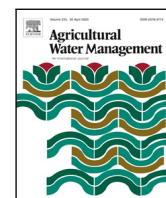




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Review

Standard single and basal crop coefficients for vegetable crops, an update of FAO56 crop water requirements approach

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ABSTRACT

Many research papers on crop water requirements of vegetables have been produced since the publication of the FAO56 guidelines in 1998. A review of this literature has shown that determination of crop evapotranspiration (ET_c) using the K_c - ET_o approach, *i.e.*, the product of the specific crop coefficient (K_c) by the reference evapotranspiration (ET_o), is the most widely-used method for irrigation water management. Consequently, a review was made to provide updated information on the K_c values for these crops. The reviewed research provided various approaches to determine K_c in its single and dual versions. With this purpose, actual crop ET ($ET_{c\ act}$) was determined with lysimeters, or by performing the soil water balance using measured soil water content and computational models, or by using Bowen ratio energy balance and eddy covariance measurements, or by using remote sensing applications. When determining the basal K_c (K_{cb}), the partitioning of $ET_{c\ act}$ was evaluated using different approaches, though mainly using the FAO56 dual K_c method. Since the accuracy of experimentally-determined K_c and K_{cb} values depends upon the procedure used to compute ET_o , as well as accuracy in determining and partitioning of $ET_{c\ act}$, the adequacy of the measurement requirements for each approach was carefully reviewed. The article discusses in detail the conceptual methodology relative to crop coefficients and the requirements for transferability, namely distinguishing between actual and standard K_c and the need to appropriately use the FAO segmented K_c curve. Hence, the research papers selected to update and consolidate mid-season and end-season standard K_c and K_{cb} were those that computed ET_o with the FAO56 PM- ET_o equation; and that also used accurate approaches to determine and partition $ET_{c\ act}$ for pristine, non-stressed cropping conditions. Under these experimental conditions, the reported K_c and K_{cb} values relative to the mid- and end-season could be considered as transferable standard K_c and/or K_{cb} values after adjustment to the standard climate adopted in FAO56, where average $RH_{\min} = 45\%$ and average $u_2 = 2\ m\ s^{-1}$ over the mid-season and late season growth stages. For each vegetable crop, these standard values were then compared with the FAO56 tabulated K_c and K_{cb} values to define the updated values tabulated in the current article. In addition, reported ancillary data, such as maximum root zone depth, maximum crop height, and soil water depletion fraction for no water stress, were also collected from selected papers and tabulated in comparison with those given for the crops in FAO56. The presentation of updated crop coefficient results is performed by grouping the vegetables differently than in FAO56, where distinction is made according to their edible parts: (1) roots, tubers, bulbs and stem vegetables; (2) leaves and flowers vegetables; (3) fruit and pod vegetables; and (4) herbs, spices and special crops, with most of them being newly introduced herein. The updated K_c and K_{cb} of vegetable crops based on this review are generally coincident with those in FAO56, although slightly lower for several crops. Close agreement of selected paper values with FAO56 values provides good evidence of their quality and also confirms the reliability of the original FAO56 tabulated values. It is noteworthy that many papers surveyed from the past 20 years did not satisfy the adopted K_c requirements in terms of ET_o computation method nor provide solid evidence of measurement accuracy for $ET_{c\ act}$. It is recommended that

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future K_c research of vegetables should sufficiently address these issues with objectives broadened to provide more transferable data to other regions. Also, new data on vegetable K_c and K_{cb} values should be carefully scrutinized in the context of these results and those provided in FAO56.

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1. Introduction

The use of water for irrigation of crops is under pressure due to climate and environmental changes, which call for reducing water losses and wastages and for improved productivity of the irrigated crops. A paramount approach consists in closing the gaps between water application and crop water requirements. These gaps refer to various irrigation issues such as improved irrigation methods and related irrigation and delivery scheduling, use of information and communication technologies, more precise cropping and water management practices, and farmers training and self-governance. On the base of related developments is knowledge and, particularly, knowledge on crop water requirements, thus on crop evapotranspiration processes and determination methods.

Evapotranspiration (ET) is commonly measured with instrumentation that require relatively complex physical principles and techniques (e.g., Farahani et al., 2007; Verstraeten et al., 2008; Allen et al., 2011a,b). Crop ET is typically computed or modeled using weather data and algorithms that describe the aerodynamic characteristics of the vegetation and surface energy driving ET, namely when adopting the FAO56 method (Allen et al., 1998; Pereira et al., 1999). This method uses the simple K_c - ET_0 approach that consists of the product of a crop coefficient (K_c) by the grass reference evapotranspiration (ET_0), where the latter represents the actual evaporative demand of the atmosphere and K_c represents an integration of the effects of the primary characteristics that distinguish the crop from the grass reference in terms of the energy balance (Allen et al., 1998; Pereira et al., 1999). Despite the simplicity of the K_c - ET_0 approach, its application requires the best accuracy of measurements and computations, particularly when deriving crop coefficients for a given crop using field observations (Allen et al., 2011a).

Thousands of papers have been published during the last 20 years reporting on the use of K_c values and K_c curves for nearly all cultivated crops, with hundreds of studies dealing with the derivation of K_c values for numerous crops and vegetation types. However, objectives of studies were quite diverse resulting in contradictory approaches when aiming at the transferability of K_c values to different environments. Limitations to transferability are due to a variety of factors: (1) using an ET_0 estimation method different than the standard

PM- ET_0 equation; (2) using non-standard cultivation conditions, such as mulch, plastic tunnels, intercropping and greenhouses/screenhouses; (3) adopting crop management practices that may cause various types of stresses, e.g., relative to the use of fertilizers, chemicals, or wastewater; (4) cropping under soil and water salinity/sodicity stress; (5) using non-optimal plant density and/or planting dates; (6) adopting deficit irrigation stresses; (7) insufficient size of experimental plots; (8) inadequate lysimeter management; (9) using energy balance instrumentation without adopting an appropriate energy balance closure (EBR); (10) lack of appropriate estimation of soil water fluxes that affect accuracy of soil water balance (SWB), particularly amount of water passing through the bottom boundary of the control volume; (11) lack of consideration of possible occurrence of local and regional advection; (12) using non-calibrated vegetation indices when remote sensing is adopted; (13) insufficient description of the experiments, namely of the plant density, height and vigor, and of the instrumentation used and of their accuracy. In addition, reported K_c curves often do not follow the FAO segmented curves, or K_c results are presented as time dependent polynomial equations, or are just referred to weekly, 10-day or, more often, monthly values. Crop growth stages are sometimes defined contradictorily relative to definitions adopted in FAO56 (Allen et al., 1998) and previously in FAO24 (Doorenbos and Pruitt, 1977). Information provided in those papers may be sufficient relative to objectives of the studies reported but is insufficient to provide for the transferability of reported K_c into different environments. These limitations obliged to a careful review of published material to check when derived K_c are only of local interest and/or represent non-standard experimental conditions, contrasting to K_c relative to recognizable potential evaporative crop conditions resulting from optimal, pristine cropping practices (Pereira et al., 2015), therefore transferable to other environments when adequately adjusted to climate.

Aiming at providing accurate standard and updated K_c values, it was required that the ET data, ET models, and related model calibrations reported in the literature were exempt of biases caused by flaws in experimental design, measurement equipment, vegetation management, data handling, model parameterization, and interpretation of results, as discussed by Allen et al. (2011a). 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. They were also checked to avoid potential computational

flaws and shortcomings in data handling and in model calibration and validation, as well as to contain the climatological information to adjust K_c to the standard climate.

This paper aims at providing standard updated single and basal K_c values (K_c and K_{cb}) for field and vegetable crops corresponding to the standard climate as adopted in FAO56 (minimum relative humidity $RH_{\min}=45\%$ and wind speed at 2 meters height $u_2 = 2 \text{ m s}^{-1}$). Therefore, Section 2 focuses on the basic concepts underlying the derivation and use of K_c values in order to make clear the approaches adopted including K_c concepts, K_c curves and crop stage dates, and factors influencing K_c , such as, mulches and soil management, irrigation methods and scheduling, and soil salinity. The Section 3 revises factors that influence the derivation of K_c and K_{cb} values, namely (1) measuring systems including soil water balance, lysimeters, Bowen ratio, eddy covariance, and sap flow, (2) plot size constraints, fetch limitations, and advection issues, and (3) requirements for estimating ET by remote sensing, including vegetation index-based crop coefficients, and surface energy balance techniques. Section 4 consists of a literature review on the derivation of K_c and K_{cb} from field research, including related ancillary data. Differently from the FAO56 crop tables, we follow the format assumed by the International Society of Horticultural Sciences, in which vegetables crops are grouped according to the edible parts of the plant: (1) roots, tubers, bulbs, and stems; (2) leaves and flowers; (3) fruit and pod; (4) herbs, spices, and special crops. Section 5, based on that review and on the FAO56 tabled data, provides for updates on standard K_c and K_{cb} for vegetable crops. Section 6 updates ancillary data and the final section consists of conclusions and recommendations for users.

2. Crop coefficients: Basic concepts and approaches

2.1. Basic concepts

Adopting the FAO56 method, crop evapotranspiration, ET_c [mm], is calculated by multiplying the reference evapotranspiration, ET_o [mm], by a dimensionless crop coefficient, K_c :

$$ET_c = K_c ET_o \quad (1)$$

The reference crop is a hypothetical crop with an assumed height of 0.12 m having 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 and adequately watered. The daily reference evapotranspiration ET_o [mm d^{-1}] is computed with the PM- ET_o , Eq. (2), which resulted from parameterizing the aerodynamic and surface resistance terms of the Penman–Monteith combination equation, thus:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (2)$$

where $R_n - G$ is the net balance of energy available at the surface [$\text{MJ m}^{-2} \text{ d}^{-1}$], T is mean daily air temperature [$^{\circ}\text{C}$] 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, Δ represents the slope of the saturation vapor pressure–temperature relationship at mean air temperature [$\text{kPa } ^{\circ}\text{C}^{-1}$], γ is the psychrometric constant [$\text{kPa } ^{\circ}\text{C}^{-1}$]. The reference crop incorporates most of the weather effects into ET_o estimates and, thus, ET_o represents the climatic demand on evaporation. However, advective heat energy fluxes are not considered in ET_o because the PM- ET_o equation considers only vertical fluxes of heat and vapor (Pereira et al., 1999). It results that K_c varies predominantly with the specific crop characteristics and little with climate. This enables the transfer of standard values for K_c between locations and climates when local and/or regional advection is excluded.

Expressing ET_c and ET_o in terms of the Penman–Monteith combination equation (Monteith, 1965), and expressing K_c as the ratio of ET_c to ET_o Eq. (1) results in:

$$K_c = \frac{ET_c}{ET_o} = \frac{\frac{\Delta_c(R_{n,c} - G_c) + \rho_a c_p (e_s - e_a)_c / r_{a,c}}{\Delta_c + \gamma(1 + r_{s,c}/r_{a,c})}}{\frac{\Delta_o(R_{n,o} - G_o) + \rho_a c_p (e_s - e_a)_o / r_{a,o}}{\Delta_o + \gamma(1 + r_{s,o}/r_{a,o})}} \quad (3)$$

where, R_n , G , $(e_s - e_a)$, Δ , and γ were defined above, ρ_a is air density (kg m^{-3}), c_p is specific heat of air ($1013 \text{ J kg}^{-1} \text{ } ^{\circ}\text{C}^{-1}$), r_a is aerodynamic resistance to heat and vapor transport from the surface to z height (s m^{-1}), and r_s is bulk surface resistance (s m^{-1}). The “c” subscripted parameters refer to the actual crop vegetation and the “o” subscript in the denominator refers to the grass reference vegetation. Using this ratio, one can visualize that K_c represents an integration of the effects of three primary characteristics that distinguish the crop from the reference: crop height, that affects roughness and aerodynamic resistance r_a ; bulk crop–soil surface resistance r_s , which relates to leaf area, fraction of ground covered by the vegetation, leaf age and condition, degree of stomatal control, and soil surface wetness; and albedo of the crop–soil surface that influences R_n and is determined by the fraction of ground covered by vegetation and soil surface wetness. The derivation of K_c is generally not performed using the relation of Eq. (3) but by using some empirical approaches that must be consistent relative to the above represented theoretical background; however, related literature often does not refer to that theoretical background.

Two K_c approaches are considered in FAO56: the first consists of a time-averaged single K_c that includes multi-day effects of evaporation from the soil in addition to plant transpiration; the second refers to the dual K_c , consisting of a basal crop coefficient (K_{cb}) and an evaporation coefficient (K_e) representing the ratios of, respectively, the crop transpiration (T_c) and soil evaporation (E_s) to ET_o , i.e., $K_{cb} = T_c/ET_o$ and $K_e = E_s/ET_o$. Thus, it results that $K_c = K_{cb} + K_e$.

For transferability purposes, FAO56 (Allen et al., 1998) adopted the concept of standard or potential K_c and ET_c , which refer to optimal, well-watered conditions and are the basis for the tabularized K_c . In the field and in common practice, crop conditions are often not optimal due to insufficient or non-uniform irrigation, crop density, salinity, soil and agronomic management as referred before. Under these conditions, ET_c is then replaced by the actual $ET_{c \text{ act}}$, with $ET_{c \text{ act}} = ET_c$ only when the crop is well-irrigated and cultivated under standard optimal conditions. The resulting K_c is then renamed actual K_c ($K_{c \text{ act}}$), which corresponds to the product $K_{c \text{ act}} = K_s K_c$ using a stress coefficient (K_s) depending upon the sufficiency of available soil water to maintain the crop ET rate. In the case of using the dual K_c approach, only the basal K_{cb} is modified into $K_{cb \text{ act}}$, resulting in:

$$K_{c \text{ act}} = K_s K_c = K_s K_{cb} + K_e \quad (4)$$

Adopting this concept facilitates consistent estimation and transferability of measured and standardized K_c ; otherwise, it would be necessary to define multiple K_c values for the same crop. The concepts of standard K_c and potential crop ET_c and related terminology are progressively being accepted by the user communities. The transferability of K_c among climate and locations applies only to standard K_c . The theoretical basis and limitations of the standard K_c concept reflect primarily differences in the aerodynamic and surface resistances of the reference crop and of the crop being considered under well-watered conditions (Eq. (3)), so that differences in ET_c are influenced mainly by climate (Pereira et al., 1999). This contrasts with $K_{c \text{ act}}$ because their differences may additionally be due to unique levels of water or salinity stress, including when deficit irrigation is adopted, or by specific non-standard cropping practices, e.g., when mulching or site-specific irrigation management are applied. Such factors influencing crop management cause values for $K_{c \text{ act}}$ to vary widely, contrary to standard K_c . The extension of K_s to saline environments is analyzed by Minhas et al. (2020).

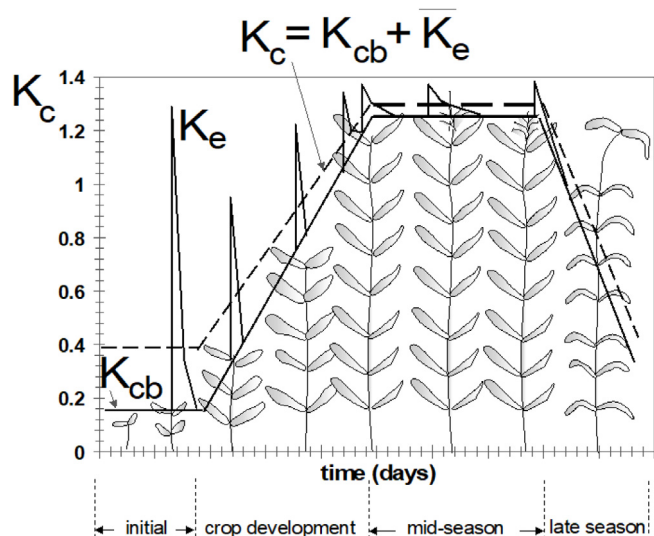


Fig. 1. Crop coefficient K_c , basal crop coefficient K_{cb} and soil evaporation coefficient K_e curves with identification of the four crop growth stages. Source: FAO56.

2.2. The crop coefficient curve

The crop coefficient curve (Fig. 1) represents the changes in K_c or K_{cb} over the length of the growing season (Allen et al., 1998). Both the single, time-averaged K_c and the dual K_c , i.e., K_{cb} and K_e are represented. The K_c segmented curve is similar for K_c and K_{cb} , while K_e are represented by peaks that occur when soil wettings produce evaporation from the soil surface. The curve consists of four linear segments representative of the four crop stages identified in Fig. 1. Indicative time durations of crop stages were given in Tables in FAO56 and in publications by Allen et al. (2007c) and Jensen and Allen (2016). Despite FAO56 recommendations for observing actual stage durations in field studies, many articles refer to an inappropriate use of such tabulated crop growth stage lengths and deeply criticized them. Consequently, it is now recommended to refrain from using the indicative durations in FAO56 but instead use the actual field observations of crop growth stage durations as a function of days past planting, as well as with cumulative growing degree days (CGDD). An earlier study on the subject is that by Sammis et al. (1985). Various authors quoted in the current review used that approach.

The segmented curves for K_c and K_{cb} are approximate representations of changes in crop vegetation from planting to harvest that affect the ratio ET_c/ET_0 and, inherently, the ratio T_c/ET_0 . Shortly after planting, the value for K_c is often small because the crop is in its earliest stage of development, before attaining 10% cover. This is the initial crop stage when K_c and K_{cb} are denoted $K_{c\ ini}$ and $K_{cb\ ini}$. They are represented (Fig. 1) by a horizontal line because initial-stage variation with time is small, so they can be estimated by a single average value. The next crop growth stage corresponds to crop development, which concerns a great change of crop cover and height, thus a large change in the ET_c/ET_0 and in T_c/ET_0 ratios. That change is represented by a segment whose slope corresponds to the average time-rate of increase in K_c from $K_{c\ ini}$ until its maximum, which is attained during mid-season, thus noted $K_{c\ mid}$ and $K_{cb\ mid}$. The $K_{c\ mid}$ and $K_{cb\ mid}$ values refer to the period from when crop development growth ends and is replaced by the reproductive period, until senescence starts. During the mid-season the ratios ET_c/ET_0 and T_c/ET_0 have relatively small changes and $K_{c\ mid}$ may be approximated by a horizontal line. After senescence starts, the ratios ET_c/ET_0 and T_c/ET_0 decrease until harvesting or the end of the crop season. During this crop stage, called late-season, K_c and K_{cb} decrease with an approximately constant rate, which allow representing K_c and

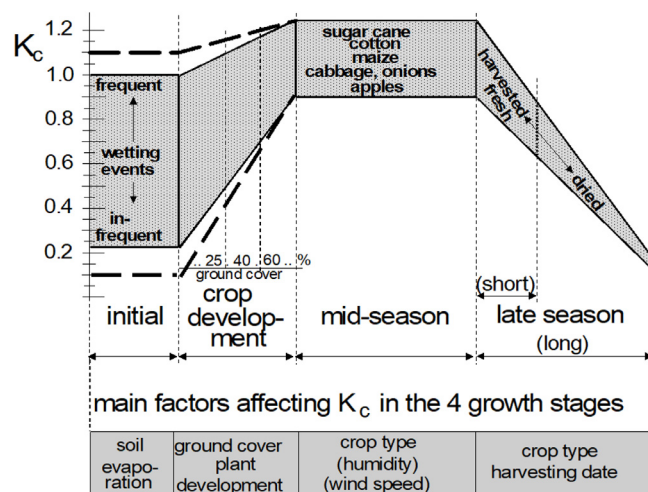


Fig. 2. Main factors affecting crop coefficients relative to the four crop growth stages. Source: FAO56.

