et al., 2007; Alberto et al., 2011). For that reason, studies having such large $K_c$ were excluded from this review.

In addition to the cases where mid or late-season $K_c$ are above the referred threshold, rice studies were not retained when:

- There was an insufficient or inexistent description of the lysimeter facilities used, of the quality control measures adopted and of the data handling procedures applied. In fact, poor lysimeter settings and management are prone to local transport of heat from the surrounding area, including the occurrence of clothesline effects. Lack of quality control allows that measurements and data handling become prone to errors. All these aspects often cause crop coefficients that increase much above expected values (Allen et al., 2011b; Evett et al., 2012a), thus, reason why it is considered relevant to describe well the lysimeter facilities when reporting related research (Allen et al., 2011a). Therefore, an overestimation of $K_c$ may often occur.
- Poor or insufficient description of the soil water balance (SWB) approaches used, namely roughly known or lack of soil hydraulic characteristics of the location under study, insufficient description of computational procedures adopted for each term of the SWB, as well as insufficient information about the equipment used, the SWC sensors placement and frequency of observations. The corresponding need for information has been also stressed (Allen et al., 2011b,a). SWB inaccuracies cause inaccurate estimations of the water fluxes through the bottom boundary of the soil root zone, namely causing underestimation of deep percolation and of lateral seepage, which then lead to overestimation of crop ET and $K_c$.
- The calibration and validation procedures of any model used to perform the SWB are often insufficiently described or at the limit, the SWB is sometimes performed without reference to soil water observations. For such, ET and $K_c$ may be over- or underestimated, with particular relevance for errors relative to percolation and seepage.
- The description of eddy covariance and BREB equipment and of its management and quality control of related observed data were lacking, namely not referring to the closure error that is required to assure that accuracy of data was appropriate. Inaccurate estimation of ET and $K_c$ may then result despite using good quality sensors. ET and $K_c$ may then be over- or under-estimated.

$K_c$ values reported in selected studies focusing on the derivation of $K_c$ for rice are summarized in Table 9. However, only two $K_{cb}$ studies were selected (Vories et al., 2013; Alberto et al., 2014) and related $K_{cb}$ data are also included in Table 9. Most reported studies refer to flooded rice paddies adopting reduced water depths aimed at water saving (Tyagi et al., 2000a; Mao et al., 2004; Vu et al., 2005; Alberto et al., 2011, 2014; Arif et al., 2012; Kadiyala et al., 2012; Hatiye et al., 2015; Linquist et al., 2015; Djaman et al., 2019; Diaz et al., 2019). Three of those studies report on adopting dry seeding (Alberto et al., 2014, in the Philipines; Linquist et al., 2015, in California; Diaz et al., 2019, in Brazil). Rainfed paddies are the object of a study developed in Thailand. Intermittent flooding irrigation is reported in four Asian studies (Agrawal et al., 2004; Arif et al., 2012; Hatiye et al., 2015; Oue and Laban, 2019). Aerobic rice cropping is reported by Asian researchers relative to surface irrigation (Alberto et al., 2011; Kadiyala et al., 2012; Choudhury et al., 2013) and by Europeans relative to sprinkler irrigation (Spanu et al., 2009; Moratiel and Martínez-Cob, 2013), which coincide with the dominant type of irrigation of rice in Asia and Europe, respectively. None of $K_c$ referred studies reported advection; the occurrence of stress was generally not identified by the authors.

A variety of ET estimation methods were used in the reported studies (Table 9). A paddy water balance (PWB) approach was adopted using pairs of microlysimeters with open and closed bottom for assessing deep percolation, where twice studies adopted a simplified model with a Darcy approach to consider the different behaviors of the plowed layer, the compacted layer and the lower layer (Paulo et al., 1995; Mao et al., 2004; Hatiye et al., 2015). Choudhury et al. (2013) also used microlysimeters in combination with the SWB when studying intermittent irrigation. The use of weighing lysimeters is reported by Tyagi et al. (2000a) and of drainage lysimeters is referred by Vu et al. (2005). BREB was used in the study with rainfed rice (Attarod et al., 2006). More recent studies reported on the use of eddy covariance (Alberto et al., 2011, 2014; Linquist et al., 2015; Diaz et al., 2019) and surface renewal (Moratiel and Martínez-Cob, 2013). The model AIS (Arkansas Irrigation Scheduling) was adopted by Vories et al. (2013) who used Watermark sensors data to assess soil water content.

Values for rice $K_c$ (Table 9) are quite variable but there is good consistency in $K_c$ among many studies. However, the mid-season $K_c$ reported by Linquist et al. (2015) is much lower than those presented by other authors for flooded paddies; this was taken into consideration when defining the consolidated $K_{c\,mid}$ values later. $K_{c\,ini}$ values depend upon various factors that influence evaporation from a free water surface; as previously noted in FAO56, $K_{c\,ini}$ tends to increase when climates are dry and windy. Nevertheless, the set of values reported describe insufficiently that initial period and variability of $K_{c\,ini}$ among studies may relate to differences in defining the initial crop growth stage. Management may also influence $K_{c\,ini}$. For flooded rice, with the referred exception, all values for $K_{c\,mid\,(std)}$ are in a relatively narrow range, from 1.11 to 1.29. However, for $K_{c\,end\,(std)}$, the range (0.87 to 1.14) is greater due to different management approaches to drain the paddies, which depend upon the harvesting practices utilized, as well as the target grain moisture at harvesting. $K_c$ values for non-flooded rice vary with the practices adopted and in general standard $K_{c\,ini}$ and $K_{c\,end}$ values were lower than for flooded rice. On the other hand, standard $K_{c\,mid}$ values were not very different from those for flooded paddies with intermittent irrigation, although they were lower in some aerobic rice studies. For $K_{c\,end}$, variability in non-flooded rice is also due to management related issues.

Ancillary rice parameters are dealt insufficiently with in literature as per Table 10. Information on root depths was scarce, but it would have been desirable to have comparisons about $Z_r$ when studies compare intermittent irrigation or aerobic cropping with flooded paddies. Information about crop heights was also scarce but the available data showed $h_{max}$ to vary in a wide range. Similarly, information on $LAI_{max}$ varied much, likely due to both management and the crop variety. Data on $f_{c\,max}$ was only for a single value. Relative to the soil water depletion fraction for no stress (p), a large insufficiency refers to aerobic rice, for which no information is available. This is unfortunate since a good estimate for p is highly needed to support the development of new irrigation management and cropping practices for rice.

## 4. Updated single and basal standard crop coefficients

### 4.1. Grain legumes

The updating and consolidation of $K_c$ and $K_{cb}$ values for grain legumes was performed comparing the literature reported crop coefficients adjusted to the standard sub-humid climate ($RH_{min}$=45% and $u_2 = 2\ m\ s^{-1}$) with the $K_c$ values tabulated in FAO56 (Allen et al., 1998) (Table 11). However, for some crops, appropriate $K_c$ observations were lacking and thus the standard FAO56 values were either unchanged (lentil and dry pea), or slightly revised based on our analysis referred to below (green bean, green gram, green cowpea, and fresh fababean).

The available $K_c$ values for crops reported in Table 1 are well in agreement with those tabulated in FAO56 for $K_{c\,mid}$. From the related analysis, mainly considering the literature reported values (Table 1), it resulted that the standard $K_{c\,mid}$ values were increased by 0.05 relative to those formerly tabulated in the case of black gram and cowpea but, contrarily, were decreased by 0.10 for dry bean and 0.05 for fababean. $K_{c\,end}$ values, having more complexity due to the variability of observed values and the difficulties in getting true values from literature, were

**Table 9**

Field derived actual $K_c$ and $K_{cb}$ for rice (*Oryza sativa* L.) and respective values adjusted to the standard climate ($RH_{min}$ = 45%, $u_2$ = 2 m $s^{-1}$) with identification of the article reference, location of the field study, methods used for determination and partition of $ET_{cact}$ and irrigation method.