K_{cb} with a segmented slope, corresponding to the rate of decrease of the ratios ET_c/ET_0 and T_c/ET_0 . That segment ends at harvesting or the end of the crop season when K_c and K_{cb} are denoted $K_{c\ end}$ and $K_{cb\ end}$.

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 stage ($K_{c\ mid}/K_{cb\ mid}$) and that at harvesting or at the end season ($K_{c\ end}/K_{cb\ end}$). K_c values during crop development and late-season stages are then just linearly interpolated with time, based on the three values. Using non-linear K_c or K_{cb} representations requires appropriate curve fitting and various parameters to describe such curves, which generally vary from a location to another and from a year to the next, thus making it quite difficult, if not impossible, to transfer the K_c information. Using more than four crop growth stages also increases the difficulties in transferring K_c values since not only are more K_c values required to represent the crop season, but it is necessary to define the time limits of more crop stages.

K_c and K_{cb} are subject to a large number of influencing factors as summarized in Fig. 2. 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, 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, $K_{c\ ini}$ values are not proposed herein; instead, the computational procedures proposed by Allen et al. (1998 – pg 114–121 -, 2005b) are recommended. 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_c should be computed taking into consideration all the factors affecting soil evaporation as detailed by Allen et al. (2005a).

The same factors affect soil evaporation during the crop development stage but in a lesser extent since the fraction of ground shaded by the crop progressively increases, thus reducing the amount of energy available for soil evaporation. The effect of mulches also progressively

reduces because the mulch cover slowly loses its potential characteristics, particularly organic mulches. Plastic tunnels are generally removed during this stage for not affecting crop development. During this crop stage, more important than controlling E_s is providing for good crop growth, thus for the transpiration to increase. During the crop development stage, the aim is to provide rapid growth of healthy vegetation, which leads K_c and K_{cb} to increase at, often, a great rate. That large variation of K_c and K_{cb} makes it inappropriate to represent K_c or K_{cb} by an average value, which would be necessarily over estimated at the earlier stage of crop growth and largely under-estimated when approaching mid-season as well evidenced in Figs. 1 and 2.

When canopy is fully developed during mid-season and the reproductive phase develops, $K_{c\ mid}$ and $K_{cb\ mid}$ are at maximum levels. The fraction of ground shaded by vegetation is then maximal while the energy available for evaporation is minimal; thus, soil evaporation, and K_e , are minimal. $K_{c\ mid}$ and $K_{cb\ mid}$ are largely dependent upon the plant density and height (Allen and Pereira, 2009; Pereira et al., 2020b). By the mid-season, the effects of various practices to control soil evaporation become less important while $K_{c\ mid}$ and $K_{cb\ mid}$ turn to be more influenced by climate, particularly RH_{\min} and u_2 , especially when crop height is high. During the late-season annual crops are senescing, leaves turn yellow and fall, f_c progressively decreases, and E_s increases while K_c and K_{cb} decrease. It is therefore inappropriate to represent K_c or K_{cb} by a late-season average value since their rate of decrease may be quite large, particularly when $K_{c\ end}$ or $K_{cb\ end}$ are much lower than $K_{c\ mid}$ and $K_{cb\ mid}$ (Figs. 1 and 2). Impacts of climate may be less important. However, during late-season, the main influencing factor refers to the objective of crop harvesting, e.g., if the crop is to be consumed fresh the $K_{c\ end}$ is high, as for table vegetables; contrarily, if to be stored dry, as with small grains, $K_{c\ end}$ is low.

This variety of conditions determining the K_c and K_{cb} values make it challenging to tabulate them and, naturally, just allow to adequately tabulate values referring to the mid-season and end-season (harvesting). However, difficulties are increased when reported information about the experiments is insufficient. The quoted papers Allen et al. (2011a,b) were prepared at request of Journal Editors to avoid that lack of information. In the following, reviewed data focused on papers producing reasonable information and cropping under standard conditions only.

2.3. Adjustment of observed K_c and K_{cb} to climate

The standard, transferable $K_{c\ mid}$ and $K_{c\ end}$ values represent $K_{cb} + K_c$ for irrigation management and precipitation frequencies typical of a sub-humid climate where $RH_{\min} = 45\%$ and $u_2 = 2\ m\ s^{-1}$ as defined in FAO56 (Allen et al., 1998). Under humid and calm conditions, the K_c for “full-cover” agricultural crops generally do not exceed 1.0 by more than about 0.05 because “full-cover” agricultural crops and the reference crop behave similarly regarding absorption of short-wave radiation, the primary energy source for evaporation under humid and calm conditions. Because the VPD is small under humid conditions, differences in ET caused by differences in the aerodynamic resistance r_a between the agricultural and the reference crop are also small, especially with low-to-moderate wind speed as explained by Allen et al. (1998) and Pereira et al. (1999). Then, the values of K_c are less dependent on differences between the aerodynamic components of ET_c and ET_o (Eq. (3)). On the contrary, under arid conditions, the effect of differences in r_a between the agricultural and the reference crop on ET_c become 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.

Because the transferable $K_{c\ mid}$ and $K_{c\ end}$ should represent conditions where $RH_{\min} = 45\%$ and $u_2 = 2\ m\ s^{-1}$, 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 the standard K_c values, $K_{c\ mid\ (std)}$ and $K_{c\ end\ (std)}$ as:

$$K_{c\ mid\ (std)} = K_{c\ mid\ (obs)} - [0.04(u_2\ mid - 2) - 0.004(RH_{\min\ mid} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (5a)$$

$$K_{c\ end\ (std)} = K_{c\ end\ (obs)} - [0.04(u_2\ late - 2) - 0.004(RH_{\min\ late} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (5b)$$

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 the observations during respectively the mid- and late-season. The same adjustments apply to K_{cb} , thus:

$$K_{cb\ mid\ (std)} = K_{cb\ mid\ (obs)} - [0.04(u_2\ mid - 2) - 0.004(RH_{\min\ mid} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (6a)$$

$$K_{cb\ end\ (std)} = K_{cb\ end\ (obs)} - [0.04(u_2\ late - 2) - 0.004(RH_{\min\ late} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (6b)$$

where the symbols are the same as applied in Eqs. (5a) and (5b). When crops are allowed to senesce and dry in the field ($K_{c\ end} < 0.45$), no adjustment is necessary.

Crop height should be observed in the field. Indicative values for h are tabulated by Allen et al. (1998) and in ancillary data tabulated in Section 6. However, it should be noted that tabulated h values may deviate from reality, thus should not replace field observations.

3. Accuracy and requirements of field measurements for derivation of crop coefficients

3.1. Limits on maximum values for ET and crop coefficients with consideration of advection

Evaporation consists of the conversion of liquid water to vapor, which requires substantial amounts of energy. As discussed in various papers, particularly by Allen et al. (2011a), the availability of energy incident to vegetation constrains the potential evaporation rate and forces adherence to the law of conservation of energy. Considering the basic equation of the balance of energy,

$$R_n - G = \lambda ET + H \quad (7)$$

it may be noticed that the available energy at the surface, $R_n - G$, is the source for both the latent and sensible heat flux, respectively λET and H . If λET exceeds $R_n - G$, it means that an additional energy is extracted from the atmosphere via downward sensible heat flux (H), via convective transfer through the equilibrium boundary layer of air above the surface (Allen et al., 2011a). Increasingly negative H requires the transport by wind of the required H to the surface to support the conversion to ET (De Bruin et al., 2005). As a result, there is an upper limit on ET, even under extreme advection, caused by limitations on aerodynamic transport and on equilibrium forces above a vegetation canopy as discussed by Allen et al. (2011a). That upper limit on potential crop evapotranspiration (ET_c) is readily approximated by comparing against the widely used reference ET_o through the crop coefficient (K_c). 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. (3)).

In humid climates, ET is dominated more by net radiation availability and less by aerodynamics and VPD. Because the grass reference crop has an albedo similar to that of many crops at full cover, based on total energy constraints, where a majority of energy for the ET process is from net radiation and regional advection is relatively minor, the K_c

generally cannot exceed about 1.2 to 1.3 relative to the grass reference. In arid and semiarid climates, differences in aerodynamic and surface resistances, 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 (Allen et al., 2011a).

Measuring ET from small expanses of vegetation should be avoided when the objective is to represent general conditions of crop ET for medium to large (say > 200 m) fields or clusters of small fields. As discussed by Allen et al. (2011a), “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”. Moreover, small expanses of vegetation surrounded by shorter or dry cover cause a “clothesline effect” and ET from the isolated stands may be significantly greater than the corresponding ET_0 , thus not representing large expanses. This may also happen when using lysimeters since the vegetation inside the lysimeter may function as a clothesline. Allen et al. (1991b) reported measured ET from 0.6 m fescue grass to increase by 1.6 times relative to the Penman–Monteith equation when the surrounding grass was clipped to 0.1 m, but the vegetation inside the lysimeter remained at 0.6 m. Summarizing, 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.

Advective transport of heat is referred above as an additional source of latent heat through conversion of sensible heat. Sensible heat advection may play a major role in crop ET. Studies on crop ET reporting on advection were more common a few decades ago than they are at present despite progresses in instrumentation, which would allow an easy use of indicators. Under advection, λET exceeds $(R_n - G)$ and H becomes very small, often negative, which corresponds also to the Bowen ratio $\beta = H/\lambda ET$ to become null or negative.

There is not a common terminology relative to advection. Brakke et al. (1978) referred to local and regional advection of sensible heat and reported that regional advection observed for an alfalfa irrigated field largely depended upon wind speed while advection at local scale mainly depended upon dryness of air, thus from VPD. Their observations, performed in the American Great Plains, indicated that regional sensible heat advection supplied 7 to 40% of energy consumed as latent heat while local advection corresponded to 1 to 14% of such energy. Local advection was referred by Itier et al. (1978) as depending upon the fetch, the roughness length of the crop, the wind speed friction velocity and the temperature difference between the dry and irrigated fields. These authors proposed to correct *a posteriori* the ET measured by means of weighing lysimeters, soil water balance, or sap flow method when the fetch is not large enough to avoid advection effects. This correction can be of 1–2 mm d^{-1} for temperature differences between dry and irrigated fields of 5–10 °C (Itier et al., 1978; Rana and Katerji, 2000). The conceptual approaches used by Brakke et al. (1978) and Itier et al. (1978) are different but not contradictory. Differently, a previous study by Hanks et al. (1971) defined large scale advection, however not corresponding to the regional advection referred by previous referred authors, and border advection, considered to occur over most of the plot irrigated but mainly from 0 to 40 m from the upwind edge and yielding sufficient energy to account for about 30% of the energy used for evapotranspiration. The former large scale and border advection are different from the regional and local advection defined by Brakke et al. (1978) and Itier et al. (1978). These differences illustrate conceptual difficulties that do not favor assessments of advection in current crop ET studies.

De Bruin et al. (2005) performed micrometeorological observations over extensive, well-irrigated alfalfa fields in Kimberly, Idaho, and observed that, on a number of days and during daytime, H was negative and $\lambda ET > R_n$. The energy required for $\lambda ET > R_n$ was therefore “advected from elsewhere”, which the authors referred to as “regional

advection” since the fields were large. Differently, those authors designed as “local advection” the advection process where the wet to dry transition is on a field scale. They observed $\lambda ET > R_n$ by about 50% for most of August and September when dry air was advected from large desert areas upwind of Kimberly. De Bruin et al. (2005) assumed that for “large horizontally homogeneous fields where the atmospheric flow is in equilibrium with the underlying surface, the air temperature and humidity in the atmospheric surface layer are well adapted to the irrigated field and no longer have the properties of the dry upwind terrain”. This assumption implies that a negative H occurs if the atmosphere just above the surface is stably stratified and the negative buoyancy effects suppress turbulent motions. Thus, the turbulence needed for vertical transfer of water vapor only occurs if there is enough wind to offset the damping effects of stability and the influence of the upwind dry terrain will increase with increasing wind speed. Contrarily, under calm conditions daily λET cannot exceed R_n . As referred by those authors, “considering vertical exchange of eddies or air parcels under conditions that $H < 0$ and $\lambda ET > 0$, it is expected that upward moving eddies contain relatively cool and wet air, whereas downward moving parcels will be warm and dry. Consequently, the correlation coefficient of turbulent temperature and humidity measurements, RTq , is expected to be negative”. Conversely, when both H and λET are > 0 , RTq should be positive. Those authors therefore proposed RTq as indicator for advection conditions. Moreover, the referred behavior of the eddies disturbs eddy covariance measurements and impacts the energy balance closure, thus obliging to careful corrections (Paw et al., 2000; Chávez et al., 2009; Xu et al., 2017).

Energy and water balance of paddies evidenced the occurrence of advection considering that the temperature difference of flooded paddies to surrounding areas was quite large. This is the case of the study by Lourence and Pruitt (1971) who demonstrated the occurrence of advection through the ratio $\lambda ET/R_n$, where values close to or larger than 1 indicate a reduced or negative H . The same approach was used by Peterschmitt and Perrier (1991). Lang et al. (1974) studied advection in paddy rice defining a linear relationship between advection and the distance to the upwind edge of the field. More recently, various studies recognized impacts of advection on various field crops ET in the Great Plains (USA), e.g., Tolk et al. (2006) referred that advected H contributed up to 38% of energy used in λET of alfalfa and with up to 3 mm d^{-1} of night-time ET, and Payero and Irmak (2013) relative to soybean. Studies from northwest China also identified an important contribution of regional advection to crop ET, e.g. the study by Ding et al. (2015) reporting that advection H may contribute with 4 to 28% of the K_c value, and the study by Tian et al. (2017) relative to cotton. However, there are no indications that oversized K_c or K_{cb} due to advection were corrected when to be used as standard values.

Microscale advection was referred by Kar et al. (2007) relative to crop coefficient studies of oilseed crops due to small size of plots, which may have induced K_c values up to 23% higher than the values reported by FAO56. Lund and Soegaard (2003) referred to within canopy advection of sensible heat from the dry soil to the millet plants, so increasing transpiration. This type of micro-advection was earlier reported by Hanks et al. (1971) for sorghum and by Heilman et al. (1994) for a vineyard. The within canopy advection results from the conversion of H at the inter-row into λET of the plants row. This micro-advection justifies why plastic mulch contributes to increased transpiration while reducing K_c less than it could be expected (Lund and Soegaard, 2003). However, studies referring to plastic mulch effects on K_c generally do not consider this process.

References above refer to field crops and only a few studies relative to vegetable crops have reported on solutions for experimental layouts aiming at minimizing advection impacts. Nevertheless, it is important to recognize that the accuracy of determining K_c and/or K_{cb} for vegetable crops implies considering when advection contributes to increased energy available for ET, thus augmenting K_c values with implications on their transferability.

3.2. ET measurement accuracy and requirements

The exceedance of measured or reported K_c above 1.2 for grass reference in sub-humid regions or above about 1.2 to 1.4 for grass reference in arid regions should give cause for intense scrutiny of the ET measurements, the weather data used to calculate ET_0 , and the data processing procedure. That scrutiny is basically formulated by Allen et al. (2011a,b) when revising the requirements for accurate ET measuring and the need for related data reporting. Readers are therefore referred to both papers. Nevertheless, herein we emphasize some essential aspects influencing accuracy of measurements which therefore relate with the quality of derived K_c values.

A deep and complete analysis on field measurements using weighing lysimeters, neutron probes soil water balance, Bowen ratio energy balance (BREB) instruments, and eddy covariance flux towers, including the assessment of advection effects, has been provided by Evett et al. (2012a,b). Scintillometers are not referred in the selected papers reporting on K_c values, but they are useful ET measuring devices that proved accurate, as analyzed by Moorhead et al. (2017).

Determining ET through computing the soil water balance (SWB) by measuring the change in soil water over the crop season or a selected period of time has been used for a long time, earlier using gravimetric soil sampling, lately with a variety of sensors, including continuous measurements, e.g., reviews by Evett et al. (2006, 2012c). Major potential errors in ET determined by the SWB using gravimetric, neutron scattering, capacitance, time domain reflectometry, or water potential measurement of soil water include:

- Insufficient characterization of the soil hydraulic properties, including their spatial and vertical variability, and often inadequate consideration of properties over the full root zone depth, i.e., without referring to the entire depth where root uptake activity takes place.
- Inadequate vertical spacing of observations and/or frequency of observations, as well as inadequate representativeness of observed data of actual field conditions.
- Inaccuracies in measuring precipitation and irrigation applications, or in measuring soil water content and/or potential, mainly when sensors are not duly calibrated.
- Differential spatial wetting of soil due to local spatial variation in irrigation (or precipitation), for example with bed-furrow systems, partial drip line wetting, or with plastic mulch, as well as due to non-uniformity of irrigation application.
- Inadequate estimation of deep percolation losses and/or gains by capillary rise.
- Differential spatial extraction of soil water due to spatial variation in root systems, e.g., in the case of trees and when partial root zone drying is used.
- Lack of care in obtaining samples or taking readings (or installing access tubes or sensors), which can significantly alter the plant cover at the sampling site and/or alter the density, aeration and infiltration characteristics of the surface soil from foot traffic; and lack of care during excavation or backfilling soil, which may alter soil water extraction and result in poor estimates of ET that do not represent actual field ET.

Adopting a reliable soil water balance simulation model and taking care in model calibration and validation can be very helpful in overcoming most of the referred problems in estimating ET since they provide an alternative means to detect soil water behavior over time. Various examples relative to the accurate derivation of K_c and K_{cb} using the models ISAREG and SIMDualKc are referred throughout this paper. In addition, results from a calibrated model may provide appropriate support for irrigation scheduling and estimation of deep fluxes.

Lysimeters have been used extensively to provide baseline information on ET and crop coefficients. However, lysimeter measurements

of ET are extremely sensitive to environmental factors, many of which are ignored in practice. Lysimeter measurements are point measurements, representing ET from areas ranging from 0.05 to 40 m² but they are commonly used to characterize ET and K_c for large areas. Extrapolating data from small to large areas requires that vegetative and environmental conditions of lysimeter systems closely duplicate one-dimensional ET from the larger areas. If improperly managed from an environmental context, measured ET can differ from the actual ET of a large expanse of vegetation by as much as 50% to 100%. The Lysimetry Symposium edited by Allen et al. (1991b) provides several examples of poor lysimeter systems and guidelines for the operation of lysimeters to ensure high quality data for ET.

Lysimeters can be grouped as constant water-table types, drainage types and weighing types. The latter, when well-managed, can provide the most accurate data for short time periods. When lysimeter facilities are appropriate, results from drainage or percolation lysimeters can be accurate if there is also accuracy in observing changes in soil water content. The use of models may help produce accurate K_c and ET results with these systems (Liu et al., 1998).