| Irrigation method | Reference | Local | Method for estimating $ET_{c\,act}$ | $K_c/K_{cb}$ derived from field observations | | | $K_c/K_{cb}$ adjusted to the standard climate | | |
|---|---|---|---|---|---|---|---|---|---|
| **Single crop coefficient** | | | | $K_{c\,ini\,(obs)}$ | $K_{c\,mid\,(obs)}$ | $K_{c\,end\,(obs)}$ | $K_{c\,ini\,(std)}$ | $K_{c\,mid\,(std)}$ | $K_{c\,end\,(std)}$ |
| Flooded paddies | Tyagi et al. (2000a) | Karnal, India | WL | 0.99 | 1.14 | 0.85 | 0.99 | 1.24 | 0.87 |
| | Mao et al. (2004) | Yongning &Pingluo, Ningxia, China | Microlys. & PWB | 1.04 | 1.27 | 1.16 | 1.04 | 1.22 | 1.14 |
| | Vu et al. (2005) | Tsukuba, Japan | DL | 1.11 | 1.20 | n/r | 1.11 | 1.25 | n/r |
| | Alberto et al. (2011) | Los Baños, Philipines | EC | n/r | 1.11 | 0.97 | n/r | 1.14 | 1.00 |
| | Arif et al. (2012) | Bekasi, West Java, Indonesia | PWB | 0.97 | 1.21 | 0.95 | 0.97 | 1.29 | 1.03 |
| | Kadiyala et al. (2012) | Hyderabad, India | Microlys, SWB, PWB | 1.10 | 1.15 | 0.90 | 1.10 | 1.15 | 0.91 |
| | Hatiye et al. (2015) | Roorkee, India | DL, SWB, ISAREG | 1.10 | 1.20 | 0.67 | 1.10 | 1.29 | 0.73 |
| | Linquist et al. (2015) | Colusa, CA, USA | EC, Surface Renewal | 1.16 | 1.04 | 1.05 | 1.16 | 1.01 | 1.00 |
| | Djaman et al. (2019) | Fanaye, Senegal | PWB | 1.01 | 1.31 | 1.00 | 1.01 | 1.27 | 0.96 |
| | Diaz et al. (2019) | Cachoeira do Sul, RS, Brazil | EC | 1.06 | 1.16 | 1.08 | 1.06 | 1.21 | 1.13 |
| Flooded with dry seeding | Alberto et al. (2014) | Los Baños, Philipines | EC | 0.83 | 1.10 | 1.07 | 0.83 | 1.11 | 1.09 |
| | Linquist et al. (2015) | Colusa, CA, USA | EC, Surface Renewal | 1.10 | 1.08 | 1.01 | 1.10 | 1.00 | 0.96 |
| | Diaz et al. (2019) | Cachoeira do Sul, RS, Brazil | EC | 0.67 | 1.21 | 1.14 | 0.67 | 1.26 | 1.19 |
| Intermittent irrigation | Agrawal et al. (2004) | Kharagpur, India | PWB | 1.05 | 1.16 | 1.03 | 1.05 | 1.21 | 1.04 |
| | Arif et al. (2012) | Bekasi, West Java, Indonesia | PWB | 0.70 | 1.24 | 1.15 | 0.70 | 1.32 | 1.23 |
| | Hatiye et al. (2015) | Roorkee, India | DL, SWB, ISAREG | 1.10 | 1.20 | 0.67 | 1.10 | 1.29 | 0.73 |
| | Oue and Laban (2019) | Bajeng Barat, Indonesia | BREB | 1.00 | 1.20 | 0.73 | 1.00 | 1.24 | 0.79 |
| Aerobic, sprinkling | Spanu et al. (2009) | Sardinia, Italy | SWB | 0.91 | 1.08 | 0.97 | 0.91 | 1.07 | 0.96 |
| | Moratiel and Martínez-Cob (2013) | Zaragoza, Spain | Surface renewal | ≈0.92 | ≈1.06 | ≈1.03 | ≈0.92 | 1.03 | 1.01 |
| Aerobic, basin irrigation | Alberto et al. (2011) | Los Baños, Philipines | EC | 0.95 | 1.00 | 0.93 | 0.95 | 1.04 | 0.98 |
| | Kadiyala et al. (2012) | Hyderabad, India | SWB, PWB | 0.80 | 1.05 | 0.80 | 0.80 | 1.06 | 0.79 |
| | Choudhury et al. (2013) | New Delhi, India | Microlys. & SWB | 0.60 | 1.20 | 0.55 | 0.60 | 1.17 | 0.51 |
| Aerobic, furrow irrigation | Choudhury et al. (2013) | New Delhi, India | Micro-lys. & SWB | 0.62 | 1.16 | 0.55 | 0.62 | 1.13 | 0.51 |
| Rainfed | Attarod et al. (2006) | Sukhotai, Thailand | BREB and SWB-TDR | 0.75 | 1.20 | 0.80 | 0.75 | 1.23 | 0.82 |
| **Basal crop coefficient** | | | | $K_{cbini(obs)}$ | $K_{cb\,mid\,(obs)}$ | $K_{cb\;\;end(obs)}$ | $K_{cbini(std)}$ | $K_{cb\,mid\,(std)}$ | $K_{cb\,end\,(std)}$ |
| Flooded with dry seeding | Alberto et al. (2014) | Los Baños, Philipines | EC | 0.07 | 0.95 | 0.70 | 0.07 | 0.96 | 0.72 |
| Aerobic, center-pivot | Vories et al. (2013) | Portageville, MO, USA | Resist., AIS model | 0.20 | 1.18 | 0.55 | 0.20 | 1.21 | 0.58 |

DL — Drainage Lysimeter; WL — Weighing Lysimeter; EC — Eddy Covariance; BREB — Bowen ratio energy balance; SWB — Soil Water Balance; PWB — Paddy field water balance; microlys. — microlysimeter; TDR — Time-Domain Reflectometry; Resist. — resistance probe.

mostly unchanged relative to the tabulated ones. The exceptions are for pea and soybean, whose standard $K_{c\,end}$ decreased because all reported values were smaller than the tabulated ones in FAO56. The available study on $K_c$ referred to pea harvested fresh for industry, where strict cropping rules apply including for high planting density, led to increase by 0.05 both $K_{c\,mid}$ and $K_{c\,end}$.

Reported $K_{cb}$ values from literature were quite limited but the few available generally confirmed the FAO56 tabulated values. As with $K_{c\,mid}$, the $K_{cb\,mid}$ for dry bean and faba bean were slightly decreased, while those for black gram, chickpea and cowpea were slightly increased. An increase of 0.05 of both $K_{cb\,mid}$ and $K_{cb\,end}$ was adopted for pea harvested fresh for industry, thus in agreement with changes in $K_c$ values referred above. Also, the $K_{cb\,mid}$ values for crops that may be harvested green or dry were equalized since differences for mid-season are not justified. An exception is for fresh pea that, in agreement with industry requirements, has now both mid and end $K_{cb}$ values larger than for dry pea. Due to the disagreement of values observed for various crops for $K_{cb\,end}$, we could not find sufficient reason to alter them, and therefore, they were unchanged relative to the FAO56 tables.

### 4.2. Fiber, oil and sugar crops

Only data for cotton were obtained from literature relative to $K_c$ and $K_{cb}$ of fiber crops. A sufficient number of reported $K_c$ and $K_{cb}$ values for cotton permitted a consolidation of both the mid-season and end-season values, and to avoid the confusion of the former tabulated pairs of values relative to full or deficit water supplied, since the latter does not correspond to pristine cultivation and standard crop coefficients. Viewing that much lower than former FAO56 mid-season $K_c$ were reported for drip-irrigated cotton, lowering the $K_{c\,mid}$ to 1.10 is considered appropriate (Table 12). It is also justifiable to lower $K_{cb\,mid}$ to 1.05. Single values for $K_{c\,end}$ and $K_{cb\,end}$ are also assumed as 0.50 and 0.40, respectively, which correspond to the lower values tabulated in FAO56. However, we bear in mind that end-season values can vary much with

**Table 10**
Observed ancillary crop parameters for rice reported in selected literature.

| Irrigation method | Reference | $Z_{r\,max}$ (m) | $h_{max}$ (m) | $LAI_{max}$ ($m^2\ m^{-2}$) | $f_{c\,max}$ | p |
|---|---|---|---|---|---|---|
| Flooded paddies | Tyagi et al. (2000a) | n/r | n/r | 3.9 | n/r | n/r |
| | Vu et al. (2005) | n/r | 0.55 | n/r | n/r | n/r |
| | Arif et al. (2012) | n/r | 1.36 | n/r | n/r | n/r |
| | Kadiyala et al. (2012) | n/r | n/r | 3.32 | n/r | n/r |
| | Linquist et al. (2015) | n/r | 0.90–1.00 | n/r | n/r | n/r |
| | Hatiye et al. (2015) | 0.30 | n/r | n/r | n/r | 0.10 of saturation |
| Flooded, dry seeding | Alberto et al. (2014) | 0.70 | 0.90 | 4.2 | n/r | n/r |
| Intermittent irrigation | Agrawal et al. (2004) | 0.45 | n/r | n/r | n/r | 0.20 of saturation |
| | Arif et al. (2012) | n/r | 1.36 | n/r | n/r | n/r |
| | Hatiye et al. (2015) | 0.30 | n/r | n/r | n/r | 0.10 of saturation |
| Aerobic, sprinkling | Spanu et al. (2009) | 0.40 | 0.83 | n/r | n/r | n/r |
| | Moratiel and Martínez-Cob (2013) | n/r | 0.70 | n/r | 0.95 | n/r |
| Aerobic, basin irrigation | Choudhury et al. (2013) | n/r | n/r | 5.2 | n/r | n/r |
| Aerobic, furrow irrigation | Choudhury et al. (2013) | n/r | n/r | 4.0 | n/r | n/r |

$Z_{r\,max}$ – maximum root depth; $h_{max}$ – maximum crop height; $LAI_{max}$ – maximum leaf area index; $f_{c\,max}$ – maximum fraction of ground cover; p – soil water depletion fraction for no stress; n/r – not reported.

the particular cotton variety and with harvesting opportunity decisions. Reported literature data on linseed for oil allowed a refinement of the $K_{c\,mid}$ and $K_{cb\,mid}$ values for the same crop for fiber, denoted as flax in Table 12. Thus, $K_{c\,mid}$ and $K_{cb\,mid}$ for flax were decreased by 0.05 but $K_{c\,end}$ and $K_{cb\,end}$ remained unchanged. Relative to sisal, no data were available from literature. Considering the characteristics of this crop, an indicative $K_c$ and $K_{cb}$ value was assumed, corresponding to the average value of the previous FAO56 tabulated values.

Selected bibliography provided information on $K_c$ and $K_{cb}$ for three oil crops not handled in FAO56: camelina, linseed, and mustard. Literature data for these crops have the appropriate accuracy requirements for defining the standard $K_{c\,mid}$ and $K_{c\,end}$ for all three crops. Also, the new oil crops $K_c$ and $K_{cb}$ values were in good agreement with those of the other oil crops reviewed (Table 12). Formerly, FAO56 tabulated values for canola, safflower and sunflower consisted of pairs of $K_{c\,mid}$ values with the lower one for deficit irrigation, which does not correspond to standard $K_c$ conditions. Literature data, however, allowed a selection of single $K_{c\,mid}$ values for these crops, presumably cultivated under nearly pristine conditions, particularly without water stress or low density. Those single values are slightly smaller (by 0.05) than the former tabulated upper value in the case of canola and safflower. Differently, for sunflower, the various available studies confirmed the FAO56 $K_{c\,mid}$ value of 1.15 and the $K_{cb\,mid}$ value of 1.10. The $K_{c\,mid}$ value for castorbean and sesame were decreased by 0.05 considering the reported data available. The $K_{c\,end}$ values for the oil crops that were in FAO56 were kept equal to the FAO56 tabulated values since the reported information did not provide data that could justify changes. An exception is sunflower, in which the $K_{c\,end}$ value was decreased by 0.05.

Regarding oil crops basal crop coefficients, consolidation options were similar to those for single $K_c$. The pairs of tabulated $K_{cb\,mid}$ values for canola, safflower and sunflower were replaced by unique $K_{cb\,mid}$ values close to the former upper value, i.e., the value representing pristine conditions. The $K_{cb\,mid}$ value for castorbean and sesame were also decreased by 0.05. The $K_{cb\,mid}$ and $K_{c\,end}$ values for the newly considered linseed and mustard were obtained from the corresponding $K_c$ values following the related FAO56 guidelines referred in Section 2 above, i.e. by subtracting 0.05 to the $K_{c\,mid}$ since both crops covered the ground well, reducing $E_s$; and also by subtracting $K_{c\,end}$ by 0.05 to define $K_{cb\,end}$ because, commonly, there is no rain or irrigation towards the end of the crop season. Reported $K_{cb}$ data for camelina led to $K_{cb}$ values that would be close to those using the referred FAO56 guidelines based on $K_c$.

Results for consolidated $K_c$ and $K_{cb}$ values for sugar crops are presented in Table 12. The set of $K_{c\,mid\,(std)}$ and $K_{c\,end\,(std)}$resulting from the bibliography are close to the FAO56 tabulated values. However, the analysis led to decrease the standard $K_{c\,mid}$ by 0.10 of both sugarbeet and sugar cane and, inversely, increase by 0.05 the standard $K_{c\,end}$ of both crops. Observed basal coefficients are lacking for both crops, thus $K_{cb\,mid}$ and $K_{cb\,end}$ were also changed similarly to the corresponding $K_c$ values. The reported data indicated that $K_c$ values may be different in the planting and ratoon years, smaller in the latter, but information was not sufficient to tabulate different values for planting and ratoon years.

It may be remarked that mid-season $K_c$ and $K_{cb}$ values for many of the above crops were often decreased relative to the previously tabulated ones. This fact reflects the increasing use of drip irrigation, thus producing water savings in crop water use that induces smaller mid-season $K_c$ and $K_{cb}$ values compared to other irrigation systems.

### 4.3. *Cereals*

The updated $K_c$ and $K_{cb}$ for the mid- and end-season values for cereals resulting from the previous review analysis are presented in Table 13 together with the range of the observed values adjusted to the standard climate and the FAO56 tabulated $K_c$ and $K_{cb}$. Overall, only small changes relative to the tabulated FAO56 were required for updating the standard $K_c$ and $K_{cb}$ from those formerly tabulated. Data for amaranthus grain, quinoa and teff were reported and therefore are newly tabulated, based on the available information.

The most reported $K_c$ and $K_{cb}$ data are for the most highly cultivated crops, wheat and maize. As previously defined, distinction is made when harvesting is made with low or high moisture grain. While the consolidated wheat and maize $K_c$ and $K_{cb}$ values for mid-season were the same as in FAO56, some of the $K_c$ and $K_{cb}$ for the end-season were updated, depending on grain moisture. It is important to note that various papers reporting high $K_{c\,mid}$ or $K_{cb\,mid}$ for wheat and maize did not refer to the possible influence of advection on their results. Thus, consolidated values for $K_{c\,mid}$ or $K_{cb\,mid}$ of these cereal crops were not increased relative to FAO56 because regional advection is likely to have occurred in the related dry and hot areas. A recent study on maize in Hetao, a hot and arid irrigated area of the upper Yellow River in northern China, demonstrated an important advection occurrence Wang et al. (2020).

**Table 11**
Updated standard $K_c$ and $K_{cb}$ for grain legumes.

| Crop | Observed, standard $K_c$ and $K_{cb}$ | | FAO56 tabulated $K_c$ and $K_{cb}$ | | Updated standard $K_c$ and $K_{cb}$ | |
|---|---|---|---|---|---|---|
| | $K_{c\,mid\,(std)}$ | $K_{c\,end\,(std)}$ | $K_{c\,mid}$ | $K_{c\,end}$ | $K_{c\,mid}$ | $K_{c\,end}$ |
| ***Single crop coefficient*** | | | | | | |
| Bean (*Phaseolus vulgaris*) | | | | | | |
| Green | n/r | n/r | 1.05 | 0.90 | **1.05** | **0.95** |
| Dry | 0.98–1.12 | 0.47–0.49 | 1.15 | 0.35 | **1.05** | **0.40** |
| Black and green gram (*Vigna mungo*) | | | | | | |
| Black gram (dry) | 1.22 | 0.39 | 1.05 | 0.35 | **1.15** | **0.35** |
| Green gram | 0.88–0.94 | 0.29–0.40 | 1.05 | 0.60 | **1.15** | **0.65** |
| Chickpea (garbanzo) (*Cicer arietinum*) | 0.95–1.03 | 0.29–0.47 | 1.00 | 0.35 | **1.10** | **0.35** |
| Cowpea (*Vigna unguiculata*) | | | | | | |
| Green | n/r | n/r | 1.05 | 0.60 | **1.10** | **0.60** |
| Dry | 1.11–1.23 | 0.49–0.55 | 1.05 | 0.35 | **1.10** | **0.45** |
| Fababean (*Vicia faba*) | | | | | | |
| Fresh | n/r | n/r | 1.15 | 1.10 | **1.10** | **1.05** |
| Dry | 1.03–1.16 | 0.54 | 1.15 | 0.30 | **1.10** | **0.40** |
| Groundnut (peanut) (*Arachis hypogaea*) | 0.88–1.18 | 0.61–0.63 | 1.15 | 0.60 | **1.10** | **0.60** |
| Lentil (*Lens culinaris*) | n/r | n/r | 1.10 | 0.30 | **1.05** | **0.30** |
| Pea (*Pisum sativum*) | | | | | | |
| Fresh | 1.21 | 1.16 | 1.15 | 1.10 | **1.15** | **1.10** |
| Dry | n/r | n/r | 1.15 | 0.30 | **1.10** | **0.30** |
| Soybean (*Glycine max*) | 0.99–1.16 | 0.18–0.45 | 1.15 | 0.50 | **1.15** | **0.35** |
| ***Basal crop coefficient*** | $K_{cb\,mid\,(std)}$ | $K_{cb\,end\,(std)}$ | $K_{cb\,mid}$ | $K_{cb\,end}$ | $K_{cb\,mid}$ | $K_{cb\,end}$ |
| Bean (*Phaseolus vulgaris*) | | | | | | |
| Green | n/r | n/r | 1.00 | 0.80 | **1.00** | **0.85** |
| Dry | n/r | n/r | 1.10 | 0.25 | **1.10** | **0.30** |
| Black and green gram (*Vigna mungo*) | | | | | | |
| Black gram (dry) | 1.14 | 0.33 | 1.00 | 0.25 | **1.10** | **0.30** |
| Green gram | n/r | n/r | 1.00 | 0.55 | **1.10** | **0.55** |
| Chickpea (*Cicer arietinum*) | 0.92 | 0.25 | 0.95 | 0.25 | **1.05** | **0.25** |
| Cowpea (*Vigna unguiculata*) | | | | | | |
| Green | n/r | n/r | 1.00 | 0.55 | **1.05** | **0.50** |
| Dry | n/r | n/r | 1.00 | 0.25 | **1.05** | **0.35** |
| Fababean (*Vicia faba*) | | | | | | |
| Fresh | n/r | n/r | 1.10 | 1.05 | **1.05** | **0.95** |
| Dry | n/r | n/r | 1.10 | 0.20 | **1.05** | **0.30** |
| Groundnut (peanut) (*Arachis hypogaea*) | n/r | n/r | 1.10 | 0.50 | **1.05** | **0.50** |
| Lentil (*Lens culinaris*) | n/r | n/r | 1.05 | 0.20 | **1.00** | **0.20** |
| Pea (*Pisum sativum*) | | | | | | |
| Fresh | 1.16 | 1.13 | 1.10 | 1.05 | **1.10** | **1.05** |
| Dry | n/r | n/r | 1.10 | 0.20 | **1.05** | **0.25** |
| Soybean (*Glycine max*) | 1.05–1.13 | 0.15–0.35 | 1.10 | 0.30 | **1.10** | **0.25** |