López-Urrea et al. (2006) and Evett et al. (2016) provided for appropriate descriptions and related analysis on using weighing lysimeters for ET determination. Care placed on setting the lysimeters in field, on their management, and on the management of the crops in the field and in the lysimeters have clearly improved the quality of derived K_c values reported in various studies performed with lysimeter ET facilities as reported in papers by López-Urrea et al. (2009a,b,c, 2014). Contrarily, some high crop coefficients reported in the literature may result from inappropriate settings and management of lysimeters that caused local and micro-scale advection, as well as clothesline effects.

As reported by Allen et al. (2011a), the ET accuracy of lysimeters, thus, of derived K_c values depend upon a variety of factors including:

- Soil conditions inside the lysimeters must be the same as those outside to insure that the vegetation density, water availability, vigor, evaporation from the soil surface, and thus ET are the same.
- The lysimeter must be surrounded by the same vegetation that is growing in the lysimeter to insure one-dimensionality of the measurement (Allen et al., 1991a). Lysimeters surrounded by sidewalks or gravel or planted with vegetation different from that outside will not provide accurate ET results due to local advection, clothesline effect.
- Lysimeters should be located with a fetch large enough from the edge of the field such that the equilibrium boundary layer of air can be considered to be fully adjusted above the lysimeter.
- Differences in growth and maturity between the lysimeter plants and surrounding plants must be minimal to avoid differences in ET measured inside and outside of the lysimeter relative to ET measured in the surrounding area (Pruitt and Lourence, 1985). In addition, flawed lysimeter results can be due to the so-called “bloom effect” where the area of exposed plant canopy has exceeded the effective area of the lysimeter. The effective evaporating and transpiring area of the lysimeter must be well recognized.
- A high, exposed rim that must be avoided due to its thermal conditions and advective effects.

The Bowen Ratio Energy Balance (BREB) method enables solving the energy balance equation by measuring simple gradients of air temperature (T) and vapor pressure (e_a) in the near surface layer above the evaporating surface. The method works best when soil water is not limiting ET. As water becomes less readily available, the Bowen ratio (BR) increases, and the relative error in ET increases. Payero et al. (2003) described relative errors associated with the BREB method as well as techniques for data quality analysis. The BREB equation for application to vegetation is:

$$\lambda ET = \frac{R_n - G}{1 + \beta} \quad (8)$$

where λET is latent heat flux, *i.e.*, ET expressed in terms of energy, R_n is net radiation, G is soil heat flux density into the ground and β is the Bowen ratio ($H/\lambda ET$). Details on BREB computations can be found in [Fritschen and Fritschen \(2005\)](#). Large differences in measured ET between BREB and lysimeters were reported by [Todd et al. \(2000\)](#) when the Bowen ratios were < 0 on hot, dry and windy days, or when the λET flux exceeded the available energy ($R_n - G$), thus, there is need for careful scrutiny of BREB observations when advection occurs.

Requirements of the Bowen Ratio include:

- Sufficient distance of fetch to establish an equilibrium boundary layer deeper than the instrument height;
- Sufficient elevation of instrument above the canopy to avoid the roughness sublayer;
- Representative measurement of R_n and G ;
- Multiple net radiometers and soil heat flux stations when observations are performed over a heterogeneous or sparse crop.

Eddy covariance (EC) systems are widely used at present for ET measurement because of ease of set up, reduced costs for sensors, and the ability to co-measure H , λE and CO_2 fluxes, depending on the equipment configuration ([Allen et al., 2011a](#)). The concept of eddy covariance refers to the statistical covariance between vertical fluxes of vapor or sensible heat within upward and downward legs of turbulent eddies. ET can also be computed as a residual from the energy balance equation as $\lambda ET = R_n - G - H$, where sensible heat flux density is measured by eddy covariance, which has advantages in terms of instrumentation required, however with the need to measure R_n and G accurately. The vertical component of wind, w , is generally measured using a sonic anemometer and T is measured using ultra fine wire thermocouples or using sonically determined temperature corrected for humidity effects. Specific humidity is measured using quick response hygrometers.

Numerous corrections are required, and a variety of software are available for correction of EC data. [Paw et al. \(2000\)](#) reported on equations to correct eddy-covariance measurements for both fluctuations in density and non-zero mean advection, induced by convergence or divergence of flow, and spatial source/sink inhomogeneity, under steady-state and transient conditions. Corrections and precautions for eddy covariance were reviewed by [Burba \(2013\)](#). The quality of data highly depends upon the environmental conditions; for instance, flux divergence due to the local advection of warm and dry air over the irrigated fields was analyzed by [Alfieri et al. \(2012\)](#), Assessments of correction needs and related improvements are reported by several authors, particularly [Evelt et al. \(2012b\)](#), who provided for an adjustment for the effect of advection of energy across the field to the EC stations resulting in reducing the EC station ET error to the 6%–7% range.

Much literature documented energy balance closure error for eddy covariance data referring to the fact that the sum of measured $\lambda ET + H$ does not equal measured $R_n - G$. Often λE and H can be undermeasured relative to $R_n - G$ by as much as 30% ([Wilson et al., 2002](#); [Foken, 2008](#); [Sánchez et al., 2019](#)). Possible reasons for the lack of closure include storage of heat in canopies, horizontal advection, energy used by photosynthesis, change in storage of heat in the developing boundary layer below the instrumentation (causing flux divergence), measurement errors of turbulent fluxes, separation of sensors, and error or bias in R_n or G . Commonly, users ‘close’ the energy balance by scaling H and λE in the same proportion until the sum equals $R_n - G$. However, the method used to enforce the energy balance closure is less important than making sure that EC measurements are coherent with conservation of energy ([Twine et al., 2000](#)). A recent study by [Kutikoff et al. \(2019\)](#) demonstrated that days associated with advection exhibited poor surface energy balance compared to all other days; heat storage pushed the daytime energy balance closure upward by as much 25% during advection conditions. Energy balance closure cannot be considered as a data quality test, since closure error can still be present

even if data acquired by the eddy covariance system are of high quality and vice versa ([Allen et al., 2011a](#)).

Requirements of the eddy covariance method include:

- Sufficient, quite large fetch to establish an equilibrium boundary layer deeper than the instrument height;
- Sufficient elevation of instruments above the canopy to reduce roughness sublayer impacts and to increase mean eddy size to match the sensor path length;
- Performing the required data “corrections”, particularly adjustments to consider the effects of advection;
- Accurate, high frequency instrumentation and ability to recognize the occurrence of advection because advective energy modifies energy partitioning which further enhances turbulent fluxes as observed by [Kutikoff et al. \(2019\)](#);
- Correcting data for the energy balance closure error ($R_n - G = \lambda E + H$), namely caring for the effects of advection;
- Check data when wind direction changes, and/or when flow lines change with turbulence, and when advection occurs.

Remote sensing vegetation indices (VI) have been often used to estimate crop coefficients ([Bausch and Neale, 1987](#); [Hunsaker et al., 2005](#); [Campos et al., 2010](#); [Calera et al., 2017](#)). The estimate of K_c and K_{cb} from VIs relates to the fact that there is generally a close correspondence between vegetation amount and transpiration, *i.e.*, as vegetation cover increases, leaf area increases, and transpiration increases (reviewed in [Glenn et al., 2011](#)). In addition, frequent monitoring of crops with a VI can provide guidance to adjust the durations of crop growth stages and adjust fractional crop cover, which are difficult to assess visually in real-time ([Hunsaker et al., 2007](#)). Difficulties arise in VI-based methods when trying to estimate evaporation from bare soil because related soil water processes cannot be adequately reflected in a VI. However, once the crop is established, VIs can monitor the seasonal crop growth adequately. The most commonly-used VI for K_c and K_{cb} estimation is the Normalized Difference Vegetation Index (NDVI; [Glenn et al., 2011](#)), which is estimated from reflectance in the red (~ 0.6 – $0.7 \mu m$) and the near infrared bands (~ 0.7 – $1.3 \mu m$). Linear relationships between the NDVI and the crop coefficient are referred in numerous studies, namely some referred hereafter. Generally, NDVI values from different satellites show close correlation ([Calera-Belmonte et al., 2005](#)) but some differences occur due to differences in band-widths. However, the degree and type of atmospheric correction of the image can also influence those differences.

With K_c vs. NDVI or other VI, it is important to distinguish whether the relationships are to represent the average ET that includes soil evaporation or are to represent just the ‘basal’ K_{cb} . The latter condition assumes that the VI-based relationships are established to represent conditions where the soil surface is dry and soil evaporation is low when compared to transpiration. The relationship K_{cb} vs. NDVI is more consistent than K_c vs. NDVI because transpiration is more closely associated with the vegetation amount (as estimated by NDVI) than is total ET that includes evaporation from soil. When K_{cb} vs. NDVI relationship is used, estimates for soil evaporation must be determined separately and added to produce total ET ([Burnett et al., 2008](#)). [Allen et al. \(2011b\)](#) showed that NDVI was a better basis for the K_c vs. VI relationship than was the Soil Adjusted Vegetation Index (SAVI; [Huete, 1988](#)) because while NDVI tends to reach a maximum value at about the same time as does K_c , SAVI tends to continue to increase with increasing LAI beyond 3.0. [Pôças et al. \(2015\)](#) observed that NDVI- K_{cb} relationships were better than SAVI- K_{cb} ones for field crops but SAVI- K_{cb} relationships were better for olives. [Allen et al. \(2011b\)](#) also showed that the VI calculation can be based on ‘top of atmosphere reflectance’ or on ‘at-surface reflectance’ with little reduction in estimation accuracy. Meanwhile, with the new satellite Sentinel2, a slightly better performance of new VIs has been reported, *e.g.*, [Rozenstein et al. \(2018\)](#). The current use of K_c -VI relationships to estimate ET requires

field validation, such as EC measurements or using satellite-based ET energy balance. Large areas can be covered with remote sensing and data may be used to map ET in such areas. However, the K_c values obtained in those circumstances are based on actual ET conditions and thus not standard and transferable; but the latter may be obtained when applications focus on specific areas where crops are managed in a pristine way as described by Hunsaker et al. (2003, 2005) for cotton and wheat. These matters are reviewed by Pôças et al. (2020) in the current Special Issue.

Remote sensing energy balance is often used to estimate ET from large areas. Some ‘operational’ satellite-based energy balance models such as SEBAL (Bastiaanssen et al., 1998a,b, 2005) and METRIC (Allen et al., 2007a,b) employ an internal calibration technique referred to as CIMEC (‘calibration using inverse modeling at extreme conditions’) (Allen et al., 2008). They may also be used to estimate K_c of small expanses of vegetation. Good results were obtained by Mateos et al. (2013) and Pôças et al. (2015); Paço et al. (2014) used the energy balance model METRIC combined with the soil water balance model SIMDualKc. Remotely sensed energy balance techniques are useful for identifying areas experiencing water stress and corresponding reductions in ET. For example, the two-source energy balance (TSEB; Kustas et al., 2004), also a thermal model, can be used to diagnose ET under a wide range of crop water stress and also has the capacity to estimate both transpiration and evaporation (French et al., 2018). Users of this information must bear in mind that satellite-based ET data are simply retrievals, or best estimates, of an aerodynamic and radiative process, as viewed from space, and cannot be considered “measurements”. Nevertheless, remotely sensed energy balance is discussed here because of its increasing use to estimate K_c and ET over large areas. Estimation by remotely sensed energy balance should be expected to adhere to the same limitations and physics as other measurement methods.

3.3. Implications on collecting K_c information from literature

Crop coefficients K_c and K_{cb} reported in literature were obtained from studies having a variety of objectives, field methods and data handling procedures. The related publication resulted from diverse publication criteria resulting from the Journal requirements and the objectives of the studies.

As described before, difficulties in using the published information relate to the insufficiencies of information provided which could affect the accuracy of methods and procedures used. As much as possible, the aspects dealt by Allen et al. (2011a,b) were followed as referred in Section 3.2 above particularly for crops that were the focused on numerous studies. Exceptions were for crops that have been object of few, rare studies. When insufficient climatic data were available, RH_{min} and u_2 used with Eqs. (5) and (6) where obtained from the internet for the locations where experimentation took place. If various studies were available, such data sets were discarded. Data relative to experiments where K_c or K_{cb} were given by selected periods, or using a non-linear equation relating then to time were only used to approximate their mid-season values if data on the considered crop were insufficient.

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, K_c data were treated as influenced by advection. 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 15% as a rule of thumb to correct excess K_c due to less good lysimeter 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. When lacking adequate description of procedures used with SWB, BREB, EC or else that could justify those high values. A similar rule of thumb 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.

There is a good number of studies on deriving crop coefficients, K_c and K_{cb} , for most vegetable crops. However, only a part of the published studies is effectively usable when aiming at consolidated updates of standard K_c and K_{cb} values. Updates were only performed for the mid- and end-season values given the enormous variability of values reported for the initial stage. Non-selected crop coefficient literature refers to studies that:

- Did not adopt the FAO56 segmented crop coefficient curve, namely, describing K_c as a non-linear function of time, which may be adequate for local purposes in climates with small variability of climate.
- Were performed along a single crop season with insufficient discussion that could allow evaluation of whether one-year environmental characteristics led to appropriately or poorly assessed K_c or K_{cb} values.
- Adopted a reference evapotranspiration different from the grass FAO-PM or the grass ASCE-PM (ET_o), such as pan ET, the FAO24 Penman, or the Hargreaves–Samani equation.
- Insufficiently described the methods used to measure or estimate crop evapotranspiration and, therefore, did not allow understanding about the quality of performed field work and related data analysis.
- Lacked 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.

A common problem was that climate descriptions were insufficient and, consequently, the papers presenting data on the variables used to adjust observed K_c and K_{cb} to the standard climate (Eqs. (5) and (6)), i.e., RH_{min} , u_2 , and crop height averages for the mid- and end-season, were very rare. Therefore, it was necessary to find estimated parameters using internet information to resolve the observed K_c or K_{cb} data to the standard climate. Knowing the location of the experiments, a search for climate data relative to those experimental years and growth periods was performed, and the resultant climate values were used. In cases when data for the experimental location could not be found, data for a nearby location was used. While it was evident that the average climate values used from the internet searches provided less-accurate adjustment for the actual K_c and K_{cb} reported, however, without that data, it would not have been possible to perform that adjustment for most of collected information. The large majority of papers also did not provide information on observed crop heights and so the maximum heights tabulated in FAO56 for the crops were used for this adjustment.

The included papers refer to a variety of approaches used to estimate $ET_{c\ act}$. The approaches consist of:

- Weighing lysimeters (WL): data were used when WL were installed in large fields where it is possible to assume that local advection or clothesline effects did not affect results. When weighing lysimeter description was 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, those 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 DL and WTL 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 reported, correction methods were mentioned, and closure error was discussed.

- Soil water balance (SWB): data were selected when there was adequate information on location, depth and frequency of observations, deep percolation was considered, and there was evidence that computed soil moisture dynamics followed that of observations. In addition, plots in accepted studies had to have a minimum size to avoid local advection or clothesline effects.
- SWB models: data were used when there was evidence of model calibration and validation. Models considered included ISAREG (Pereira et al., 2003; Chaterlán et al., 2011), MOPECO (Domínguez et al., 2011; Martínez-Romero et al., 2019) and SIMDualKc (Rosa et al., 2012; Paredes et al., 2018). The growth-yield model AquaCrop (Rinaldi et al., 2011) was also considered.
- Remote sensing of vegetation index (NDVI or SAVI): used when at least two years of observations were used, information allowed to perceive that NDVI or SAVI were obtained for a non-stressed crop, and when the relationship between the crop coefficient and the vegetation index were properly calibrated/tested.
- Remote sensing energy balance: used when measurements adhered to the same limitations and physics as other measurement methods.

The subscript (obs) is adopted to identify the collected K_c and K_{cb} values reported in literature as being obtained from field observations of $ET_{c\ act}$. Aiming at transferability, those collected crop coefficients were adjusted to the standard climate and are identified with the subscript (std), thus indicating that such values are standard single or basal crop coefficients. Reported $K_{c\ (std)}$ or $K_{cb\ (std)}$ were very rare, so the adjustments to climate using Eqs. (5) and (6) were the rule. For all crops, actual $K_{c\ (obs)}$ are reported more often than $K_{cb\ (obs)}$, likely because the derivation of the latter requires the partition of $ET_{c\ act}$. Performing that partition is quite demanding both in terms of field data collection, e.g., with WL, or the use of a specific computation algorithm, which may be incorporated in simulation models, such as the SIMDualKc model.

Collected information are presented in Tables for all groups of crops. For each group, Tables include:

- 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 allow a sense of the climate type;
- The field method used to gather data aimed at estimating $ET_{c\ act}$ (as discussed above);
- The irrigation method used;
- Information on the reported $K_{c\ mid\ (obs)}$ and $K_{c\ end\ (obs)}$, or on the $K_{cb\ mid\ (obs)}$ and $K_{cb\ end\ (obs)}$; 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 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}).

For many crops, unfortunately, the ancillary information is incomplete or lacking. It may be noted that most of ancillary parameters were provided by studies using a soil water balance approach or when a dual K_c approach was adopted. However, we did include ancillary data for certain studies, though not usable for standard crop coefficients due to non-pristine crop conditions (e.g., obvious water stress). These studies

with ancillary data were retained, as they met all other requirements, e.g., proper ET_o and $ET_{c\ act}$ measurements, large fields, etc.

General guidelines to derive K_{cb} from the standard K_c values tabulated are those used in FAO56 (Allen et al., 1998):

Mid-season:

Ground cover (f_c) more than 80%

$$K_{cb\ mid} = K_{c\ mid} - 0.05 \quad (9a)$$

Ground cover (f_c) less than 80%

$$K_{cb\ mid} = K_{c\ mid} - 0.10 \quad (9b)$$

At end of season:

Infrequently irrigated or wetted during late season

$$K_{cb\ end} = K_{c\ end} - 0.05 \quad (10a)$$

Frequently irrigated or wetted during late season

$$K_{cb\ end} = K_{c\ end} - 0.10 \quad (10b)$$

When f_c is large, as it commonly occurs with vegetables, soil evaporation is small because most of the ground area is shadowed, therefore a limited amount of short-wave radiation is available for providing energy for soil water evaporation. This fact limits differences among irrigation methods and the effects of mulch. Since mulch effects were not considered in this report, users should make the necessary adjustments, if required.

4. Review on derived single and basal crop coefficients

4.1. Roots, tubers, bulbs and stem vegetable crops

Collected single and basal crop coefficients obtained from literature for roots, tubers, bulbs and stem vegetable crops are presented in Table 1. $K_{c\ mid\ (std)}$ and $K_{c\ end\ (std)}$ tabulated in Table 1, as well as $K_{cb\ mid\ (std)}$ and $K_{cb\ end\ (std)}$, were compared among studies relative to the same or similar crop and with values tabulated in FAO56. The crop coefficient values reported in the selected literature generally show coherence. However, discrepancies exist that mainly occur at the end-season of some crops, e.g. onion and garlic, because crop management and environmental conditions prior to harvesting, which influence the duration of senescence and the soil dryness at the harvest, may differ from a location to another and with the crop variety.