Silage maize has a lower $K_{c\,mid}$ than grain maize. The same occurs for silage sorghum relative to grain sorghum. Differently, $K_{c\,end}$ values for silage maize and silage sorghum were set closer to the $K_{c\,mid}$ values. The same was set for sweet sorghum. $K_{cb}$ values were in agreement or, when not available, were computed using the guidelines expressed in FAO56 and presented in Section 2.

Reported data for barley led to decrease the values of $K_{c\,mid}$ and $K_{cb\,mid}$ by 0.05 relative to FAO56. For this reason, these values are now slightly smaller than for wheat. Similarly, $K_{c\,mid}$ and $K_{cb\,mid}$ were also decreased for oats relative to FAO56. However, $K_{c\,end}$ and $K_{cb\,end}$ of both barley and oats were kept equal to those values for wheat harvested with low grain moisture. The $K_c$ values for rye were added on the basis of non-cited material. Data were not available for pearl millet resulting that $K_c$ and $K_{cb}$ were not changed from FAO56.

### 4.4. Rice

The updated single and basal crop coefficients for the various types of rice irrigation methods are presented in Table 14, respectively, and the values can be compared with the $K_c$ and $K_{cb}$ values (shown in round brackets in Table 14) that were tabulated for flooded rice paddies in FAO56 (Allen et al., 1998). Table 14 also includes the range of values observed in the cited field studies after adjustment to the standard climate ($RH_{min}$ = 45% and $u_2$ = 2 m $s^{-1}$). As seen in Table 14, the updated $K_c$ values correspond well to those observed when the related papers were not limited in number. The updated $K_c$ mid-season values for flooded and intermittent irrigation methods are the same as for flooded paddies in FAO56 but were decreased by 0.10 for aerobic and rainfed conditions. The $K_{c\,ini}$, except in permanent flooding, were decreased depending on irrigation method relative to the FAO56 initial

**Table 12**
Updated standard $K_c$ and $K_{cb}$ for fiber crops, oil crops and sugar crops.

| Crop | Observed, standard $K_c$ and $K_{cb}$ | | FAO56 tabulated $K_c$ and $K_{cb}$ | | Updated standard $K_c$ and $K_{cb}$ | |
|---|---|---|---|---|---|---|
| | $K_{c\,mid\,(std)}$ | $K_{c\,end\,(std)}$ | $K_{c\,mid}$ | $K_{c\,end}$ | $K_{c\,mid}$ | $K_{c\,end}$ |
| ***Single crop coefficient*** | | | | | | |
| **Fiber crops** | | | | | | |
| Cotton (*Gossypium hirsutum*) | 0.88–1.22 | 0.20–0.75 | 1.15–1.20 | 0.70–0.50 | **1.10** | **0.50** |
| Flax (Linseed) (*Linum usitatissimum*) | n/r | n/r | 1.10 | 0.25 | **1.05** | **0.25** |
| Sisal (*Agave sisalana*) | n/r | n/r | 0.40–0.70 | 0.40–0.70 | **0.55** | **0.55** |
| **Oil crops** | | | | | | |
| Camelina (*Camelina sativa*) | 1.12 | 0.47 | n/r | n/r | **1.10** | **0.45** |
| Canola (*Brassica napus*) | 1.15 | 0.35 | 1.00–1.15 | 0.35 | **1.10** | **0.35** |
| Castorbean (*Ricinus communis*) | 1.09 | 0.82 | 1.15 | 0.55 | **1.10** | **0.55** |
| Linseed (Flax) (*Linum usitatissimum*) | 0.95–0.97 | 0.20–0.26 | n/r | n/r | **0.95** | **0.25** |
| Mustard (*Brassica juncea*) | 1.00–1.17 | 0.35–0.45 | n/r | n/r | **1.15** | **0.40** |
| Safflower (*Carthamus tinctorius*) | 1.04–1.22 | 0.22–0.30 | 1.00–1.15 | 0.25 | **1.10** | **0.25** |
| Sesame (*Sesamum indicum*) | 1.00 | n/r | 1.10 | 0.25 | **1.05** | **0.25** |
| Sunflower (*Helianthus annuus*) | 1.07–1.20 | 0.10–0.36 | 1.00–1.15 | 0.35 | **1.20** | **0.30** |
| **Sugar crops** | | | | | | |
| Sugar beet (*Beta vulgaris*) | 0.96–1.11 | 0.82–0.83 | 1.20 | 0.70 | **1.05** | **0.75** |
| Sugar cane (*Saccharum officinarum*) | 1.03–1.23 | 0.56–0.83 | 1.25 | 0.75 | **1.20** | **0.80** |
| **Basal crop coefficient** | $K_{cb\,mid\,(std)}$ | $K_{cb\,end\,(std)}$ | $K_{cb\,mid}$ | $K_{cb\,end}$ | $K_{cb\,mid}$ | $K_{cb\,end}$ |
| **Fiber crops** | | | | | | |
| Cotton (*Gossypium hirsutum*) | 1.02–1.21 | 0.15–0.56 | 1.10–1.15 | 0.50–0.40 | **1.05** | **0.40** |
| Flax (Linseed) (*Linum usitatissimum*) | n/r | n/r | 1.05 | 0.20 | **1.00** | **0.20** |
| Sisal (*Agave sisalana*) | n/r | n/r | 0.40–0.70 | 0.40–0.70 | **0.50** | **0.50** |
| **Oil crops** | | | | | | |
| Camelina (*Camelina sativa*) | 1.09–1.10 | 0.37–0.47 | n/r | n/r | **1.05** | **0.40** |
| Canola (*Brassica napus*) | 0.94–1.11 | 0.20 | 0.95–1.10 | 0.25 | **1.05** | **0.25** |
| Castorbean (*Ricinus communis*) | n/r | n/r | 1.10 | 0.45 | **1.05** | **0.45** |
| Linseed (Flax) (*Linum usitatissimum*) | 0.92 | 0.18 | n/r | n/r | **0.90** | **0.20** |
| Mustard (*Brassica juncea*) | n/r | n/r | n/r | n/r | **1.10** | **0.35** |
| Safflower (*Carthamus tinctorius*) | n/r | n/r | 0.95–1.10 | 0.20 | **1.05** | **0.20** |
| Sesame (*Sesamum indicum*) | n/r | n/r | 1.05 | 0.20 | **1.00** | **0.20** |
| Sunflower (*Helianthus annuus*) | 1.10–1.16 | 0.20–0.25 | 0.95–1.10 | 0.25 | **1.15** | **0.25** |
| **Sugar crops** | | | | | | |
| Sugar beet (*Beta vulgaris*) | 1.11 | n/r | 1.15 | 0.50 | **1.00** | **0.65** |
| Sugar cane (*Saccharum officinarum*) | n/r | n/r | 1.20 | 0.70 | **1.15** | **0.70** |

value; however, $K_{c\,end}$ are somewhat higher than the highest end value of 0.90 in FAO56, except for rainfed rice.