The number of selected papers reporting on deriving K_c or K_{cb} for roots, tubers, bulbs and stem vegetable crops was not large. Many papers on these crops had to be discarded because they did not use the $PM-ET_o$ equation and/or did not adopt research practices in agreement with the experimental requirements defined above, which are needed for K_c accuracy. In addition, some papers could not be selected as they did not provide a clear description of the crop itself, nor of the field methods, thus limiting ability to assess the accuracy of observations. Papers on various root crops, whose K_c and K_{cb} were provided in FAO56 – parsnip, turnip and table beets –, tuber crops – radish and rutabaga – and stem crops – asparagus and celery, are not available and related updates were not possible. Contrasting, a common tropical/sub-tropical crop not previously considered in FAO56, the taro (*Colocasia esculenta*), is now added. Its edible part is a corm. The study Mabhaudhi et al. (2013) was developed in South Africa to assess the performance of three varieties under drip irrigation; a SWB based on FDR observations was used and has shown that $K_{c\ end}$ is almost as high as $K_{c\ mid}$ due to the crop preference for high moisture soils.

Two papers were selected for cassava, both referring to studies developed in Thailand using BREB and referring to rainfed crops (Watanabe et al., 2004; Attarod et al., 2006). However, reported $K_{c\ mid}$ and $K_{c\ end}$ are different between both studies, which likely is a consequence of different rainfall conditions since both studies refer to rainfed crops.

Table 1

Field derived actual K_c (obs) and K_{cb} (obs) for mid and end season and respective values adjusted to the standard climate ($RH_{min} = 45\%$, $u_2 = 2 \text{ m s}^{-1}$), K_c (std) and K_{cb} (std) for roots, tubers, bulbs and stem vegetable crops.

Crop	Reference	Location	Methods to estimate ET_c act	Irrigation method	K_c/K_{cb} derived from field observations		K_c/K_{cb} adjusted to the standard climate	
					K_c mid (obs)	K_c end (obs)	K_c mid (std)	K_c end (std)
Single crop coefficient								
Carrots (<i>Daucus carota</i>)	Chaterlán et al. (2011)	Alquizar, Havana, Cuba	SWB-gravimet., ISAREG	Micro-sprinkler	0.96	0.80	1.01	0.84
	Carvalho et al. (2016)	Seropédica, Brazil	SWB-TDR	Sprinkler	1.02	0.96	1.04	0.98
Cassava (<i>Manihot esculenta</i>)	Watanabe et al. (2004)	Khon Kaen, Thailand	BREB	Rainfed	1.20	0.80	1.19	0.80
	Attarod et al. (2006)	Konburi, Thailand	BREB	Rainfed	0.90	0.60	0.95	0.63
Garlic (<i>Allium sativum</i>)	Villalobos et al. (2004)	Córdoba, Spain	EC	Sprinkler	1.20	0.70	1.17	0.66
	Bryla et al. (2010)	Five Points, CA, USA	WL	SDI	1.30	0.15	1.18	0.15
	Chaterlán et al. (2011)	Alquizar, Havana, Cuba	SWB-gravimet., ISAREG	Micro-sprinkler	0.83	0.75	0.88	0.80
Onion (<i>Allium cepa</i>)								
Dry	López-Urrea et al. (2009a)	Albacete, Spain	WL	Sprinkler	1.20	0.75	1.13	0.68
	Piccinni et al. (2009)	Uvalde, TX, USA	WL	SDI	0.87	0.70	0.84	0.63
	Chaterlán et al. (2011)	Alquizar, Havana, Cuba	SWB-gravimet., ISAREG	Micro-sprinkler	1.04	0.45	1.09	0.51
	Bossie et al. (2009)	Awash Melkassa, Ethiopia	DL and SWB-neutron	Furrow	0.99	0.46	0.95	0.42
Green	Carvalho et al. (2018)	Seropédica, RJ, Brazil	SWB-TDR	Sprinkler	1.00	0.80	1.02	0.81
Potato (<i>Solanum tuberosum</i>)	Sousa and Pereira (1999)	Chaves, Portugal	SWB-neutron, ISAREG	Furrow	1.15	0.10	1.11	0.10
	Zairi et al. (2003)	Siliana, Tunisia	SWB-neutron, ISAREG	Surface	1.15	0.40	1.10	0.40
	Tasumi and Allen (2007)	Magic Valley, Idaho, USA	RS, METRIC model	Sprinkler & furrow	1.14* 1.17**	n/r n/r	1.08* 1.11**	n/r n/r
	Paredes et al. (2018)	Bari, Italy	SWB-gravimet., SIMDualKc	Drip	1.14	0.45	1.14	0.45
	Martínez-Romero et al. (2019)	Álava, Spain	SWB — Resist., MOPECO	Sprinkler	1.10	n/r	1.13	n/r
Sweet potato (<i>Ipomoea batatas</i>)	Gomes and Carr (2003)	Umbelúzi, Mozambique	SWB — neutron	Sprinkler	1.20	0.80	1.21	0.81
	Mulovhedzi et al. (2020)	Roodeplaar, South Africa	EC	Sprinkler	0.97	0.44	0.93	0.44
Taro (<i>Colocasia esculenta</i>)	Mabhaudhi et al. (2013)	Roodeplaar, South Africa	SWB — FDR	Drip	1.15	1.10	1.15	1.10
Basal crop coefficient					K_{cb} mid (obs)	K_{cb} end (obs)	K_{cb} mid (std)	K_{cb} end (std)
Garlic (<i>Allium sativum</i>)	Bryla et al. (2010)	Five Points, CA, USA	WL	SDI	1.05	0.15	1.00	0.15
	Johnson and Trout (2012)	Five Points, CA, USA	RS-NDVI	SDI	1.00	0.35	0.95	0.35
Onion (Dry) (<i>Allium cepa</i>)	López-Urrea et al. (2009a)	Albacete, Spain	WL	Sprinkler	1.10	0.65	1.03	0.58
Potato (<i>Solanum tuberosum</i>)	Paredes et al. (2018)	Bari, Italy	SWB-gravimet., SIMDualKc	Drip	1.10	0.35	1.10	0.35

* Short season; ** Long season;

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

Five papers relative to the potato crop were selected (Sousa and Pereira, 1999; Zairi et al., 2003; Tasumi and Allen, 2007; Martínez-Romero et al., 2019; Paredes et al., 2018), the latter using the dual K_c approach. Values for K_c for the mid-season are quite similar but those for the end season diverge. In particular, the very low $K_{c \text{ end (std)}} = 0.10$

reported by Sousa and Pereira (1999) refers to a specific management practice with harvesting after natural vine kill in the field. The paper by Tasumi and Allen (2007) is the only one that distinguishes long from short season potato; however, both $K_{c \text{ mid}}$ values are very close, while no information was provided for $K_{c \text{ end}}$. Two papers on sweet potato

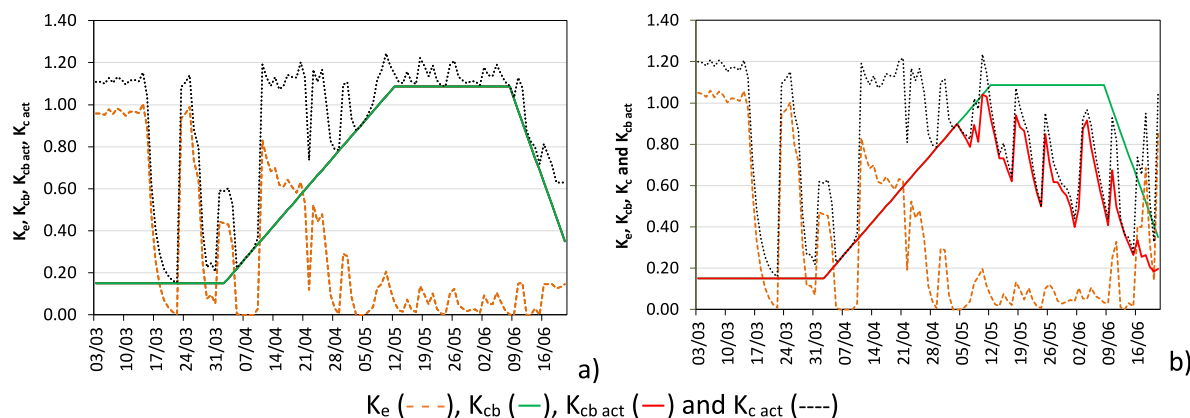


Fig. 3. Example of simulated seasonal dynamics of the crop coefficients using the model SIMDualKc after proper calibration for: (a) fully-irrigated and (b) water stressed potato cropped at Valenzano, Italy (Paredes et al., 2018).

were selected, the first referring to the determination of $ET_{c\ act}$ with a SWB supported by neutron probe measurements, however without using a model (Gomes and Carr, 2003), and the second reporting on the use of EC to measure $ET_{c\ act}$ (Mulovhedzi et al., 2020). The latter, a more recent study, reported smaller mid- and end-season crop coefficients than the former, likely in relation to the variety, the precision of the applied sprinkler irrigation, and the accuracy of ET measurements used. The studies on potato and sweet potato derived seasonal $ET_{c\ act}$ from a soil water balance (SWB) based upon field observations. The exceptions were the study by Tasumi and Allen (2007), which used remote sensing observations combined with the METRIC model, and that by Mulovhedzi et al. (2020) using EC in a large sweet potato field. Soil water content (SWC) measurements were performed with various methods and data analysis was performed with different SWB models: the ISAREG model (Sousa and Pereira, 1999; Zairi et al., 2003), the SIMDualKc model (Paredes et al., 2018), and the MOPECO model (Martínez-Romero et al., 2019).

An example of the dynamics of the crop coefficients for a fully-irrigated and a water stressed potato crop is presented in Fig. 3 (Paredes et al., 2018). Results of both irrigation management strategies clearly show that K_e is the main component of K_c during the initial and early development stages, which relates to the low soil coverage by the crop during those stages. Differently, during the mid- and late-season stages K_{cb} is the main component of K_c . Under water stress conditions (Fig. 3b), the $K_{cb\ act}$ curve lays below the K_{cb} curve, starting shortly before mid-season. Due to the effects of water stress, plant canopy was also observed to cover less soil, particularly in the late season, which corresponded to higher K_e peaks than those for fully-irrigated potato. Water stress also influenced the actual K_c curve, which remained below the potential K_{cb} curve during the mid-season stage. The analyses in Fig. 3 illustrate why selected papers were required to provide evidence that their derived K_e or K_{cb} were obtained for crops grown in well-watered conditions.

Five studies were also selected for onions. Two of them used weighing lysimeters (López-Urrea et al., 2009a; Piccinni et al., 2009), one used SWB with the model ISAREG (Chaterlán et al., 2011), another consisted of drainage lysimeters using neutron probes to perform the water balance (Bossie et al., 2009), and the last used a SWB supported by TDR (Carvalho et al., 2018). The latter study refers to harvesting onion green, and thus, $K_{c\ end\ (std)}$ was higher than those for dry onions, while they had similar $K_{c\ mid\ (std)}$ values. The study by López-Urrea et al. (2009a) derived both K_e and K_{cb} for onions, whose time-trends are depicted in Fig. 4 along one season. Results show that onion K_{cb} is the main K_c component during the mid and late season stages despite the numerous wetting events that occur during these stages. This relates with the high ground cover by the crop during these stages. However, authors refer that advection may have influenced $K_{c\ mid\ (obs)}$. The $K_{c\ mid\ (std)}$ values reported in the selected papers for onions vary by

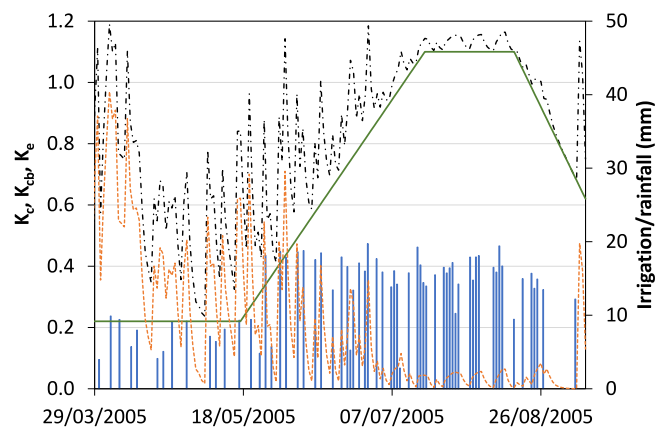


Fig. 4. Season dynamics of onion (K_{cb} , —), single crop coefficient (K_c , - - -), and soil evaporation coefficient (K_e , - - -) obtained from weighing lysimeter measurements. Also depicted wetting events by irrigation or precipitation (■). Source: Adapted from López-Urrea et al. (2009a).

about 20% but differences for $K_{c\ end\ (std)}$ are larger, particularly when green harvested onion is considered.

There are four studies selected on garlic. One used eddy covariance for $ET_{c\ act}$ measurement (Villalobos et al., 2004) and another used the ISAREG model, as referred to before (Chaterlán et al., 2011). The study by Bryla et al. (2010) reported on $ET_{c\ act}$ measured with weighing lysimeters while the last paper used remote sensing for deriving basal crop coefficients (Johnson and Trout, 2012). The first two papers in the table report close $K_{c\ mid\ (std)}$ values, but the Chaterlán et al. (2011) mid-season value is much lower. However, the high $K_{c\ end\ (std)}$ values for two papers indicate harvest before senescence is completed, while the two other studies provided low $K_{c\ end\ (std)}$ and $K_{cb\ end\ (std)}$ values, indicating harvesting after vine kill. These two latter studies are from California and indicate that garlic cropping practices there were similar, likely with machine harvesting, but quite different from those adopted elsewhere, where harvesting is practiced before the crop fully senesces.

Only two papers were selected for carrots (Chaterlán et al., 2011; Carvalho et al., 2016), which describe SWB applications for $ET_{c\ act}$, the first using a gravimetric approach with the ISAREG model, and the second, a SWB application based on TDR observations, but without modeling. Both studies had similar $K_{c\ mid\ (std)}$. The study by Carvalho et al. (2016) shows a $K_{c\ end\ (std)}$ value quite close to $K_{c\ mid\ (std)}$, which indicates an early harvest for consuming fresh.

It is important to recognize the diverse geographical origin of the selected studies, which were conducted in several European countries

Table 2
Observed ancillary crop parameters for roots, tubers, bulbs and stem vegetable crops 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}
Carrots (<i>Daucus carota</i>)	Chaterlán et al. (2011)	0.30	0.30	n/r	1.0	0.30	0.30	0.30
	Carvalho et al. (2016)	n/r	0.30	n/r	n/r	n/r	n/r	n/r
Garlic (<i>Allium sativum</i>)	Bryla et al. (2010)	n/r	0.60	n/r	0.85	n/r	n/r	n/r
	Johnson and Trout (2012)	n/r	0.60	n/r	0.80	n/r	n/r	n/r
	Villalobos et al. (2004)	n/r	0.65	4.0	n/r	n/r	n/r	n/r
	Chaterlán et al. (2011)	0.30	n/r	n/r	n/r	0.30	0.30	0.30
Onion (Dry) (<i>Allium cepa</i>)	López-Urrea et al. (2009a)	0.40	n/r	n/r	0.72	0.30	0.30	0.30
	Chaterlán et al. (2011)	0.30	n/r	n/r	n/r	0.30	0.60	0.60
Potato (<i>Solanum tuberosum</i>)	Zairi et al. (2003)	0.50	n/r	n/r	n/r	0.50	0.38	0.47
	Paredes et al. (2018)	0.50	0.60	n/r	0.88	0.40	0.40	0.40
Sweet potato (<i>Ipomoea batatas</i>)	Gomes and Carr (2003)	1.00	n/r	n/r	n/r	0.35	0.35	0.35
	Mulovhedzi et al. (2020)	1.00	0.50	2.5	0.98	0.50	0.50	0.50
Taro (<i>Colocasia esculenta</i>)	Mabhaudhi et al. (2013)	0.30	1.20	4.3	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 the initial, mid- and end-season stages, respectively; n/r – not reported.

– Germany, Italy, Portugal and Spain –, North, Central, and South American countries – USA, Cuba and Brazil, – northern and southern African countries – Ethiopia, Tunisia, South Africa and Mozambique –, and Thailand. These wide origins indicate that good studies were performed for various environmental and socio-economic conditions, which allow practitioners to better select appropriate research options, when required.

Often, studies were performed with drip irrigation; a few used micro-sprinklers, micro-sprayers, sprinklers, or surface irrigation. Generally, single crop coefficients tended to be smaller with drip irrigation, corresponding with less soil wetting and smaller soil evaporation losses. However, due to the small set of papers for these crops, it was not possible to quantitatively relate mid-season differences in K_c to irrigation method. In addition, regardless of irrigation method, most crops attained effective full cover of the soil by the mid-season, which mitigates the possible reduction of $K_{c \mid mid}$ due to mulches.

Studies indicated in Table 1 provided some information about main ancillary crop parameters that are used in water balance studies in conjunction with K_c -based ET_c estimates, particularly for irrigation scheduling purposes. These parameters are presented in Table 2. Unfortunately, that information is missing or incomplete for various crops. However, the derived parameters are generally consistent for a given crop, except for the p fractions in dry onions. In general, the ancillary crop data are also close to the FAO56 parameters for these crops. It may be noted that most of parameters were provided by studies using a soil water balance approach or when a dual K_c approach was adopted.

4.2. Leaves and flowers vegetable crops

Collected single and basal crop coefficients obtained from literature for leaves and flowers vegetable crops are presented in Table 3. Tabled K_c values are lower than those originally reported in cases when authors assumed $K_{c \mid mid}$ as a maximum average for a period smaller than the mid-season. If the data were graphically presented, it was then possible to estimate a lower average value for $K_{c \mid mid (obs)}$ and it was also possible to better estimate $K_{c \mid end (obs)}$. For a few cases, when papers include a graphical presentation of the season dynamics of K_{cb} and K_c , the K_c values were estimated from K_{cb} .

Most studies were performed with drip irrigation; only a few used micro-sprinkling or micro-sprayers, and even fewer used furrow irrigation. The K_c tend to be smaller with drip irrigation since less soil is wetted, often under the shadow provided by the canopy, thus soil evaporation is smaller. However, since the frequency of drip irrigation may be very high, E_s may be less reduced comparatively to micro-sprinklers or sprayers. Soil evaporation also is not high when, by the

mid-season, a full cover condition occurs and the energy available at the soil for evaporation is small. Because harvesting of leaves and flowers vegetable crops is commonly performed before senescence starts, or when only a slight maturation occurs, ground cover by vegetation is kept high and, therefore, soil evaporation is maintained small until harvesting. Therefore, reductions in K_c when using drip irrigation relative to micro-sprinklers or micro-sprayers likely do not exceed around 5%, i.e., $K_{c \mid mid \ act}$ for drip irrigation may be smaller by about 0.05 than for micro-sprinklers or sprayers. However, various papers refer to larger K_c differences, up to 30%, but do not show a justification for that high difference in actual ET since values of the fraction of crop ground cover or differences in the radiation energy available at the soil are not reported. Since K_{cb} values do not include soil evaporation, K_{cb} values likely do not change or change little with the irrigation method in the case of vegetable crops, i.e., $K_{cb \mid mid}$ and $K_{cb \mid end}$ values should not change, or change little, when the crop nearly fully covers the ground. Contrarily, E_s varies much during the first crop stages when there is an incomplete ground cover. Differently, the effects of mulch are expected to be larger. When a plastic mulch is used, the possible inter-row process of conversion of sensible into latent heat may reduce the effects of the plastic mulch as noted by Lund and Soegaard (2003), who reported on the within canopy advection of sensible heat. However, this process was not referred in any of the selected studies.