Related literature observations were lacking for all rice $K_{cb}$ values. Thus, our updated $K_{cb\,mid}$ values (Table 14), were defined by assuming $K_{cb} = K_c - 0.05$ as was done in the FAO56 $K_{cb}$ table. While the FAO56 table decreased $K_{cb\,end}$ by 0.15–0.20 from $K_{c\,end}$, updated values were decreased 0.10–0.15 below the $K_{c\,end}$, varying with irrigation method. Very differently, because the FAO56 tabulated value for $K_{cb\,ini}$ was exclusively dedicated to flooded paddies, it was defined in such a way that the paddy water evaporation was not considered distinctively separate from the plant transpiration, thus FAO56 tabulated value was $K_{cb\,ini} = 1.00$. However, at present, various and different irrigation methods are considered, namely dry seeding, intermittent irrigation, aerobic rice, and rainfed paddies. These approaches correspond to different amounts of water evaporation, thus to different $K_e$ values. Users of $K_{cb}$ having an initial value of 0.15 are therefore advised to consider $K_e$ values that represent the paddy water evaporation and soil water evaporation. For instance, the FAO56 tabulated value for flooded rice implies that $K_{cb\,ini}$ is 0.15 and $K_e$ would be equal to 0.90, thus resulting $K_{c\,ini} = 1.05$. A smaller $K_e$ should be considered for other irrigation methods depending on the amount and frequency of irrigation and rainfall events, thus resulting in a smaller $K_{c\,ini}$ for dry seeding, intermittent irrigation, aerobic rice and rainfed paddies. A rough estimation is that when wettings are frequent $K_e$ would be about 0.90, resulting in $K_{c\,ini} = 1.05$, and when wettings are less frequent $K_e$ would vary around 0.60–0.70, which translates to $K_{c\,ini}$ values ranging between 0.75–0.85.

Overall, despite the limitations due to the diversity of conditions reported in literature, present authors are convinced that the proposed crop coefficients can be very useful for further developments in the domain of rice evapotranspiration and water management. Unfortunately, the absolute lack of data impeded any chance to characterize floating rice ET.

**Table 13**
Updated standard $K_c$ and $K_{cb}$ for cereals.

| Crop | Observed, standard $K_c$ and $K_{cb}$ | | FAO56 tabulated $K_c$ and $K_{cb}$ | | Updated standard $K_c$ and $K_{cb}$ | |
|---|---|---|---|---|---|---|
| | $K_{c\,mid\,(std)}$ | $K_{c\,end\,(std)}$ | $K_{c\,mid}$ | $K_{c\,end}$ | $K_{c\,mid}$ | $K_{c\,end}$ |
| ***Single crop coefficient*** | | | | | | |
| Amaranth grain (*Amaranthus* sp.) | 1.15 | 0.20 | n/r | n/r | **1.10** | **0.25** |
| Barley (*Hordeum vulgare*) | 0.98–1.07 | 0.20–0.30 | 1.15 | 0.25 | **1.05** | **0.25** |
| Oats (*Avena sativa*) | n/r | n/r | 1.15 | 0.25 | **1.05** | **0.25** |
| Pearl Millet (*Pennisetum glaucum*) | n/r | n/r | 1.00 | 0.30 | **1.10** | **0.35** |
| Quinoa (*Chenopodium quinoa*) | 1.01–1.15 | 0.40–0.67 | n/r | n/r | **1.10** | **0.50** |
| Rye (*Secale cereale*) | n/r | n/r | n/r | n/r | **1.00** | **0.35** |
| Teff (*Eragrotis tef*) | 1.09 | 0.25 | n/r | n/r | **1.05** | **0.25** |
| Wheat, common (*Triticum aestivum*) | | | | | | |
| Winter, low grain moisture | 1.02–1.28 | 0.10–0.42 | 1.15 | 0.25 | **1.15** | **0.25** |
| Winter, high grain moisture | 1.06–1.26 | 0.45–0.64 | 1.15 | 0.40 | **1.15** | **0.55** |
| Spring, low grain moisture | 1.11–1.17 | 0.20–0.32 | 1.15 | 0.25 | **1.15** | **0.25** |
| Spring, high grain moisture | n/r | n/r | 1.15 | 0.40 | **1.15** | **0.45** |
| Wheat, durum (*Triticum durum*) | | | | | | |
| Winter, low grain moisture | 1.03 | 0.25 | n/r | n/r | **1.05** | **0.25** |
| Winter, high grain moisture | n/r | n/r | n/r | n/r | **1.05** | **0.55** |
| Maize (*Zea mays*) | | | | | | |
| Low grain moisture | 1.04–1.28 | 0.15–0.56 | 1.20 | 0.35 | **1.20** | **0.30** |
| High grain moisture | 1.03–1.30 | 0.55–0.80 | 1.20 | 0.60 | **1.20** | **0.65** |
| Silage | 1.01–1.21 | 0.54–1.01 | n/r | n/r | **1.20** | **0.95** |
| Sweet | n/r | n/r | 1.15 | 1.05 | **1.15** | **1.05** |
| Sorghum (*Sorghum bicolor*) | | | | | | |
| Grain | 0.91–1.25 | 0.40–0.76 | 1.00–1.10 | 0.55 | **1.10** | **0.45** |
| Silage | 0.90 | 0.90 | n/r | n/r | **1.10** | **0.90** |
| Sweet | 0.90–1.10 | 0.55 | 1.20 | 1.05 | **1.15** | **0.95** |
| **Basal crop coefficient** | $K_{cb\,mid\,(std)}$ | $K_{cb\,end\,(std)}$ | $K_{cb\,mid}$ | $K_{cb\,end}$ | $K_{cb\,mid}$ | $K_{cb\,end}$ |
| Amaranth grain (*Amaranthus* sp.) | 1.05 | 0.13 | n/r | n/r | **1.05** | **0.20** |
| Barley (*Hordeum vulgare*) | 1.00–1.04 | 0.10 | 1.10 | 0.15 | **1.00** | **0.20** |
| Oats (*Avena sativa*) | n/r | n/r | 1.10 | 0.15 | **1.00** | **0.20** |
| Pearl Millet (*Pennisetum glaucum*) | n/r | n/r | 0.95 | 0.20 | **1.05** | **0.25** |
| Quinoa (*Chenopodium quinoa*) | 1.00 | 0.20 | n/r | n/r | **1.05** | **0.45** |
| Rye (*Secale cereale*) | n/r | n/r | n/r | n/r | **0.95** | **0.30** |
| Teff (*Eragrostis tef*) | 0.90 | n/r | n/r | n/r | **1.00** | **0.20** |
| Wheat, common (*Triticum aestivum*) | | | | | | |
| Winter, low grain moisture | 0.99–1.12 | 0.25–0.30 | 1.10 | 0.15 | **1.10** | **0.20** |
| Winter, high grain moisture | 1.14 | 0.30–0.59 | 1.10 | 0.30 | **1.10** | **0.45** |
| Spring, low grain moisture | 1.05–1.15 | 0.15–0.25 | 1.10 | 0.15 | **1.10** | **0.20** |
| Spring, high grain moisture | 1.12 | 0.35 | 1.10 | 0.30 | **1.10** | **0.40** |
| Wheat, durum (*Triticum durum*) | | | | | | |
| Winter, low grain moisture | 0.91 | 0.23 | n/r | n/r | **1.00** | **0.20** |
| Winter, high grain moisture | n/r | n/r | n/r | n/r | **1.00** | **0.45** |
| Maize (*Zea mays*) | | | | | | |
| Low grain moisture | 1.02–1.17 | 0.20–0.30 | 1.15 | 0.15 | **1.15** | **0.25** |
| High grain moisture | 0.93–1.23 | 0.45–0.77 | 1.15 | 0.50 | **1.15** | **0.60** |
| Silage | 1.09–1.18 | 0.54–0.87 | n/r | n/r | **1.15** | **0.85** |
| Sweet | n/r | n/r | 1.10 | 1.00 | **1.10** | **1.05** |
| Sorghum (*Sorghum bicolor*) | | | | | | |
| Grain | 0.87–0.99 | 0.39–0.55 | 0.95–1.05 | 0.35 | **1.05** | **0.35** |
| Silage | n/r | n/r | n/r | n/r | **1.05** | **0.85** |
| Sweet | 0.90–1.08 | 0.35 | 1.15 | 1.00 | **1.10** | **0.90** |

**Table 14**
Updated standard $K_c$ and $K_{cb}$ values for rice (*Oryza sativa* L.) compared with reported observed data adjusted to the standard sub-humid climate and the FAO56 tabulated values for flooded paddies *(italics, in brackets)*.

| **Irrigation method** | **Observed $K_c$ adjusted to climate** | | | **Updated crop coefficients** | | |
|---|---|---|---|---|---|---|
| **Single crop coefficient** | $K_{c\,ini\,(std)}$ | $K_{c\,mid\,(std)}$ | $K_{c\,end\,(std)}$ | $K_{cini}$ | $K_{c\,mid}$ | $K_{c\,end}$ |
| Flooded | 0.97–1.16 | 1.01–1.29 | 0.73–1.14 | **1.05**<br>*(1.05)* | **1.20**<br>*(1.20)* | **1.05**<br>***(0.90–0.60)*** |
| Flooded, dry seeding | 0.67–1.10 | 1.00–1.26 | 0.96–1.19 | **0.85** | **1.20** | **1.05** |
| Flooded, anticipated cut-off | n/r | n/r | n/r | **1.05** | **1.20** | **0.80** |
| Intermittent | 0.70–1.05 | 1.21–1.32 | 0.73–1.23 | **0.95** | **1.20** | **1.00** |
| Aerobic, sprinkler irrigation | 0.91–0.92 | 1.03–1.07 | 0.96–1.01 | **0.90** | **1.10** | **0.95** |
| Aerobic, surface irrigation | 0.60–0.95 | 1.04–1.17 | 0.51–0.98 | **0.90** | **1.10** | **0.95** |
| Rainfed | 0.75 | 1.23 | 0.82 | **0.80** | **1.10** | **0.80** |
| ***Basal crop coefficient*** | | | | $K_{cb\,ini}$ | $K_{cb\,mid}$ | $K_{cb\,end}$ |
| Flooded | n/r | n/r | n/r | **0.15**<br>*(1.00)* | **1.15**<br>*(1.15)* | **0.90**<br>***(0.70–0.45)*** |
| Flooded, dry seeding | 0.07 | 0.96 | 0.72 | **0.15** | **1.15** | **0.90** |
| Flooded, dry late season | n/r | n/r | n/r | **0.15** | **1.15** | **0.70** |
| Intermittent | n/r | n/r | n/r | **0.15** | **1.15** | **0.85** |
| Aerobic, sprinkler irrigation | 0.20 | 1.21 | 0.58 | **0.15** | **1.05** | **0.85** |
| Aerobic, surface irrigation | n/r | n/r | n/r | **0.15** | **1.05** | **0.85** |
| Rainfed | n/r | n/r | n/r | **0.15** | **1.05** | **0.70** |

## 5. Updated ancillary data

Values for ancillary crop data reported in the quoted studies were tabulated in Tables 2, 4, 6, 8, and 10 for grain legumes, fiber, oil and sugar crops, small grain cereals, maize and sorghum, and rice, respectively. These tabulated values were then consolidated by crop and combined in Table 15 for all the crops except rice, whose data are provided in Table 16. For each crop, values are presented for the range of observed maximum root depths, $Z_{r\,max}$, crop heights, $h_{max}$, ground cover fractions, $f_{c\,max}$, and mid-season p fraction of soil water depletion for no stress. For rice (Table 16), the data are separated for three conditions: flooded paddies, intermittent irrigation and aerobic rice. These ranges of reported values were compared with the FAO56 tabulated $Z_{r\,max}$, $h_{max}$, and p fractions, therefore, resulting in updated values for these three ancillary parameters, which could be quite useful in characterizing crop conditions when performing a SWB for irrigation planning and management when related observations are not available.

In general, observed root depths were similar to the FAO56 tabulated ones. Updated $Z_{r\,max}$ values are given as a range, with the smaller value more appropriate for heavy soils and more frequent irrigation, and larger values for light soils and/or larger intervals between irrigations. Differently, updated maximum crop heights are mostly given with a single value; however, crop varieties may be very distinct in different parts of the world and, for several crops, a range of $h_{max}$ values is given. The indicative values provided for $Z_{r\,max}$ and $h_{max}$ should be used with care because they vary much with the crop variety, environmental conditions and crop management. Single values are given to the p fractions, which refer to the crop ET of 5 mm $d^{-1}$ and should be modified following the guidelines in Table 22 of FAO56. Values in Table 15 are indicative and should be compared with measured observations whenever possible. Updated values for rice are also based upon those proposed in FAO56 and those reported in the current bibliography. Notably, updated root depths are largest for aerobic rice, however, crop height is reduced for aerobic rice. Also, considerably higher allowable soil water depletion (higher p value) is associated with the aerobic condition. However, users are called upon to make the necessary parameter modifications whenever necessary.

## 6. Conclusions and recommendations

The first conclusion drawn from the present study is that the performed crop coefficient review essentially confirms the tabulated $K_c$ and $K_{cb}$ values in FAO56 (Allen et al., 1998), although the updates we propose often show small differences relative to FAO56. Secondly, the review results added new $K_c$ and $K_{cb}$ data for several crops that were unavailable in the literature prior to FAO56 publication. This was the case for three important oil crops – camelina, linseed, and mustard – for two increasingly popular pseudo cereals – amaranth and quinoa – and for an emerging grain cereal, teff. Clearly, with so many new crops emerging in recent years reviews like the present one will be needed soon to help extend $K_c$-$ET_o$ application to these crops.

Greater differences between the FAO56 rice $K_c$ values and those presently provided occur because our updated values, unlike FAO56, include various water management alternatives to continuous flooding that are generally aimed at water saving, e.g., flooded paddies with dry seeding, flooded paddies with anticipated cut-off, intermittent irrigation of paddies, irrigation of aerobic rice by flooding, furrows or sprinkling, as well as rainfed rice in monsoon areas. No data were available for floating rice.

Relative to maize and sorghum crop coefficients, a distinction has now been made between production for grain, silage, and energy uses. Relative to maize and wheat for grain, $K_c$ distinctions are now made to characterize the late season water use differences in cases when harvest is made with high or low moisture, thus with short or long duration of the late season and the consequent larger or smaller $K_{c\,end}$ value. Similarly, for gram and cowpea legumes, the distinction is also made relative to green and dry harvests because the latter have a longer late season and a $K_{c\,end}$ smaller than green.

The organization of the crop coefficient and ancillary data in the present study expands the knowledge base beyond that provided in FAO56. On the one hand, in addition to the consolidated $K_c$ and $K_{cb}$ values, tables are also presented to show the standard values for the mid-season and the end-season obtained from the reviewed research after conversion to the standard sub-humid climate with $RH_{min}$ = 45% and $u_2$ = 2 m $s^{-1}$. This information allows readers to have a better perception of the different environmental conditions from which data used to consolidate $K_c$ and $K_{cb}$ values were obtained. On the other hand, ancillary data available from the cited literature are also tabulated in complement to the observed standardized $K_c$ values, thus also allowing readers to have some, however limited, insight of the experiments. The primary ancillary data refer to crop rooting depths, crop heights, and the soil water depletion fraction for no stress (p). For

**Table 15**

Updated indicative ancillary crop parameters for grain legumes, fiber, oil and sugar crops and cereals.