Research studies on deriving K_c or K_{cb} for Brussels sprouts and cauliflower were not found. Only the study by Grattan et al. (1998) was selected for artichoke. In this study, furrow irrigation was used, and $ET_{c \ act}$ was measured using BREB instrumentation with good fetch. However, their mid-season K_c was quite low when compared to artichoke tabled in FAO56.

Three studies relative to broccoli were selected (López-Urrea et al., 2009b; Bryla et al., 2010; Johnson and Trout, 2012), which provided data on actual K_c and K_{cb} . The first two were developed with weighing lysimeters and the latter with RS-NDVI. All of them provided for K_{cb} data. However, different than the tabulated value for broccoli in FAO56, they reported end season values equal to the mid-season ones, which indicates that harvesting for fresh human consumption is done when broccoli is green and tender, i.e., before senescence starts to occur. The same equality for mid- and end-season K_c and K_{cb} happens with lettuce and spinach (Table 3).

An example showing the dynamics of K_{cb} , K_c and K_{cb} for broccoli is presented in Fig. 5. Broccoli ET_c measurements were obtained from a large weighing lysimeter (López-Urrea et al., 2009b). Specifically, ET_c values were calculated from lysimeter's daily mass loss minus drainage

Table 3

Field derived actual K_c (obs) and K_{cb} (obs) for mid and end season and respective values adjusted to the standard climate ($RH_{min} = 45\%$, $u_2 = 2 \text{ m s}^{-1}$), K_c (std) and K_{cb} (std) for leaves and flowers vegetable crops.

Crop	Reference	Location	Methods to estimate ET_c act	Irrigation method	K_c / K_{cb} derived from field observations		K_c / K_{cb} adjusted to the standard climate	
					K_c mid (obs)	K_c end (obs)	K_c mid (std)	K_c end (std)
Single crop coefficient								
Artichoke (<i>Cynara scolymus</i>)	Grattan et al. (1998)	Castroville, CA, USA	BREB	Furrow	0.76	n/r	0.77	n/r
Broccoli (<i>Brassica oleracea</i>)	López-Urrea et al. (2009b)	Albacete, Spain	WL	Sprinkler	1.10	1.10	1.09	1.09
	Bryla et al. (2010)	Five Points, CA, USA	WL	SDI	1.05	1.05	1.11	1.11
Cabbage (<i>Brassica oleracea</i>)	Chaterlán et al. (2011)	Alquizar, Havana, Cuba	ISAREG, SWB-gravimet.	Micro-sprinkler	1.05	0.95	1.10	1.00
	Zhang et al. (2011)	Wellesbourne, UK	SWB-Resist., Inverse model	Drip	1.05	1.05	1.05	1.05
Lettuce (<i>Lactuca sativa</i>)	Bryla et al. (2010)	Five Points, CA, USA	WL	SDI	1.00	1.00	1.02	1.02
	Fernández-Pacheco et al. (2014)	Fuente Álamo, Murcia, Spain	BREB & Digital-image	Drip	1.03	0.98	0.99	0.94
	Oliveira et al. (2005)	Maricopa, AZ, USA	DL, SWB-TDR	SDI	0.95	0.95	0.92	0.92
	Giménez et al. (2019)	Salinas, CA, USA; Cordoba, Spain	VegSyst-Outdoors	Sprinkler	1.10	1.10	1.08	1.08
Spinach (<i>Spinacia oleracea</i>)	Piccinni et al. (2009)	Uvalde, TX, USA	WL	SDI	1.02	1.02	0.98	0.98
	Giménez et al. (2019)	Cordoba, Spain	VegSyst-Outdoors	Sprinkler	1.00	1.00	0.98	0.98
Basal crop coefficient					K_{cb} mid (obs)	K_{cb} end (obs)	K_{cb} mid (std)	K_{cb} end (std)
Broccoli (<i>Brassica oleracea</i>)	López-Urrea et al. (2009b)	Albacete, Spain	WL	Sprinkler	0.95	0.95	0.94	0.94
	Bryla et al. (2010)	Five Points, CA, USA	WL	SDI	1.00	1.00	1.01	1.01
	Johnson and Trout (2012)	Five Points, CA, USA	RS-NDVI	SDI	1.00	1.00	1.01	1.01
Cabbage (<i>Brassica oleracea</i>)	Zhang et al. (2011)	Wellesbourne, UK	SWB-Resist., Inverse model	Drip	0.95	0.90	0.96	0.90
Lettuce (<i>Lactuca sativa</i>)	Bryla et al. (2010)	Five Points, CA, USA	WL	SDI	0.95	0.95	0.97	0.97
	Johnson and Trout (2012)	Five Points, CA, USA	RS-NDVI	SDI	0.90	0.90	0.92	0.92
	Ramírez-Cuesta et al. (2019)	Murcia, Spain	RS-SAVI, model DualKc-ArcPy	Drip	0.85	0.80	0.84	0.80

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

loss and the mass from irrigation and/or rainfall was added. K_c data were calculated as the ratio of the lysimeter measured ET_c to ET_o computed daily with the FAO56-PM equation. The soil evaporation coefficient (K_e) was calculated with the standard FAO56 approach (Allen et al., 1998) and, afterwards, the basal crop coefficient (K_{cb}) was obtained from the lysimeter K_c values minus the calculated K_e values. Results in Fig. 5 show several K_e peaks, occurring in response to wetting events. These peaks are particularly high during the initial and early crop development stages, when the fraction of ground cover by the crop (f_c) is small and, therefore, solar energy is largely available at the soil surface for evaporation. During the mid and late seasons, when f_c is higher, the K_e peaks are smaller and K_{cb} becomes the main component of K_c . As previously pointed out, $K_{cb\ end}$ equals $K_{cb\ mid}$ because the broccoli was harvested before senescence.

Cabbage crop coefficients are reported in a few papers but only two studies could be selected (Chaterlán et al., 2011; Zhang et al., 2011). Both performed a SWB, the first using a gravimetric approach along with the ISAREG model, and the latter using Watermark soil moisture

sensors and a purposefully developed inverse modeling approach. Their calibrated K_c values are close to those tabulated in FAO56, thus with $K_{cb\ end\ (std)}$ slightly smaller or equal to $K_{cb\ mid\ (std)}$. This means that cabbage harvesting was performed early to assure tender produce, thus with high $K_{cb\ end}$ values. Zhang et al. (2011) also reported on basal K_{cb} values.

There are various studies reporting on K_c and K_{cb} for lettuce. Values for the mid-season are not very different. Discordance comes from the fact that while three of them (Oliveira et al., 2005; Bryla et al., 2010; Giménez et al., 2019) reported equal values for $K_{cb\ mid\ (std)}$ and for $K_{cb\ end\ (std)}$, the study by Fernández-Pacheco et al. (2014) proposes a lower value for $K_{cb\ end\ (std)}$. The K_{cb} values proposed for iceberg lettuce by Bryla et al. (2010) and Johnson and Trout (2012) are similar and both papers report a $K_{cb\ end\ (std)}$, corresponding to early harvest, when leaves are green and tender; differently, Ramírez-Cuesta et al. (2019) report a lower $K_{cb\ end}$. There is no apparent justification for this difference when it is well known that tenderness of leaves is paramount for marketing lettuce for green salad. K_c and K_{cb} were

Table 4
Observed ancillary crop parameters for leaves and flowers vegetables crops 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}
Artichoke (<i>Cynara scolymus</i>)	Grattan et al. (1998)	n/r	n/r	n/r	0.60	n/r	n/r	n/r
Broccoli (<i>Brassica oleracea</i>)	López-Urrea et al. (2009b)	0.40	0.50	n/r	n/r	0.45	0.45	n/r
	Bryla et al. (2010)	n/r	0.60	n/r	1.0	n/r	n/r	n/r
	Johnson and Trout (2012)	n/r	0.60	n/r	0.95	n/r	n/r	n/r
Cabbage (<i>Brassica oleracea</i>)	Chaterlán et al. (2011)	0.30	n/r	n/r	n/r	0.40	0.40	0.40
Lettuce (<i>Lactuca sativa</i>)	Bryla et al. (2010)	0.30	0.30	n/r	0.70	n/r	n/r	n/r
	Johnson and Trout (2012)	n/r	n/r	n/r	0.70	n/r	n/r	n/r
	Fernández-Pacheco et al. (2014)	n/r	0.37	n/r	0.55	n/r	n/r	n/r
	Ramírez-Cuesta et al. (2019)	n/r	0.21	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 the initial, mid- and end-season stages, respectively; n/r – not reported.

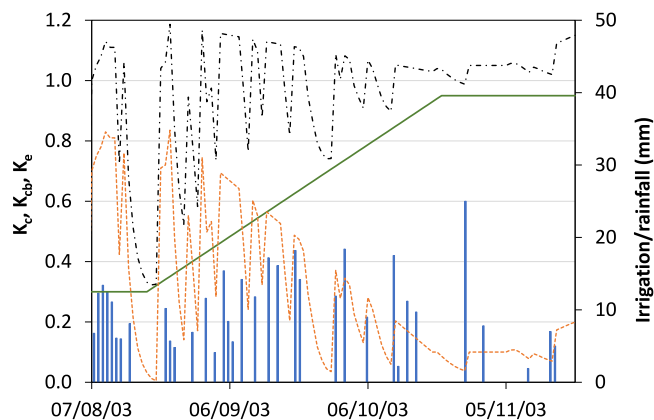


Fig. 5. Broccoli basal crop coefficient (K_{cb} , —) single crop coefficient (K_c , - - -), and soil evaporation coefficient (K_s , ···) derived from weighing lysimeter measurements. Also depicted wetting events by irrigation or precipitation (■).

Source: Adapted from López-Urrea et al. (2009b).

obtained with various methods: Bryla et al. (2010) used weighing lysimeters; Oliveira et al. (2005) performed a SWB and used DL with TDR observations; Fernández-Pacheco et al. (2014) used BREB and digital-image processing; and Giménez et al. (2019) used the model VegSyst-Outdoors calibrated and validated with dry matter production data. Finally, Johnson and Trout (2012) computed K_{cb} values with RS-NDVI and Ramírez-Cuesta et al. (2019) used RS-SAVI.

The crop coefficients for spinach reported by Piccinni et al. (2009) and Giménez et al. (2019) are very similar, with $K_{c\ end(std)} = K_{c\ mid(std)}$. The former refers to determining ET_{cact} with WL, while the latter computed ET_{cact} using the model VegSyst-Outdoors as referred above.

The reported studies provided ancillary data relative to a few crops only – artichoke, broccoli, cabbage and lettuce – which are presented in Table 4.

4.3. Fruit and pod vegetable crops

Table 5 presents, 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 $K_{c\ end(std)}$. Similarly, observed and adjusted K_{cb} values are shown in Table 5. Most selected studies refer to estimating single K_c and only a few derived basal K_{cb} values, likely because the derivation of the latter is more demanding in terms of observations and computations aimed at the partition of ET_{cact} into crop transpiration (T_{cact}) and soil evaporation (E_s). Some of the non-selected papers for these crops are highly cited but had insufficient description of methodologies for computing ET_{cact} . A good number of selected K_c studies used lysimeters, both WL

and DL, which included performing the SWB supported by either TDR or FDR sensors. In studies for tomato, BREB and EC instrumentation were used. In addition, a few SWB studies were performed based upon neutron probe, FDR, TDR and gravimetric data collection. The selected K_{cb} studies used various approaches, including one that estimated K_{cb} from NDVI remote sensing data. Others used precise WL, SWB with models such as SIMDualKc (Rosa et al., 2012), which was purposefully developed for application of the FAO56 dual K_c approach (Allen et al., 2005a,b).

The reported K_c information in many selected papers was corrected for several reasons, such as advection and clothesline effects, as previously discussed. Tabled values reported by Kong et al. (2012), Yang et al. (2018), and Bastos et al. (2012), obtained in small plots, were corrected to reduce those effects which likely caused the high K_c values reported. The $K_{c\ end(obs)}$ value for bell pepper reported by Shukla et al. (2013) was corrected to avoid the observed $K_{c\ end}$ value exceeding $K_{c\ mid}$. For papers using the CIMIS-Penman ET_o , knowing that the latter exceeds the-PM ET_o by 8% (Ittenfisu et al., 2003), the K_c values were then corrected by 8% (i.e., case of studies by Grattan et al., 1998; Hanson and Bendixen, 2004; Hanson and May, 2006). The studies by Karam et al. (2009), Yaghi et al. (2013) and Zhang et al. (2018) were retained because they provided good ancillary information, despite conducting experiments under water stress conditions and attaining low mid-season K_c values, which were not considered for the updated K_c values.

A number of research studies were performed with mulch, mainly plastic sheets (Carvalho et al., 2012; Melo et al., 2013; Shukla et al., 2013, 2014; Zheng et al., 2013; Biswas et al., 2015; Borges et al., 2015; Yang et al., 2018; Zhang et al., 2018). Their effect was not considered since this review does not refer to the periods before the mid-season when impacts of mulch in lowering E_s are greater. Moreover, by the mid-season, the canopy cover of vegetables that are consumed for fruit and pod is quite high, thus reducing the impacts of mulches. Nevertheless, users are invited to adopt a 5 to 10% K_c correction if considered appropriate for their uses. The study by Carvalho et al. (2012) evidenced a consistent reduction of $K_{c\ mid(std)}$ and $K_{c\ end(std)}$ when no-till was used, i.e., when crop residues act as a mulch. Nevertheless, it has not been possible to assess the impacts of mulches, which certainly tend to reduce both $K_{c\ mid}$ and $K_{c\ end}$, however depending on the fraction of ground cover, f_{c} , which is rarely reported.

Drip irrigation is the most common method referred in the selected references. The research on squash reported by Amer (2011) shows that K_c values are larger for furrow irrigation comparatively to drip irrigation, with $K_{c\ mid(std)}$ of 1.07 for furrows and 1.01 for drip. The difference is small but gives some evidence. Assuming that the worldwide tendency will be towards adopting drip irrigation in vegetable crops production, consideration needs to be given on adopting reduced K_c (and K_{cb}) values for drip. As these selected papers using drip

Table 5

Field derived actual K_c (obs) and K_{cb} (obs) for mid and end season and respective values adjusted to the standard climate ($RH_{min} = 45\%$, $u_2 = 2 \text{ m s}^{-1}$), K_c (std) and K_{cb} (std) for fruit and pod vegetables.

Crop	Reference	Location	Methods to estimate ET_c act	Irrigation method	K_c/K_{cb} derived from field observations		K_c/K_{cb} adjusted to the standard climate	
					K_c mid (obs)	K_c end (obs)	K_c mid (std)	K_c end (std)
Single crop coefficient								
Bell pepper (<i>Capsicum annuum</i>)	Karam et al. (2009)	Tal Amara, Bekaa, Lebanon	WL, SWB-TDR	Drip	0.90	0.82	0.90	0.84
	Kong et al. (2012)	Datong, Shanxi, China	DL, SWB, TDR	SDI	1.15	0.76	1.14	0.83
	Shukla et al. (2013)	Immokalee, FL, USA	DL, SWB-FDR	Sub-irrigation	1.21	1.21	1.25	1.25
Chili pepper (<i>Capsicum annuum</i>)	Yang et al. (2018)	Wuwei, Gansu, China	SWB-gravimet.	Drip	1.22	0.84	1.13	0.76
Chili, tabasco pepper (<i>Capsicum frutescens</i>)	Miranda et al. (2006)	Paraipaba, Ceará, Brazil	WL	Drip				
					First harvest	1.22	0.65	1.32
					1.08	0.60	1.16	0.62
Cucumber (<i>Cucumis sativus</i>)	Amer et al. (2009)	Shibin El-Kom, Egypt	SWB-gravimet.	Drip	1.07	0.63	1.08	0.65
	Yaghi et al. (2013)	Hama, Syria	SWB-neutron	Drip	0.68	0.60	0.61	0.54
Eggplant (<i>Solanum melongena</i>)	Carvalho et al. (2012)	Seropédica, RJ, Brazil	WL, SWB-TDR	Micro-sprinkler				
					No-till	0.94	0.95	0.99
					1.14	1.05	1.19	1.06
Melon (<i>Cucumis melo</i>)	Miranda and Bleicher (2001)	Paraipaba, Ceará, Brazil	WL	Drip	1.20	0.97	1.20	0.97
	Borges et al. (2015)	Mossoró, RN, Brazil	BREB	Drip	0.96	0.63	0.96	0.64
Melon, cantaloupe (<i>Cucumis melo</i>)	Melo et al. (2013)	Mossoró, RN, Brazil	WL	Drip	1.06	0.85	1.04	0.81
Okra (<i>Abelmoschus esculentus</i>)	Dukes et al. (2015)	Florida, USA	SWB-capacit.	n/r	1.00	0.90	1.00	0.90
	Patil and Tiwari (2018)	Kharagpur, India	DL, SWB-capacit.	SDI	0.95	0.65	0.93	0.63
	Patil and Tiwari (2019)	Kharagpur, India	SWB-capacit., SIMDualKc	SDI	0.95	n/r	0.93	n/r
Pumpkin, winter squash (<i>Cucurbita pepo</i>)	Yavuz et al. (2015)	Konya, Turkey	SWB-gravimet.	Drip	0.95	0.65	0.91	0.60
Tomato (<i>Solanum lycopersicum</i>)								
For processing	Hanson and May (2006)	San Joaquin V., California	BREB, SWB-resist.	SDI & furrow	1.11	n/r	1.08	n/r
	Garofalo et al. (2011)	Foggia, Italy	WL	Drip	1.11	0.80	1.08	0.75
	Rana et al. (2012)	Foggia, Italy	EC, SWB-gravimet.	Drip	1.13	n/r	1.09	n/r
Fresh market	Yacoubi et al. (2010)	Ariana, Tunisia	ISAREG, SWB-neutron	Sprinkler	1.15	0.68	1.10	0.63
	Zheng et al. (2013)	Wuwei, Gansu, China	SWB-TDR, A&P approach	Drip	1.10	1.05	1.11	1.07
	Biswas et al. (2015)	Gazipur, Bangladesh	DL, gravimet.	Drip	1.08	0.86	1.08	0.84
	Alkhasha and Al-Omran (2019)	Thadiq, Saudi Arabia	SWB-gravimet., SALTMED	Drip	1.15	1.03	1.07	0.96
Squash, Zucchini (<i>Cucurbita pepo</i>)	Amer (2011)	Shibin El-Kom, Egypt	SWB-FDR	Drip	1.02	0.63	1.01	0.65
				Furrow	1.08	0.68	1.07	0.70
Strawberries (<i>Fragaria × ananassa</i>)	Grattan et al. (1998)	Oceanside, CA, USA	BREB	Drip	0.76	n/r	0.78	n/r
	Hanson and Bendixen (2004)	Santa Maria Valley, CA, USA	SWB-TDT	Drip	0.75	n/r	0.73	n/r

(continued on next page)

irrigation indicate, the updated K_c and K_{cb} values in Table 5 rarely increased relative to the FAO56 tabled values (as also discussed later in Section 5).

The selected studies relative to bell pepper and chili pepper (*Capsicum annuum* L.) used diverse research approaches to derive K_c or K_{cb} . Those by Karam et al. (2009) and Bryla et al. (2010) used

Table 5 (continued).

Crop	Reference	Location	Methods to estimate ET_c act	Irrigation method	K_c/K_{cb} derived from field observations		K_c/K_{cb} adjusted to the standard climate	
Watermelon (<i>Citrus lanatus</i>)	Miranda et al. (2004)	Paraipaba, CE, Brazil	WL	Drip	1.20	0.60	1.16	0.56
	Bastos et al. (2012)	Parnaíba, Piauí, Brazil	WL	Drip	1.23	0.41	1.17	0.41
	Shukla et al. (2014)	Immokalee, FL, USA	DL, SWB-FDR	Sub-irrigation	1.01	0.71	1.01	0.73
Basal crop coefficient					$K_{cb\ mid}$ (obs)	$K_{cb\ end}$ (obs)	$K_{cb\ mid}$ (std)	$K_{cb\ end}$ (std)
Bell pepper (<i>Capsicum annuum</i>)	Bryla et al. (2010)	Five Points, CA, USA	WL	SDI	1.10	1.08	1.06	1.03
	Johnson and Trout (2012)	Five Points, CA, USA	RS - NDVI	Drip & surface	1.05	1.00	1.01	0.95
Chili pepper (<i>Capsicum annuum</i>) cv. Long Slim cv. Malaga cv. Mareko Fana cv. Serrano ^a	Alemayehu et al. (2009)	Pretoria, South Africa	SWB model, neutron	Drip				
					1.00	1.00	1.00	1.00
					0.97	0.85	0.99	0.87
					0.93	0.93	0.95	0.95
0.88	0.88	0.90	0.90					
Okra (<i>Abelmoschus esculentus</i>)	Patil and Tiwari (2019)	Kharagpur, India	SWB-capacit., SIMDualKc	SDI	0.85	n/r	0.83	n/r
Tomato for processing (<i>Solanum lycopersicum</i>)	Rinaldi et al. (2011)	Foggia, Italy	SWB-gravimet., AquaCrop	Drip	1.13	n/r	1.12	n/r
	Zhang et al. (2018)	Hetao, China	SWB-gravimet., SIMDualKc	Drip	0.92	0.60	0.91	0.59
Squash, Zucchini (<i>Cucurbita pepo</i>)	Darouich et al. (2020)	Zahid, Akkar region, Syria	SWB-Neutron, SIMDualKc	Surface	0.91	0.63	0.96	0.67

^aLow density.

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

well-managed weighing lysimeters, well-located in large cropped fields; the first also included the computation of the SWB based upon TDR measurements. The studies by Kong et al. (2012) and Shukla et al. (2013) were conducted with drainage lysimeters and the SWB was performed with, respectively, TDR and FDR sensors. The study by Johnson and Trout (2012) obtained K_{cb} data by remote sensing of NDVI data. The studies by Alemayehu et al. (2009) and Yang et al. (2018) were both performed using a SWB procedure based upon, respectively, neutron probe and gravimetric measurements. The study on chilli tabasco pepper (*Capsicum frutescens* L.) used a WL (Miranda et al., 2006). Comparing the $K_{c\ mid}$ (std) and $K_{c\ end}$ (std) results among those studies, it could be concluded that results reported by Karam et al. (2009) referred to non-pristine cropping conditions and, therefore, could not be used to update K_c values but could be used for the ancillary information (Table 6).

The values of $K_{c\ end}$ (std) are close to the $K_{c\ mid}$ (std) values for bell pepper because harvesting is commonly performed when fruits are green and tender, thus near to the mid-season, before senescence affects the marketable and taste characteristics of the fruit. Differently, chili pepper fruits, which are not consumed green, need a longer late-season to turn red and complete the synthesis of capsaicinoids, the substances responsible for the hot taste of the fruits. Therefore, the $K_{c\ end}$ of chili peppers are lower than the $K_{c\ mid}$. The study by Alemayehu et al. (2009) compared several chili pepper varieties; however, results for those varieties having lower K_{cb} values were not included since they were likely collected under non-pristine conditions. This study clearly shows that K_{cb} or K_c values are influenced by the crop variety. The study on tabasco pepper (*Capsicum frutescens* L.) by Miranda et al. (2006) identifies another aspect influencing the K_c values for crops aimed at the fresh market: harvesting may be performed through two harvesting periods, which requires adopting two pairs $K_{c\ mid}$ - $K_{c\ end}$ instead of a unique value for the mid- and the end-season (Table 5 and Fig. 6). Results in Fig. 6 show that after the first harvest, thus during the second crop cycle, the $K_{c\ mid}$ value is lower than that of the first cycle, which may be related to less intense flowering and fruit development.

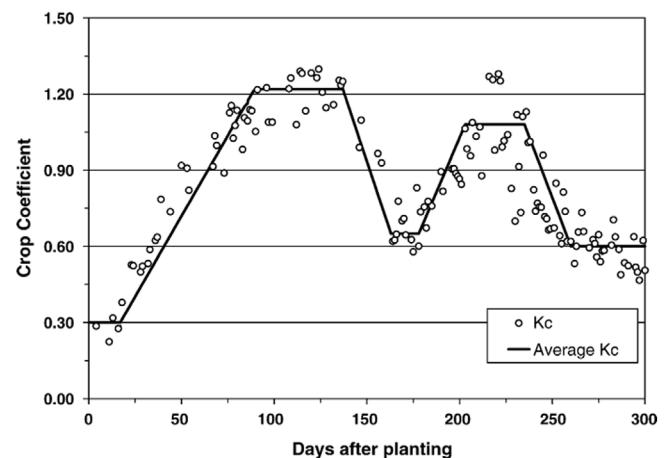


Fig. 6. Tabasco pepper single crop coefficient (K_c) estimated for first and second harvest cycles from weighing lysimeter measurements at Paraipaba, Ceará, Brazil. Source: From Miranda et al. (2006).

Few studies report on K_c or K_{cb} for eggplant and only one was retained (Carvalho et al., 2012). This study compared no-till with conventional tillage and results show that K_c for no-till are smaller than those for conventional tillage due to the effect of the residue cover. This demonstrates impacts of crop residues on K_c , quite large in the referred application since the eggplant usually leaves a relatively large ground fraction exposed to radiation. Moreover, results indicate that $K_{c\ end}$ should be close to $K_{c\ mid}$ since the fruit should be harvested tender.

Several studies focusing on tomato K_c and K_{cb} were selected. They used a variety of procedures to estimate crop ET. Hanson and May (2006) used both BREB and SWB, while Rana et al. (2012) adopted EC observations. SWB models were used by Yacoubi et al. (2010)

Table 6
Observed ancillary crop parameters for fruit and pod vegetables 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}
Bell pepper (<i>Capsicum annuum</i>)	Karam et al. (2009)	0.30	n/r	3.0	n/r	n/r	n/r	n/r
	Bryla et al. (2010)	n/r	0.60	n/r	0.90	n/r	n/r	n/r
	Johnson and Trout (2012)	n/r	n/r	n/r	0.90	n/r	n/r	n/r
	Kong et al. (2012)	0.40	0.48	n/r	n/r	n/r	n/r	n/r
	Shukla et al. (2013)	0.60	n/r	n/r	n/r	n/r	n/r	n/r
Chili pepper (<i>Capsicum annuum</i>)	Alemayehu et al. (2009)							
	cv. Long Slim	0.60	0.74	2.0	0.82	0.20 ⁽¹⁾	0.20 ⁽¹⁾	0.20 ⁽¹⁾
	cv. Malaga	0.60	0.76	2.2	0.76	0.20 ⁽¹⁾	0.20 ⁽¹⁾	0.20 ⁽¹⁾
	cv. Mareko Fana	0.60	0.73	1.7	0.73	0.20 ⁽¹⁾	0.20 ⁽¹⁾	0.20 ⁽¹⁾
	cv. Serrano ^a	0.60	0.68	1.3	0.68	0.20 ⁽¹⁾	0.20 ⁽¹⁾	0.20 ⁽¹⁾
Yang et al. (2018)	0.60	n/r	n/r	n/r	n/r	n/r	n/r	
Chili, tabasco pepper (<i>Capsicum frutescens</i>)	Miranda et al. (2006)	0.60	0.80	n/r	0.55	n/r	n/r	n/r
Cucumber (<i>Cucumis sativus</i>)	Amer et al. (2009)	0.60	n/r	n/r	n/r	n/r	n/r	n/r
	Yaghi et al. (2013)	0.60	n/r	n/r	n/r	n/r	n/r	n/r
Eggplant (<i>Solanum melongena</i>)	Carvalho et al. (2012)	0.40	n/r	n/r	n/r	n/r	n/r	n/r
Melon (<i>Cucumis melo</i>)	Borges et al. (2015)	n/r	0.30	n/r	0.95	n/r	n/r	n/r
Okra (<i>Abelmoschus esculentus</i>)	Patil and Tiwari (2018, 2019)	0.60	0.90	4.3	n/r	0.40	0.40	0.40
Pumpkin, winter squash (<i>Cucurbita pepo</i>)	Yavuz et al. (2015)	0.90	n/r	n/r	n/r	n/r	n/r	n/r
Tomato (<i>Solanum lycopersicum</i>)	Hanson and May (2006)	n/r	n/r	n/r	0.95	n/r	n/r	n/r
	Yacoubi et al. (2010)	1.0	n/r	n/r	n/r	0.45	0.31	0.45
	Garofalo et al. (2011)	n/r	n/r	n/r	n/r	0.20	n/r	n/r
	Rinaldi et al. (2011)	0.80	n/r	n/r	0.87	0.30	0.30	0.30
	Rana et al. (2012)	n/r	0.70	4.8	n/r	n/r	n/r	n/r
	Zheng et al. (2013)	0.60	0.57	6.0	n/r	n/r	n/r	n/r
	Biswas et al. (2015)	n/r	1.25	n/r	n/r	n/r	n/r	n/r
Zhang et al. (2018)	0.60	0.48	n/r	0.70	0.30	0.30	0.30	
Squash, Zucchini (<i>Cucurbita pepo</i>)	Amer (2011)	0.50	n/r	3.5	n/r	n/r	n/r	n/r
	Darouich et al. (2020)	0.45	0.55	n/r	0.99	0.60	0.50	0.50
Strawberries (<i>Fragaria × ananassa</i>)	Grattan et al. (1998)	n/r	n/r	n/r	0.80	n/r	n/r	n/r
	Hanson and Bendixen (2004)	n/r	n/r	n/r	0.75	n/r	n/r	n/r
Watermelon (<i>Citrullus lanatus</i>)	Bastos et al. (2012)	n/r	n/r	n/r	0.80	n/r	n/r	n/r

^aLow density

$Z_{r \max}$ – 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 the initial, mid- and end-season stages, respectively; (1) value used to trigger irrigation; n/r – not reported.

and Zhang et al. (2018), the former with the ISAREG model and neutron probe measurements, and the latter with the SIMDualKc model and gravimetric SWC measurements. SWB based upon gravimetric soil sampling were used by Rinaldi et al. (2011), whereas Zheng et al. (2013) used a SWB based upon tensiometer observations and derived K_c with the Allen and Pereira (2009) approach for estimating K_c from crop density and height. Garofalo et al. (2011) used WL while Biswas et al. (2015) used DL. The observed K_{cb} by Zhang et al. (2018) was quite low; the reported information allows identifying the occurrence of water stress; therefore, only related ancillary data were further used for that study (Table 6). Contrarily to the small variation of $K_{c \text{ mid (std)}}$, the tomato values for $K_{c \text{ end (std)}}$ varied widely, from 1.05 (Zheng et al., 2013) to 0.63 (Yacoubi et al., 2010). That variability in cases of tomato for fresh market likely was due to differences in crop management, particularly when harvesting is practiced throughout several days or

weeks. Differently, the studies relative to tomato for processing (Hanson and May, 2006; Rana et al., 2012) do not provide $K_{c \text{ end}}$ but their authors state that harvest was performed after the beginning of senescence; thus, under these conditions, $K_{c \text{ end}}$ should be lower but close to $K_{c \text{ mid}}$.

Only two studies focusing on K_c for cucumber were retained. Both refer to using SWB procedures, one adopting a gravimetric approach (Amer et al., 2009), and the second using neutron probe (Yaghi et al., 2013). The low K_c values reported by the latter led to assuming water stress impacts and, therefore, reported K_c values were not considered for the updates of FAO56.

Weighing lysimeters were used in two melon studies (Miranda and Bleicher, 2001; Melo et al., 2013), while a BREB was used by Borges et al. (2015). In all studies drip irrigation was used, which likely reduced soil evaporation. Impacts of plastic mulch on K_c are evident

since K_c values reported by Miranda and Bleicher (2001) when not using mulch are much larger than those reported in other studies with mulch.

Only one K_c study was selected for pumpkins (Yavuz et al., 2015), another for squash (Amer, 2011), and also one reporting on K_{cb} for zucchini (squash) by Darouich et al. (2020). The former used a SWB approach with gravimetric soil water measurements, the second also used a SWB with FDR measurements, and the latter used a SWB with neutron probe and data handling with the SIMDualKc model. In addition, the study by Amer (2011) compared K_c values for drip and furrow irrigation showing a reduction with drip relative to furrow of around 5% (Table 5).

Three publications reporting on crop coefficients for watermelon were selected. Two used weighing lysimeters (Miranda et al., 2004; Bastos et al., 2012) while the third used drainage lysimeters and installed plastic mulch (Shukla et al., 2014), thus resulting in $K_{c\ mid}$ values smaller than the former ones. The end season K_c are very different, which relates with the duration of the harvesting period, longer when $K_{c\ end}$ is smaller.

There are few publications reporting on crop coefficients for irrigated okra and information provided in these studies is insufficient. Selected references consist of those developed by the Extension Services of the University of Florida (Dukes et al., 2015) and by researchers from India (Patil and Tiwari, 2018, 2019). Results relative to $K_{c\ mid\ (std)}$ are similar but those for the end season are very different, with low $K_{c\ end\ (std)}$ values when the harvesting practice is with the fruit somewhat close to maturation. These differences likely result from different traditional marketing in the two regions.

The studies performed with plastic mulched strawberries under drip irrigation (Grattan et al., 1998; Hanson and Bendixen, 2004) considered establishing a K_c - f_c relationship useful for irrigation scheduling purposes. For estimating $ET_{c\ act}$, Grattan et al. (1998) used the BREB method while Hanson and Bendixen (2004) used a SWB supported with time domain transmissibility (TDT) sensors. Both studies were performed in coastal California climates and the respective $K_{c\ mid\ (std)}$ show quite small differences.

The studies in Table 5 provided for ancillary information that may help in characterizing the studied crops. Those data are presented in Table 6. The data gaps in Table 6 identify the insufficiencies. Data on root depths are reasonably informative but those on crop heights show numerous gaps and, in the case of tomato, identify a wide range of crop management options, with h_{max} varying from 0.48 m to 1.25 m, the latter when the crop grows on stalks. A main gap, however, is limited data on the soil water depletion fraction for no stress (p), which plays a main role in irrigation scheduling. This information is completely lacking for all but three crops. The deficiency of ancillary data probably results from the fact that the study-aims were not at providing information for irrigation scheduling using soil information but at different objectives in terms of understanding the crops behavior.

4.4. Herbs, spices and special vegetable crops

This group of crops is an upgrade relative to the FAO56 tables: on the one hand, the pineapple crop was added to the vegetable crops; on the other hand, various herbs and spice not considered in FAO56 are now added following research developed in the last decennium. The reported values for $K_{c\ mid\ (obs)}$ and $K_{c\ end\ (obs)}$ and the respective values adjusted to the standard climate $K_{c\ mid\ (std)}$ and $K_{c\ end\ (std)}$ are given in Table 7. Reported values for the basal crop coefficients are also included in Table 7 but refer to only a few herbs and spice crops.

The selected studies relative to basil used SWB with TDR measurements combined with DL (Ghamarnia et al., 2015a) or with WL measurements (Marques et al., 2015) to determine $ET_{c\ act}$. Reported $K_{c\ mid\ (std)}$ are similar among basil studies but $K_{c\ end\ (std)}$ differ much since $K_{c\ end\ (std)}$ equals $K_{c\ mid\ (std)}$ when only one harvest is practiced, while low values for $K_{c\ end\ (std)}$ correspond to multiple harvests. Similar $K_{c\ mid}$ behavior was reported for lemon balm (Ghamarnia et al.,

2015b), in which $ET_{c\ act}$ was estimated with the SWB based on TDR measurements, combined with DL, and also adopting the SIMDualKc model. However, for K_{cb} , this method was applied only for a single harvest and, thus, K_{cb} values for lemon balm are only available for this single harvest condition.

For black cumin and coriander, $ET_{c\ act}$ was also determined by a SWB with TDR measurements (Silva et al., 2013) and in combination with DL observations in studies by Ghamarnia et al. (2013, 2014) and Ghamarnia and Sasani (2015). However, the $K_{cb\ mid}$ values reported by Ghamarnia et al. (2013, 2014, 2015a) were decreased considering advection influences. The study Ghamarnia and Sasani (2015) also applied the SIMDualKc model, thus making K_{cb} values available for coriander. Both crops commonly have multiple harvests and have end-season K_c and K_{cb} smaller than for mid-season. Similarly, multiple harvests are used for parsley; however, Dukes et al. (2015) report only a value for $K_{c\ mid}$, likely because $K_{c\ end}$ varies with time at each harvest after mid-season.

Only the study by Yarami et al. (2011) was selected for saffron, where $ET_{c\ act}$ was determined by DL and a SWB with neutron probe data. That study used micro-lysimeters to support deriving K_{cb} . Also, a single paper was selected for pineapple (Azevedo et al., 2007) where BREB was used.

Herbs and spices may be subject to single or multiples harvests, which create different K_c values, as reported earlier for tabasco pepper (Table 5). In multiple harvest conditions, the $K_{c\ mid}$ refers to the peak period before harvesting and $K_{c\ end}$ refers to the period before crop regrowth. However, criteria followed in the selected references varied and information provided in Table 7 is indicative of this.

The ancillary data on crop characteristics are provided in Table 8. However, the available ancillary data from selected literature are once again scarce. Root depths, which are essential when performing a soil water balance, were commonly not given for most of herbs and spices. Moreover, the p soil water depletion fractions for no stress were also not given for most of the herbs and spices.