| Crop | Observed | | | | FAO56 tabulated | | | Updated standard | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $Z_{r\,max}$ (m) | $h_{max}$ (m) | $f_{c\,max}$ | p | $Z_{r\,max}$ (m) | $h_{max}$ (m) | p | $Z_{r\,max}$[b] (m) | $h_{max}$ (m) | p |
| **Grain legumes** | | | | | | | | | | |
| Bean (*P. vulgaris*) | 0.60–0.90 | 0.66 | n/r | 0.30 | 0.60–0.90 | 0.40 | 0.45 | 0.50–0.90 | 0.50–0.70 | 0.45 |
| Black & green gram (*V. mungo*) | | | | | | | | | | |
| Black gram (dry) | 0.60 | 0.40 | 0.94 | 0.50 | 0.60–1.00 | 0.40 | 0.45 | 0.60–1.00 | 0.50–0.70 | 0.45 |
| Green gram | 0.40 | n/r | n/r | n/r | n/r | n/r | n/r | 0.40–1.00 | 0.60–0.90 | 0.45 |
| Chickpea (*C. arietinum*) | 0.80–0.90 | 0.41 | 0.80–0.97 | n/r | 0.60–1.00 | 0.40–0.80 | 0.45 | 0.70–1.00 | 0.50–0.70 | 0.45 |
| Cowpea (*V. unguiculata*) | 1.50 | n/r | 0.80 | 0.20 | 0.600–1.0 | 0.40 | 0.45 | 0.60–1.30 | 0.60–0.80 | 0.45 |
| Fababean (*V. faba*) | n/r | n/r | 0.85 | n/r | 0.5–0.7 | 0.80 | 0.45 | 0.50–0.70 | 0.80 | 0.45 |
| Groundnut (*A. hypogaea*) | 0.60–1.00 | | 0.90 | 0.55 | 0.50–1.0 | 0.40 | 0.50 | 0.50–1.00 | 0.50 | 0.50 |
| Lentil (*L. culinaris*) | n/r | n/r | n/r | n/r | 0.60–0.8 | 0.50 | 0.50 | 0.60–0.80 | 0.50 | 0.50 |
| Pea (*P. sativum*) | | | | | | | | | | |
| Fresh | 0.80 | 0.50 | 0.98 | 0.40 | 0.60–1.0 | 0.50 | 0.35 | 0.60–1.00 | 0.60 | 0.35 |
| Dry | n/r | n/r | n/r | n/r | 0.60–1.0 | 0.50 | 0.40 | 0.60–1.00 | 0.80 | 0.45 |
| Soybean (*G. max*) | 1.00–1.40 | 0.75–1.05 | 0.98–1.00 | 0.50 | 0.60–1.3 | 0.50–1.00 | 0.50 | 0.60–1.40 | 0.80 | 0.50 |
| **Fiber crops** | | | | | | | | | | |
| Cotton (*G. hirsutum*) | 1.10–1.70 | 0.86–1.86 | 0.81–0.90 | 0.55–0.70 | 1.00–1.70 | 1.20–1.50 | 0.65 | 1.00–1.70 | 1.20 | 0.60 |
| Flax (*L. usitatissimum*) | n/r | n/r | n/r | n/r | 1.00–1.50 | 1.20 | 0.50 | 1.00–1.50 | 1.00 | 0.50 |
| Sisal (*A. sisalana*) | n/r | n/r | n/r | n/r | 0.50–1.00 | 1.50 | 0.80 | 0.50–1.00 | 1.50 | 0.80 |
| **Oil crops** | | | | | | | | | | |
| Camelina (*C. sativa*) | 1.50–1.70 | 0.65–0.83 | 0.96–0.97 | 0.60–0.65 | n/r | n/r | n/r | 1.00–1.50 | 0.80 | 0.60 |
| Canola (*B. napus*) | 0.40–1.20 | 1.00 | 0.80–0.97 | 0.45 | 1.00–1.50 | 0.60 | 0.60 | 0.80–1.30 | 1.00–1.50 | 0.50 |
| Castorbean (*R. communis*) | 0.60 | n/r | n/r | n/r | 1.00–1.50 | 0.30 | 0.60 | 0.80–1.30 | 1.00–1.50 | 0.60 |
| Linseed (*L. usitatissimum*) | 0.67 | n/r | n/r | n/r | n/r | n/r | n/r | 1.00–1.50 | 0.90 | 0.60 |
| Mustard (*B. juncea*) | 0.40–1.17 | 0.95–1.60 | n/r | 0.50 | n/r | n/r | n/r | 0.50–1.10 | 1.50–2.00 | 0.55 |
| Safflower (*C. tinctorius*) | 1.66 | 1.09 | n/r | n/r | 1.00–2.00 | 0.80 | 0.60 | 1.00–2.00 | 1.10 | 0.60 |
| Sesame (*S. indicum*) | n/r | n/r | n/r | n/r | 1.00–1.50 | 1.00 | 0.60 | 1.00–1.50 | 1.30 | 0.60 |
| Sunflower (*H. annuus*) | 0.90–2.00 | 1.20–2.00 | 0.85–0.88 | 0.25–0.80 | 0.80–1.50 | 2.00 | 0.45 | 0.80–2.00 | 2.00 | 0.45 |
| **Sugar crops** | | | | | | | | | | |
| Sugar beet (*B. vulgaris*) | 1.00 | 0.50 | 0.80 | 0.55 | 0.70–1.20 | 0.50 | 0.55 | 0.70–1.20 | 0.50 | 0.55 |
| Sugar cane (*S. officinarum*) | 0.60–0.75 | 2.54–4.00 | 0.97–0.98 | 0.65–0.80 | 1.20–2.00 | 3.00 | 0.65 | 1.00–1.50 | 3.00–4.00 | 0.60 |
| **Cereal crops** | | | | | | | | | | |
| Amaranth grain (*Amaranthus*) | 0.60 | 1.70 | 0.90 | n/r | n/r | n/r | n/r | 0.50–1.50 | 2.00 | 0.55 |
| Barley (*H. vulgare*) | 0.60–0.90 | 0.80 | 0.80–0.88 | 0.55–0.60 | 1.00–1.50 | 1.00 | 0.55 | 0.60–1.20 | 0.70–0.90 | 0.55 |
| Oats (*A. sativa*) | n/r | n/r | n/r | n/r | 1.00–1.50 | 1.00 | 0.55 | 1.00–1.50 | 0.80–1.10 | 0.55 |
| Pearl Millet (*P. glaucum*) | n/r | n/r | n/r | n/r | 1.00–2.00 | 1.50 | 0.55 | 1.00–2.00 | 2.00 | 0.55 |
| Quinoa (*C. quinoa*) | 0.55 | 1.00 | 0.60 | n/r | n/r | n/r | n/r | 0.60–1.20 | 1.00–1.20 | 0.55 |
| Rye (*S. cereale*) | n/r | n/r | n/r | n/r | n/r | n/r | n/r | 0.60–1.20 | 0.90 | 0.55 |
| Teff (*E. tef*) | 0.30–1.00 | n/r | 0.80 | n/r | n/r | n/r | n/r | 0.60–1.20 | 1.10 | 0.55 |
| Wheat, common (*T. aestivum*) | | | | | | | | | | |
| Winter | 0.55–1.50 | 0.60–1.12 | 0.80–0.98 | 0.50–0.70 | 1.50–1.80 | 1.00 | 0.55 | 1.00–1.50 | 0.70–1.10 | 0.55 |
| Spring | 1.00–1.30 | 0.68–1.30 | 0.87–0.97 | 0.45–0.80 | 1.00–1.50 | 1.00 | 0.55 | 1.00–1.50 | 0.70–1.10 | 0.55 |
| Wheat, durum (*T. durum*) | 0.55 | 1.05 | 0.94 | n/r | n/r | n/r | n/r | 1.00–1.50 | 0.70–1.10 | 0.55 |
| Maize (*Z. mays*) | | | | | | | | | | |
| Grain | 0.60–1.50 | 1.60–3.40 | 0.80–0.99 | 0.40–0.66 | 1.00–1.70 | 2.00 | 0.50 | 0.60–1.50 | 2.50–3.50 | 0.50 |
| Silage | 0.60–1.40 | 2.00–3.00 | 0.80–0.90 | 0.50–0.65 | n/r | n/r | n/r | 0.60–1.50 | 2.50–3.20 | 0.50 |
| Sweet | n/r | n/r | n/r | n/r | 0.80–1.20 | 1.50 | 0.50 | 0.60–1.50 | 1.50–2.50 | 0.50 |
| Sorghum (*S. bicolor*) | | | | | | | | | | |
| Grain | 1.00–1.40 | 1.48–1.89 | n/r | 0.55 | 1.00–2.00 | 1.00–2.00 | 0.55 | 1.00–1.50 | 1.50–2.00 | 0.55 |
| Silage | 1.40 | 3.00 | n/r | n/r | n/r | n/r | n/r | 1.00–1.50 | 2.00–3.00 | 0.55 |
| Sweet | 0.65–1.80 | 2.46–4.60 | 0.87–1.00 | 0.50 | 1.00–2.00 | 2.00–4.00 | 0.50 | 0.60–1.50 | 3.00–4.00 | 0.55 |

$Z_{r\,max}$ – maximum root depth; $h_{max}$ – maximum crop height; $LAI_{max}$ – maximum leaf area index; $f_{c\,max}$ – maximum fraction of ground cover; p – soil water depletion fraction for no stress at mid-season growth stage.

[a] All crop data depends on the crop variety and its adaptation to actual environmental conditions and cropping practices.

[b] Root depths depend on soil texture and structure. The first figure refers to heavy soils and the second to light soils.