5. Consolidated updates on standard single and basal crop coefficients

The updated standard K_c values for vegetable crops, referring to a standard sub-humid climate ($RH_{min} = 45\%$, $u_2 = 2\ m\ s^{-1}$) are presented in Table 9. They were defined taking into consideration both the observed $K_{c\ mid\ (std)}$ and $K_{c\ end\ (std)}$ values reported in Tables 1, 3, 5 and 7, and the $K_{c\ mid}$ and $K_{c\ end}$ values tabulated in FAO56 (Allen et al., 1998). In general, the updated K_c values differ little from those tabulated in FAO56.

$K_{c\ mid}$ and $K_{c\ end}$ values for roots, tubers, bulbs and stem vegetable crops were unchanged for asparagus, celery, and radish since acceptable K_c studies on these crops were not available. The values were also unchanged for carrots and potato in agreement with available research results. Following reported values in Table 1, the updated $K_{c\ mid}$ values were slightly increased for cassava and garlic. They were also slightly increased for onions harvested green to have the same $K_{c\ mid}$ values as dry and seed onions. $K_{c\ end}$ values were slightly decreased for onions but not for seed since there was no related information available. In contrast, the updated standard $K_{c\ end}$ for parsnip, rutabaga, turnip and table beets were slightly increased as to become closer to $K_{c\ mid}$, thus following trends of earlier harvest of table roots and tubers, i.e., with reduced effects of senescence. The $K_{c\ end}$ for sweet potato was slightly decreased based on the available data.

For leaves and flowers vegetable crops, $K_{c\ mid}$ and $K_{c\ end}$ values remained unchanged for artichoke. Following available research, the $K_{c\ mid}$ for broccoli was increased by 0.05 but was not changed for other crops in this category. For broccoli, Brussel sprouts, cabbage, cauliflower, lettuce and spinach, the $K_{c\ end}$ values were increased to become equal or very close to $K_{c\ mid}$ because these crops are eaten when fresh and tender. Thus, it was assumed that those crops would

Table 7

Field derived actual K_c (obs) and K_{cb} (obs) for mid and end season and respective values adjusted to the standard climate ($RH_{min} = 45\%$, $u_2 = 2 \text{ m s}^{-1}$), K_c (std) and K_{cb} (std) for herbs, spices and special crops.

Crop	Reference	Location	Methods to estimate $ET_{c \text{ act}}$	Irrigation method	K_c / K_{cb} derived from field observations		K_c / K_{cb} adjusted to the standard climate	
					K_c mid (obs)	K_c end (obs)	K_c mid (std)	K_c end (std)
Single crop coefficient								
Basil (<i>Ocimum basilicum</i>)	Ghamarnia et al. (2015a)	Kermanshah, Iran	DL, SWB-TDR	Surface				
					Single harvest	1.26	1.26	1.05
	Multiple harvest	1.26	0.70	1.05	0.53			
	Marques et al. (2015)	Piracicaba, Brazil	WL, SWB-TDR	Drip	1.00	0.32	1.00	0.32
Black cumin (<i>Nigella sativa</i>)	Ghamarnia et al. (2014)	Kermanshah, Iran	DL, SWB-TDR	Surface	1.18	0.67	1.11	0.60
Coriander (<i>Coriandrum sativum</i>)	Silva et al. (2013)	Itabaina, Brazil	SWB-TDR	Surface	1.25	0.55	1.25	0.55
	Ghamarnia et al. (2013)	Kermanshah, Iran	DL, SWB-TDR	Surface	1.20	0.92	1.12	0.81
	Ghamarnia and Sasani (2015)	Kermanshah, Iran	DL, SWB-TDR, SIMDualKc	Surface	1.24	0.85	1.16	0.74
Lemon balm (<i>Melissa officinalis</i>)	Ghamarnia et al. (2015b)	Kermanshah, Iran	DL, SWB-TDR, SIMDualKc	Surface				
					Single harvest	1.19	1.10	1.03
					1.00	0.77	0.89	0.66
Parsley (<i>Petroselinum crispum</i>)	Dukes et al. (2015)	Florida, USA	SWB-capacit. sensors	n/r	1.00	n/r	1.00	n/r
Pineapple (<i>Ananas comosus</i>)	Azevedo et al. (2007)	Paraíba, Brazil	BREB	Sprinkler	0.88	0.88	0.94	0.93
Saffron (<i>Crocus sativus</i>)	Yarami et al. (2011)	Shiraz, Iran	DL, SWB-neutron	Basin	1.00	0.35	0.95	0.35
Basal crop coefficient								
					K_{cb} mid (obs)	K_{cb} end (obs)	K_{cb} mid (std)	K_{cb} end (std)
Black cumin (<i>Nigella sativa</i>)	Ghamarnia et al. (2014)	Kermanshah, Iran	DL, SWB-TDR	Surface	1.09	0.55	1.02	0.48
Coriander (<i>Coriandrum sativum</i>)	Ghamarnia et al. (2013)	Kermanshah, Iran	DL, SWB-TDR	Surface	1.10	0.79	1.02	0.68
	Ghamarnia and Sasani (2015)	Kermanshah, Iran	DL, SWB-TDR, SIMDualKc	Surface	1.12	0.79	1.04	0.68
Lemon balm (<i>Melissa officinalis</i>)	Ghamarnia et al. (2015b)	Kermanshah, Iran	DL, SWB-TDR, SIMDualKc	Surface				
					1.16	1.16	1.00	1.00
Saffron (<i>Crocus sativus</i>)	Yarami et al. (2011)	Shiraz, Iran	DL, SWB-neutron micro-lys.	Basin	0.70	0.15	0.65	0.15

DL — Drainage lysimeter; WL — Weighing lysimeter; micro-lys. — micro lysimeters; SWB — Soil water balance; TDR — Time-Domain Reflectometry; FDR — Frequency Domain Reflectometry; TDT — Time Domain Transmissometry; Resist. — Resistance probe; Neutron — neutron probe; Gravimet. — Gravimetric sampling method; EC — Eddy Covariance; BREB — Bowen ratio energy balance; RS — Remote sensing; SDI — Subsurface drip irrigation; n/r — not reported.

Table 8

Observed ancillary crop parameters for herbs, spices and special crops reported from selected literature.

Crop	Reference	$Z_r \text{ max}$ (m)	h_{max} (m)	LAI_{max} ($\text{m}^2 \text{ m}^{-2}$)	$f_c \text{ max}$	P_{ini}	P_{mid}	P_{end}
Basil (<i>Ocimum basilicum</i>)	Ghamarnia et al. (2015a)	n/r	0.30	n/r	n/r	n/r	n/r	n/r
	Marques et al. (2015)	0.30	0.90	n/r	1.00	0.10	0.10	0.10
Black cumin (<i>Nigella sativa</i>)	Ghamarnia et al. (2014)	0.60	n/r	n/r	n/r	0.30	0.30	0.30
Coriander (<i>Coriandrum sativum</i>)	Silva et al. (2013)	n/r	0.13	n/r	n/r	n/r	n/r	n/r
	Ghamarnia et al. (2013)	0.60	n/r	n/r	n/r	0.30	0.10	0.10
Lemon balm (<i>Melissa officinalis</i>)	Ghamarnia et al. (2015b)	n/r	0.15	n/r	0.80	n/r	n/r	n/r
Pineapple (<i>Ananas comosus</i>)	Azevedo et al. (2007)	n/r	1.15	n/r	n/r	n/r	n/r	n/r
Saffron (<i>Crocus sativus</i>)	Yarami et al. (2011)	0.60	n/r	n/r	n/r	n/r	n/r	n/r

$Z_r \text{ max}$ — maximum root depth; h_{max} — maximum crop height; LAI_{max} — maximum leaf area index; $f_c \text{ max}$ — 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.

be harvested before senescence starts. The largest $K_c \text{ end}$ increase was for broccoli, which went from 0.95 to 1.10.

There was sufficient research on K_c for all fruit and pod vegetable crops considered; thus, the $K_c \text{ mid}$ and $K_c \text{ end}$ values tabulated in FAO56

Table 9
Updated standard single crop coefficients $K_{c\ mid}$ and $K_{c\ end}$ for vegetable crops.

Crop	Observed, standard K_c		FAO56 tabulated K_c		Updated standard K_c	
	$K_{c\ mid}$ (std)	$K_{c\ end}$ (std)	$K_{c\ mid}$	$K_{c\ end}$	$K_{c\ mid}$	$K_{c\ end}$
Roots, tubers, bulbs and stem vegetable crops						
Asparagus (<i>Asparagus officinalis</i>)	n/r	n/r	0.95	0.30	0.95	0.30
Carrots (<i>Daucus carota</i>)	1.01–1.04	0.84–0.98	1.05	0.95	1.05	0.95
Cassava (<i>Manihot esculenta</i>)						
Year 1	0.95–1.19	0.63–0.80	0.80	0.30	1.00	0.60
Year 2	n/r	n/r	1.10	0.50	1.10	0.60
Celery (<i>Apium graveolens</i>)	n/r	n/r	1.05	1.00	1.05	1.00
Garlic (<i>Allium sativum</i>)	0.88–1.18	0.15–0.80	1.00	0.70	1.05	0.70
Onions (<i>Allium cepa</i>)						
Dry	0.84–1.13	0.42–0.68	1.05	0.75	1.05	0.65
Green	1.02	0.81	1.00	1.00	1.05	0.90
Seed	n/r	n/r	1.05	0.80	1.05	0.80
Parsnip (<i>Pastinaca sativa</i>)	n/r	n/r	1.05	0.95	1.05	1.00
Potato (<i>Solanum tuberosum</i>)						
Long season	1.10–1.14	0.10–0.45	1.15	0.40	1.15	0.40
Short season	1.08	n/r	1.15	0.75	1.15	0.75
Radish (<i>Raphanus sativus</i>)	n/r	n/r	0.90	0.85	0.90	0.85
Rutabaga (<i>Brassica napobrassica</i>)	n/r	n/r	1.10	0.95	1.10	1.00
Sweet potato (<i>Ipomoea batatas</i>)	0.93–1.21	0.44–0.81	1.15	0.65	1.10	0.60
Table beets (<i>Beta vulgaris</i>)	n/r	n/r	1.05	0.95	1.05	1.00
Taro (<i>Colocasia esculenta</i>)	1.15	1.10	n/r	n/r	1.10	1.05
Turnip (<i>Brassica rapa var. rapa</i>)	n/r	n/r	1.10	0.95	1.10	1.00
Leaves and flowers vegetable crops						
Artichoke (<i>Cynara scolymus</i>)	0.77	n/r	1.00	0.95	1.00	0.95
Broccoli (<i>B. oleracea v. italica</i>)	1.09–1.11	1.09–1.11	1.05	0.95	1.10	1.10
Brussel sprouts (<i>B. oleracea v. gemmifera</i>)	n/r	n/r	1.05	0.95	1.05	1.05
Cabbage (<i>B. oleracea v. capitata</i>)	1.05–1.10	1.00–1.05	1.05	0.95	1.05	1.00
Cauliflower (<i>B. oleracea v. botrytis</i>)	n/r	n/r	1.05	0.95	1.05	1.00
Lettuce (<i>Lactuca sativa</i>)	0.92 – 1.08	0.92–1.08	1.00	0.95	1.00	1.00
Spinach (<i>Spinacia oleracea</i>)	0.98	0.98	1.00	0.95	1.00	1.00
Fruit and pod vegetable crops						
Bell pepper (<i>Capsicum annuum</i>)	0.90–1.25	0.83–1.25	1.05	0.90	1.10	1.05
Chili pepper (<i>Capsicum annuum</i>)	1.13	0.76	n/r	n/r	1.10	0.80
Chili, tabasco pepper (<i>Capsicum frutescens</i>)						
First harvest	1.32	0.73	n/r	n/r	1.10	0.70
Second harvest	1.16	0.62	n/r	n/r	1.05	0.60
Cucumber (<i>Cucumis sativus</i>)						
For processing	n/r	n/r	1.00	0.90	1.05	0.90
Fresh market	1.08	0.65	1.00	0.75	1.05	0.80
Eggplant (<i>Solanum melongena</i>)	0.99–1.19	0.96–1.06	1.05	0.90	1.05	1.00
Melon (<i>Cucumis melo</i>)	0.96–1.20	0.64–0.97	1.05	0.75	1.05	0.85
Melon, cantaloupe (<i>Cucumis melo</i>)	1.04	0.81	0.85	0.60	1.00	0.80
Okra (<i>Abelmoschus esculentus</i>)	0.93–1.00	0.63–0.90	n/r	n/r	0.95	0.90
Pumpkin, winter squash (<i>C. pepo</i>)	0.91	0.60	1.00	0.80	1.00	0.80
Squash, Zucchini (<i>Cucurbita pepo</i>)	1.01–1.07	0.65–0.70	0.95	0.75	1.00	0.75
Strawberries (<i>Fragaria × ananassa</i>)	0.73–0.78	n/r	0.85	0.75	0.80	0.75
Tomato (<i>Solanum lycopersicum</i>)						
For processing	1.08–1.09	0.75	1.15	0.70–0.90	1.10	0.90
Fresh market	1.08–1.11	0.63–1.07	1.20	n/r	1.10	1.00
Watermelon (<i>Citrullus lanatus</i>)	1.01–1.17	0.41–0.73	1.00	0.75	1.05	0.70

(continued on next page)

were often updated. A distinction was made between bell pepper and chili peppers within the *Capsicum annuum* crops and, within the chillies, between *Capsicum annuum* and *Capsicum frutescens* (Tabasco pepper). For the latter, single and double harvesting were considered. The standard $K_{c\ mid}$ values for bell pepper were increased by 0.05 and the same value, 1.10, was also adopted for the other peppers. For bell

pepper, often consumed fresh, $K_{c\ end}$ was increased to become closer to $K_{c\ mid}$. Differently, a smaller $K_{c\ end}$ is proposed for chili peppers because the late season of chillies is longer, to allow for the red color of chillies and for the synthesis of capsaicinoids, the substance responsible for their flavor. However, the duration of the late season, thus the $K_{c\ end}$ value too, may differ with the species and cultivar of chillies.

Table 9 (continued).

Crop	Observed, standard K_c		FAO56 tabulated K_c		Updated standard K_c	
	$K_{c \text{ mid}}$ (std)	$K_{c \text{ end}}$ (std)	$K_{c \text{ mid}}$	$K_{c \text{ end}}$	$K_{c \text{ mid}}$	$K_{c \text{ end}}$
Herbs, spices and special vegetable crops						
Basil (<i>Ocimum basilicum</i>)						
Single harvest	1.05	1.05	n/r	n/r	1.00	0.95
Multiple harvest	1.00–1.05	0.32–0.53	n/r	n/r	1.00	0.50
Black cumin (<i>Nigella sativa</i>)	1.11	0.60	n/r	n/r	1.05	0.60
Coriander (<i>Coriandrum sativum</i>)	1.12–1.25	0.55–0.81	n/r	n/r	1.10	0.75
Lemon balm (<i>Melissa officinalis</i>)						
Single harvest	1.03	0.96	n/r	n/r	1.05	1.00
Multiple harvest	0.89	0.66	n/r	n/r	0.90	0.65
Mint (<i>Mentha spicata</i>)	n/r	n/r	1.15	1.10	1.15	1.10
Parsley (<i>Petroselinum crispum</i>)	1.00	n/r	n/r	n/r	1.00	0.90
Pineapple (<i>Ananas comosus</i>)	0.94	0.93	0.30–0.50	0.30–0.50	0.90	0.90
Saffron (<i>Crocus sativus</i>)	0.95	0.35	n/r	n/r	0.95	0.35

n/r – not reported.

Table 10

Updated standard basal crop coefficients $K_{cb \text{ mid}}$ and $K_{cb \text{ end}}$ for vegetable crops.

Crop	Observed, standard K_{cb}		FAO56 tabulated K_{cb}		Updated standard K_{cb}	
	$K_{cb \text{ mid}}$ (std)	$K_{cb \text{ end}}$ (std)	$K_{cb \text{ mid}}$	$K_{cb \text{ end}}$	$K_{cb \text{ mid}}$	$K_{cb \text{ end}}$
Roots, tubers, bulbs and stems vegetable crops						
Asparagus (<i>Asparagus officinalis</i>)	n/r	n/r	0.90	0.20	0.90	0.20
Carrots (<i>Daucus carota</i>)	n/r	n/r	0.95	0.85	0.95	0.85
Cassava (<i>Manihot esculenta</i>)						
Year 1	n/r	n/r	0.70	0.20	0.90	0.45
Year 2	n/r	n/r	1.00	0.45	1.00	0.45
Celery (<i>Apium graveolens</i>)	n/r	n/r	0.95	0.90	0.95	0.90
Garlic (<i>Allium sativum</i>)	0.95–1.00	0.15–0.35	0.90	0.60	0.95	0.60
Onions (<i>Allium cepa</i>)						
Dry	1.03	0.58	0.95	0.65	0.95	0.55
Green	n/r	n/r	0.90	0.90	0.95	0.80
Seed	n/r	n/r	0.95	0.70	0.95	0.70
Parsnip (<i>Pastinaca sativa</i>)	n/r	n/r	0.95	0.85	0.95	0.90
Potato (<i>Solanum tuberosum</i>)						
Long season	1.10	0.35	1.10	0.35	1.10	0.35
Short season	n/r	n/r	n/r	n/r	1.10	0.65
Radish (<i>Raphanus sativus</i>)	n/r	n/r	0.85	0.75	0.85	0.75
Rutabaga (<i>Brassica napus</i>)	n/r	n/r	1.00	0.85	1.00	0.90
Sweet potato (<i>Ipomoea batatas</i>)	n/r	n/r	1.10	0.55	1.05	0.50
Table beets (<i>Beta vulgaris</i>)	n/r	n/r	0.95	0.85	0.95	0.90
Taro (<i>Colocasia esculenta</i>)	n/r	n/r	n/r	n/r	1.05	1.00
Turnip (<i>Brassica rapa</i>)	n/r	n/r	1.00	0.85	1.00	0.90
Leaves and flowers vegetable crops						
Artichoke (<i>Cynara scolymus</i>)	n/r	n/r	0.95	0.90	0.95	0.90
Broccoli (<i>B. oleracea</i> var. <i>italica</i>)	0.94 – 1.01	0.94–1.01	0.95	0.85	1.00	1.00
Brussel sprouts (<i>B. oleracea</i> v. <i>gemmifera</i>)	n/r	n/r	0.95	0.85	0.95	0.95
Cabbage (<i>B. oleracea</i> v. <i>capitata</i>)	0.96	0.90	0.95	0.85	0.95	0.90
Cauliflower (<i>B. oleracea</i> v. <i>botrytis</i>)	n/r	n/r	0.95	0.85	0.95	0.90
Lettuce (<i>Lactuca sativa</i>)	0.84–0.97	0.80–0.97	0.90	0.90	0.95	0.95
Spinach (<i>Spinacia oleracea</i>)	n/r	n/r	0.90	0.85	0.90	0.90

(continued on next page)

In addition, smaller $K_{c \text{ mid}}$ and $K_{c \text{ end}}$ are proposed for a second harvest when practiced.