**Table 16**

Updated indicative ancillary parameters of the rice crop (*Oryza sativa L.*) compared with reported observed values and, in brackets and italics, the tabulated FAO56 values.

| **Irrigation method** | **Observed** | | | | | **Updated standard** | | |
|---|---|---|---|---|---|---|---|---|
| | **$Z_{r\,max}$ (m)** | **$h_{max}$ (m)** | **$LAI_{max}$** | **$f_{c\,max}$** | **p** | **$Z_{r\,max}$ (m)** | **$h_{max}$ (m)** | **p** |
| Flooded paddies | 0.30-0.70<br>*(0.50–1.00)* | 0.55–1.36<br>*(1.00)* | 3.3–4.2<br>n/r | 0.95<br>n/r | 0.10 $\theta_{sat}$<br>*(0.20 $\theta_{sat}$)* | 0.50 | 1.00 | 0.20 $\theta_{sat}$ |
| Intermittent irrigation | 0.30–0.45 | 0.70–1.00 | n/r | n/r | 0.10–0.20 $\theta_{sat}$ | 0.70 | 1.00 | 0.20 $\theta_{sat}$ |
| Aerobic rice | 0.40 | 0.70–0.83 | 4.0–5.2 | 0.95 | n/r | 1.00 | 0.80 | 0.35 ASW |

$Z_{r\,max}$ — maximum root depth; $h_{max}$ — maximum crop height; $LAI_{max}$ — maximum leaf area index; $f_{c\,max}$ — maximum fraction of ground cover; p — soil water depletion fraction for no stress; $\Theta_{sat}$ — soil water at saturation; ASW — available soil water.

ease in transferring information to readers and users, all consolidated table data are compared with the ranges of values observed in the reviewed literature and with the FAO56 tabulated values. In addition, readers can easily identify in tables, the various locations around the world where the crop coefficient research was conducted.

All $K_c$ and $K_{cb}$ values reported were obtained using the FAO56 grass reference evapotranspiration definition and the consequent PM-$ET_o$ equation. Studies using any different $ET_o$ equation and computational procedure were not used because results could likely deviate from those of the PM-$ET_o$ equation. This constraint allowed the literature-reported $K_c$ and $K_{cb}$ values to be compared for the same or similar crop and, more importantly, to be compared with the FAO56 tabulated values. Since the field and computational research procedures of the related studies satisfied the basic requisites for accuracy in determining crop ET from field research, the reported $K_c$ could be appropriately computed and used to obtain the consolidated standard values tabulated herein. Therefore, the $K_c$ and $K_{cb}$ values proposed in the current study consist of the best set of standard values for every crop, relative to the mid-season and end-season that can be appropriately transferred and used worldwide. Transferring implies that the standard $K_c$ and $K_{cb}$ values need to be adjusted to the local climate (Eqs. (7a) through (8b)) and, when the crop is not cultivated in pristine conditions, their use also requires adoption of a stress coefficient (e.g., Eq. (3) and/or Eq. (5)).

The current review confirmed the appropriateness of clearly distinguishing actual from standard crop coefficients, with the latter referring to crops cultivated in pristine conditions, in which evapotranspiration may well be considered the potential ET of the considered crop under given environmental conditions. However, there is very abundant literature, not quoted, where this distinction is not made and where the $K_c$ correspond to cultivation practices far from pristine due to water stress, salinity stress, or stresses produced by various insufficiencies of agronomic nature, therefore making the observed to be not transferable $K_c$. The review, particularly for papers not selected, allowed perceiving that the distinction between actual and standard $K_c$, or between standard and potential $ET_c$, is not adopted by many researchers. This alone makes it inappropriate to transfer the research results from one location for use in another. In addition, the review has shown that differences between $K_c$ observed and those adjusted to the standard climate may be large, particularly when observations are performed in arid and windy conditions. For those reasons, it is very important that $K_c$ papers include appropriate description of methods used and of the climate during experimentation.

The review has shown that use of well calibrated and validated SWB simulation models, e.g., the SIMDualKc model, makes it possible to derive standard $K_c$ and $K_{cb}$ values despite the occurrence of water and salinity stress in the experiment. More research with focus on the use of these SWB models would be welcome since the current review found only relatively limited use of models. Such models, in addition, have been successfully applied for irrigation planning purposes and for real-time irrigation scheduling; and they can incorporate and utilize information based on remote sensing data. Remote sensing observations in real time could be especially useful in defining growth stage dates and lengths at various locations.

In the review, it was demonstrated that many $K_c$ researchers often fail to scrutinize the $K_c$ values obtained. The $K_c$ values much higher than reality could be due to either flaws in field measurements or to advection influences. For example, it was observed that exceptionally high $K_c$ values were often reported in papers where the description of methods employed was insufficient, which may relate to absence of scrutiny of research results. On the other hand, the higher reported $K_c$ may be a function of local advection impacts that were rarely considered or mentioned in research performed during the last two decades. Therefore, $K_c$ researchers are, again, strongly encouraged to include a careful and thorough inspection of results, including the time dynamics of ET, that should provide for a better analysis on the accuracy of ET estimation. Moreover, since energy balance methods, mainly EC and BREB, are becoming the choice of ET measurement in research, it is recommended that, in addition to the scrutiny of ET measured data, the dynamics of the energy balance be explored to verify when latent heat exceeds the available energy $R_n$-G, and/or when sensible heat becomes negative, so by identifying periods when ET was influenced by advection. It is then possible to correct measured ET and very high $K_c$ values can then be avoided.

It became apparent from the review that the definition and computational procedures relative to the PM-$ET_o$ equation were often not followed. Numerous $K_c$ studies included comparative assessments of ET equations, thus not focusing on the derivation of $K_c$ on the PM-ETo equation. Naturally, using an $ET_o$ different than the PM-$ET_o$ results in $K_c$ values non-comparable with the tabulated standard ones. While transferability of research results is hampered when a different $ET_o$ is used, using the FAO56 tabulated standard $K_c$ with a different ET equation leads to over- or under-estimation errors in using the $K_c$-$ET_o$ approach. It is therefore recommended that research using a different reference ET equation should consider the ratio of that $ET_o$ to the PM-$ET_o$ equation. Doing this provides a means to convert the $K_c$ data, making them comparable with tabulated standard values.

The best use of the $K_c$-$ET_o$ method implies using the segmented FAO $K_c$ curve, i.e., accepting the definition of the four crop growth stages and the definition of three $K_c$ values: $K_{c\,ini}$, $K_{c\,mid}$ and $K_{c\,end}$. Using time averaged monthly $K_c$ values or non-linear $K_c$ functions of time may be adequate for local use but these are very difficult to use predictively in different locations. The FAO $K_c$ curve is also difficult to use predictively due to inter-annual weather variability, inducing variable durations of the crop growth stages. However, this difficulty may be overcome when expressing growth durations in terms of cumulative growth degree days or with the use of remotely sensed vegetation indices. These methods consist of areas of research already underway for various field crops and that should be extended to other crops, as well.

Tabulated $K_c$ values in this article basically refer to surface, sprinkler and, less often, drip irrigation. The use of mulches could not be considered for tabulated $K_c$ but the effects of mulches were small because reported literature on $K_c$ values refer to the mid- and late-season, where the cover fraction is generally high. Nevertheless, the impacts of mulches and related water management issues described in Section 10 of FAO56 are considered valid and appropriate. However, various reported studies provide for comparing impacts of irrigation methods and mulches, which may add to what was provided in the referred FAO56 Section. Further research is required on the use of mulches but better focused, hopefully, on impacts on transpiration and soil evaporation with consideration of the fraction of soil wetted and the fraction of ground cover by the crop. Research should aim at obtaining high accuracy ET estimation and partitioning and should focus on few relevant variables in such a way that impacts on $K_c/K_{cb}$ values could be well recognized and related results transferred to other locations. At present, mulch effects are often studied with focus on a large number of variables.

Despite limitations of this review, it is recommended that users apply the updated $K_c$ and $K_{cb}$ values to determine the upper limits of crop evapotranspiration when planning irrigation programs and in real-time management of irrigation scheduling. Avoiding the use of high $K_c$, above 1. 25, which have no physical justification as analyzed, may lead to saving irrigation water. It is informative to note that maximum $K_c$ (and $K_{cb}$) values for major field crops, such as wheat, have not changed much from those given 22 years ago in FAO56. The data used for the tabulated FAO56 $K_c$ values obtained in studies over 40–50 years ago generally agree with current studies, which suggests little effect of climate change-induced differences on the ratio of $ET_C/ET_o$. However, when facing climate change challenges and related environmental consequences such as reduced water resources, it is imperative that methods like FAO56 be considered as a means to manage productive crops with efficient irrigation water use. To face global change, water conservation and saving are definitely necessary.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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