Following results reported in the literature, slightly larger $K_{c \text{ mid}}$ values are proposed for cucumber, zucchini, squash and watermelon, while both $K_{c \text{ mid}}$ and $K_{c \text{ end}}$ are increased for cantaloupe melon, becoming closer to those of the melon crop. Standard $K_{c \text{ mid}}$ values were not changed for eggplant, melon and pumpkin but were decreased for

strawberries. However, standard $K_{c \text{ end}}$ values were changed slightly, increasing for melon and eggplants, indicating that fruits at harvesting should be harvested before senescence is completed. Distinct $K_{c \text{ end}}$ values, already suggested in FAO56, were adopted when the crop is harvested for processing or for fresh market; a lower value for fresh market refers to a long period of harvesting. For okra, not considered in FAO56, a value based on observations was assumed: $K_{c \text{ mid}} = 0.95$.

Table 10 (continued).

Crop	Observed, standard K_{cb}		FAO56 tabulated K_{cb}		Updated standard K_{cb}	
	$K_{cb\ mid}$ (std)	$K_{cb\ end}$ (std)	$K_{cb\ mid}$	$K_{cb\ end}$	$K_{cb\ mid}$	$K_{cb\ end}$
Fruit and pod vegetable crops						
Bell pepper (<i>Capsicum annuum</i>)	1.01–1.06	0.95–1.03	1.00–1.10	0.80	1.05	1.00
Chili pepper (<i>Capsicum annuum</i>)	0.90–1.00	0.87–1.00	n/r	n/r	1.00	0.75
Chili, tabasco pepper (<i>Capsicum frutescens</i>)						
First harvest	n/r	n/r	n/r	n/r	1.05	0.65
Second harvest	n/r	n/r	n/r	n/r	1.00	0.55
Cucumber (<i>Cucumis sativus</i>)						
For processing	n/r	n/r	0.95	0.80	1.00	0.80
Fresh market	n/r	n/r	0.95–1.10	0.70	1.00	0.70
Eggplant (<i>Solanum melongena</i>)	n/r	n/r	1.00	0.80	1.00	0.90
Melon (<i>Cucumis melo</i>)	n/r	n/r	0.75	0.50	0.95	0.75
Melon, cantaloupe (<i>Cucumis melo</i>)	n/r	n/r	0.95	0.70	0.95	0.70
Okra (<i>Abelmoschus esculentus</i>)	0.83	n/r	n/r	n/r	0.85	0.80
Pumpkin, winter squash (<i>C. pepo</i>)	n/r	n/r	0.90	0.70	0.95	0.70
Squash, Zucchini (<i>Cucurbita pepo</i>)	0.96	0.67	0.95	0.70	0.95	0.65
Strawberries (<i>Fragaria</i> × <i>ananassa</i>)	n/r	n/r	0.80	0.70	0.75	0.65
Tomato (<i>Solanum lycopersicum</i>)						
For processing	1.12	n/r	1.10	0.60–0.80	1.05	0.85
Fresh market	n/r	n/r	1.15	0.60–0.80	1.05	0.90
Watermelon (<i>Citrus lanatus</i>)	n/r	n/r	0.95	0.70	0.95	0.60
Herbs, spices and special vegetable crops						
Basil (<i>Ocimum basilicum</i>)						
Single harvest	n/r	n/r	n/r	n/r	0.95	0.90
Multiple harvest	n/r	n/r	n/r	n/r	0.95	0.45
Black cumin (<i>Nigella sativa</i>)	1.02	0.48	n/r	n/r	1.00	0.50
Coriander (<i>Coriandrum sativum</i>)	1.02–1.04	0.68	n/r	n/r	1.05	0.70
Lemon balm (<i>Melissa officinalis</i>)						
Single harvest	1.00	1.00	n/r	n/r	1.00	0.95
Multiple harvest	n/r	n/r	n/r	n/r	0.85	0.60
Mint (<i>Mentha spicata</i>)	n/r	n/r	1.10	1.05	1.10	1.05
Parsley (<i>Petroselinum crispum</i>)	n/r	n/r	n/r	n/r	0.95	0.85
Pineapple (<i>Ananas comosus</i>)	n/r	n/r	0.25–0.45	0.25–0.45	0.80	0.80
Saffron (<i>Crocus sativus</i>)	0.65	0.15	n/r	n/r	0.85	0.30

n/r – not reported.

Since this fruit is normally consumed fresh, the $K_{c\ end}$ is close to the $K_{c\ mid}$, indicating that, for produce quality, senescence effects should be avoided.

Reported research results did not provide justification for the high FAO56 $K_{c\ mid}$ values for tomato, thus both $K_{c\ mid}$ values for processing and fresh market were decreased to the same value, 1.10. However, different $K_{c\ end}$ values were adopted, with that for processing smaller than the one for market because the fruit should not be too tender for machine harvesting. For processing, harvesting should occur when ripening starts, when soluble contents are high, which better value is reached when the fruit is still not fully mature (yellow-orange color). However, harvesting for the fresh market starts during the mid-season and lasts while there are fruits in the field; thus, in practice, $K_{c\ end}$ may be smaller than the tabulated one.

With exception of mint, all standard K_c values for herbs and spices are new and were selected considering the literature review summarized in Table 7, thus based on the selected references. Two sets of $K_{c\ mid}$ and $K_{c\ end}$ were adopted for basil and lemon balm, one for single harvest and the other for multiple harvest of these herbs.

The standard K_c values for pineapple were highly increased relative to those tabulated in FAO56. Only one reference was selected but other studies, or reviews such as that by Carr (2012), were concordant that the $K_{c\ mid}$ and $K_{c\ end}$ should be higher than those proposed in FAO56, near 0.90. In addition, equal values were selected for mid- and end-season K_c considering the common management used in South America.

The updated standard basal crop coefficients for vegetable crops, referring to a standard sub-humid climate ($RH_{min} = 45\%$, $u_2 = 2\ m\ s^{-1}$), are presented in Table 10. The updated K_{cb} values also result from considering both the observed $K_{cb\ mid\ (std)}$ and $K_{cb\ end\ (std)}$ values reported in literature (Tables 1, 3, 5 and 7) and the $K_{cb\ mid}$ and $K_{cb\ end}$ values tabulated in FAO56 (Allen et al., 1998). Their definition followed a similar approach to that used for $K_{c\ mid}$ and for $K_{c\ end}$ reported above. Nevertheless, because only few studies focused on basal crop coefficients, most proposed values in Table 10 follow the general guidelines used in FAO56 to derive K_{cb} from K_c (Section 3.3), as well as the differences between K_c and K_{cb} values in FAO56. In other words, the selection of $K_{c\ mid}$ and $K_{c\ end}$ values described above relative to Table 9 dictated the definition of $K_{cb\ mid}$ and $K_{cb\ end}$ values proposed in Table 10. Thus, differences between $K_{c\ mid}$ (Table 9) and $K_{cb\ mid}$ (Table 10) generally do not exceed 0.05 for crops fully covering the ground but differ by 0.10 otherwise. Differences between $K_{c\ end}$ and $K_{cb\ end}$ are also small, 0.10 when rain or irrigation often occur during the late season, and 0.05 for dry conditions. This indicates that E_s values ($= K_c - K_{cb}$) are small during the mid- and late-season, i.e., soil evaporation (E_s) is small since most of the ground area is shadowed, therefore receiving only a limited amount of short-wave radiation available for soil water evaporation.

Reduced E_s limits the K_c differences among irrigation methods and the effect of mulch, which are much larger in sparse canopies and during the earlier crop growth stages of vegetable crops. Most studies

were performed with drip irrigation; only a few used micro-sprinkling or micro-sprayers and, even less, furrow irrigation or sprinklers. K_c tend to be smaller with drip irrigation since less soil is wetted and, often, the wetted soil is shadowed, thus E_s is smaller than for other methods. Because harvesting of small vegetables is commonly performed before senescence starts, or when a slight maturation occurs, ground cover by vegetation is kept high and, therefore, E_s is kept small until harvesting. Therefore, reductions in K_c when using drip irrigation relative to micro-sprinklers or micro-sprayers likely do not exceed around 5 to 10%, i.e., $K_{c \text{ mid act}}$ for drip irrigation may be smaller by about 0.05 than $K_{c \text{ mid act}}$ for micro-sprinklers or sprayers. However, various papers refer to larger K_c differences, up to 30%, but do not show a justification for that high difference. Since K_{cb} values do not include soil evaporation, K_{cb} values likely do not change with the irrigation method. Similarly, K_{cb} is also generally not affected by the control of E_s by mulches. Therefore, the K_c and K_{cb} provided in Tables 9 and 10 may confidently be used in practice, namely to parameterize soil water balance and irrigation scheduling models (Pereira et al., 2020c). However, users must decide on which corrections to introduce, either due to irrigation method, the use of mulches, the adoption of deficit irrigation, small size of plots or due to the occurrence of advection, which effectively may require a decrease in K_c and K_{cb} values, however in a limited amount.

6. Ancillary data

Although ancillary data for vegetable crops were limited, considering the values reported in the cited studies, the ancillary parameter values proposed in various Tables of FAO56 could be updated. To provide better information for readers about parameter options, the ancillary values available from the selected literature (Tables 2, 4, 6 and 8) are summarized in Table 11 together with the former tabulated values in FAO56.

The information provided in the selected papers led to reducing the tabulated rooting depths in FAO56 for several crops. Vegetable crops often have short roots and because irrigation water management today is mostly with frequent water applications, e.g., by drip irrigation, smaller rooting depths are warranted. Good examples of reduced depths, with supporting data, were for cabbage, processing tomato, and melons. Differently, updated crop heights are sometimes larger than the FAO56 tabulated ones, which likely corresponds to new varieties and new crop management practices. It is noted, however, that a few updates of Z_r and h_{max} were made when information was not available but followed the personal knowledge of authors. Nevertheless, for most cases, data provided in FAO56 was kept unchanged.

Reported values for the soil water depletion fraction for no stress (p) of vegetable crops were often smaller than those tabulated in FAO56. Because drip irrigation is more often used with vegetable crops, irrigation frequency is high, and plants are generally short rooted, there is no apparent reason to adopt large p values. Instead, following the reported values, it appears preferable to adopt smaller p values, which correspond to minimizing the risk for water stress. Thus, values for p were often decreased.

While there is not an FAO56 table for maximum crop cover, and thus no need to update $f_{c \text{ max}}$, the values observed in some selected papers are summarized in Table 11. This data may prove useful for irrigation scheduling purposes of these crops mainly to parameterize soil water balance models (Pereira et al., 2020c).

7. Conclusions and recommendations

The current study led to conclusions of diverse nature. First, it is important to note that the tabulated K_c and K_{cb} values in FAO56 (Allen et al., 1998) were generally confirmed by the research conducted in the last two decennia and reviewed herein, albeit with slight refinements made for various crops. A similar conclusion was derived from the study reported in the companion paper relative to field crops (Pereira

et al., 2020a). This conclusion makes it clear that the FAO56 tabulated crop coefficients can assuredly be trusted. It is also essential to recognize the adequateness of the definition and computation of the reference evapotranspiration and of the procedures relative to the crop coefficients. With this in mind, users can also be assured that the K_c - ET_0 method proposed by FAO56 is accurate and appropriate for a variety of applications; otherwise, tabulated K_c and K_{cb} should be adapted to the prevailing conditions.

The performed review effectively demonstrated the appropriateness of clearly distinguishing actual from standard crop coefficients, with the latter referring to crops cultivated in pristine conditions, in which the evapotranspiration may well be considered the potential ET of the considered crop under given environmental conditions. In reality, there is very abundant literature where this distinction is not made and where crop coefficients correspond to cultivation practices far from pristine due to water stress, salinity stress or stresses produced by various insufficiencies of agronomic nature. The review also allowed to perceive that a distinction between actual and standard/potential conditions is often not recognized or even accepted by many researchers. This obviously makes it more difficult to transfer research results of crop coefficients from one location to another. Nevertheless, the review has shown that using well-calibrated and validated soil water balance models, e.g., the SIMDualKc model, has made it possible to overcome problems related to stress and to achieve K_c standardized values. More research along these lines is desirable since the reported use of models in the reviewed literature is scarce. In addition, research must pay attention to the adjustment of K_c to the standard climate. The review has also demonstrated that differences between K_c observed and those adjusted to the standard climate may be quite 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 also indicated that researchers often do not include any scrutiny relative to high K_c values, which could be due to either flaws in field measurements or to advection influences. On the one hand, it was observed that exceptionally high K_c values are often reported in papers where the description of methods employed were insufficient, which may relate to absence of scrutiny of research results. That lack of scrutiny could also be associated with advection impacts, which were not considered in many papers published during the last two decennia. Therefore, it is recommended that research studies of this nature include a careful analysis of results, including the time dynamics of ET that would provide better information about the accuracy of ET estimation. On the other hand, since energy balance methods, mainly EC and BREB, are becoming quite popular in ET research, it is recommended that 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, thus, identifying periods where ET was influenced by advection. In addition, it is recommended that derived K_c or K_{cb} values are scrutinized comparing them with those tabulated, which in fact correspond to a kind of upper limit of K_c values for the standard climate. This scrutiny also applies to one step $ET_{c \text{ act}}$ since, easily, the ratios $ET_{c \text{ act}}/ET_0$ may be compared with tabulated standard K_c .

It became apparent from this review that the definition and computational procedures relative to the $PM-ET_0$ equation are often not followed, or have not yet been accepted, by many researchers. This is well apparent through numerous comparative studies of ET equations, including when authors search for a K_c value for a given crop, and by the use as reference of a variety of equations different from the $PM-ET_0$ equation without considering the actual ratio between ET_0 computed with the selected equation to the $PM-ET_0$. Naturally, using an ET_0 different than the $PM-ET_0$ results in different K_c values. On the one hand, the derived K_c are negatively affected, and transferability of research results are hampered when a different ET_0 is used; on the other hand, using the FAO56 tabulated standard K_c with a different

Table 11

Updated standard crop parameters for vegetable crops: maximum root depth ($Z_{r \max}$), maximum crop height (h_{\max}), maximum fraction of ground cover ($f_{c \max}$) and soil water depletion fraction for no-stress (p) when ET_c is of 5 mm d^{-1} .

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	$Z_{r \max}$ (m)	h_{\max} (m)	p
Roots, tubers, bulbs and steams vegetable crops										
Asparagus (<i>Asparagus officinalis</i>)	n/r	n/r	n/r	n/r	1.20–1.80	0.80	0.45	1.20–1.80	0.80	0.45
Carrots (<i>Daucus carota</i>)	0.30	0.30	n/r	0.30	0.50–1.00	0.30	0.35	0.30–0.50	0.30	0.30
Cassava (<i>Manihot esculenta</i>)										
Year 1	n/r	n/r	n/r	n/r	0.50–0.80	1.00	0.35	0.50–0.80	1.00	0.50
Year 2	n/r	n/r	n/r	n/r	0.70–1.00	1.50	0.40	0.70–1.00	1.50	0.50
Celery (<i>Apium graveolens</i>)	n/r	n/r	n/r	n/r	0.30–0.50	0.60	0.20	0.30–0.50	0.60	0.20
Garlic (<i>Allium sativum</i>)	0.30	0.65	0.85	0.30	0.30–0.50	0.30	0.30	0.30–0.50	0.50	0.30
Onions (<i>Allium cepa</i>)	0.40	n/r	0.72	0.30	0.30–0.60	0.40	0.30	0.30–0.60	0.45	0.30
Parsnip (<i>Pastinaca sativa</i>)	n/r	n/r	n/r	n/r	0.50–1.00	0.40	0.40	0.50–1.00	0.40	0.40
Potato (<i>Solanum tuberosum</i>)	0.50	0.60	0.88	0.40	0.40–0.60	0.60	0.35	0.40–0.60	0.60	0.40
Radish (<i>Raphanus sativus</i>)	n/r	n/r	n/r	n/r	0.30–0.50	0.30	0.30	0.30–0.50	0.30	0.30
Rutabaga (<i>Brassica napus</i>)	n/r	n/r	n/r	n/r	0.50–1.00	0.60	0.50	0.50–1.00	0.60	0.50
Sweet potato (<i>Ipomoea batatas</i>)	1.00	0.50	0.98	0.45	1.00–1.50	0.40	0.65	1.00–1.20	0.50	0.40
Table beets (<i>Beta vulgaris</i>)	n/r	n/r	n/r	n/r	0.60–1.00	0.40	0.50	0.60–1.00	0.40	0.45
Taro (<i>Colocasia esculenta</i>)	0.30	1.20	n/r	n/r	n/r	n/r	n/r	0.30–0.40	1.20	0.40
Turnip (<i>Brassica rapa</i>)	n/r	n/r	n/r	n/r	0.50–1.00	0.60	0.50	0.50–1.00	0.60	0.50
Leaves and flowers vegetable crops										
Artichoke (<i>Cynara scolymus</i>)	n/r	n/r	0.60	n/r	0.60–0.90	0.70	0.45	0.60–0.90	0.80	0.45
Broccoli (<i>B. oleracea</i> var. <i>italica</i>)	0.40	0.60	0.95	0.45	0.40–0.60	0.30	0.45	0.40–0.60	0.60	0.40
Brussel sprouts (<i>B. oleracea</i> var. <i>gemmifera</i>)	n/r	n/r	n/r	n/r	0.40–0.60	0.40	0.45	0.40–0.60	0.75	0.40
Cabbage (<i>B. oleracea</i>)	0.30	n/r	n/r	0.40	0.50–0.80	0.40	0.45	0.30–0.50	0.40	0.40
Cauliflower (<i>B. oleracea</i> var. <i>botrytis</i>)	n/r	n/r	n/r	n/r	0.40–0.70	0.40	0.45	0.40–0.60	0.40	0.40
Lettuce (<i>Lactuca sativa</i>)	0.30	0.37	0.70	n/r	0.30–0.50	0.30	0.30	0.30–0.50	0.35	0.30
Spinach (<i>Spinacia oleracea</i>)	n/r	n/r	n/r	n/r	0.30–0.50	0.30	0.20	0.30–0.50	0.35	0.20
Fruit and pod vegetable crops										
Bell pepper (<i>Capsicum annuum</i>)	0.60	0.60	0.90	n/r	0.50–1.00	0.70	0.30	0.50–1.00	0.70	0.30
Chili pepper (<i>Capsicum annuum</i>)	0.60	0.76	0.82	0.20	n/r	n/r	n/r	0.50–1.00	0.75	0.30
Chili, tabasco pepper (<i>Capsicum frutescens</i>)	0.60	0.80	0.55	n/r	n/r	n/r	n/r	0.50–1.00	0.80	0.30
Cucumber (<i>Cucumis sativus</i>)	0.60	n/r	n/r	n/r	0.70–1.20	0.30	0.50	0.60–1.20	0.30	0.40
Eggplant (<i>Solanum melongena</i>)	0.40	n/r	n/r	n/r	0.70–1.20	0.80	0.45	0.40–1.00	0.80	0.45
Melon (<i>Cucumis melo</i>)	0.60	0.30	0.95	n/r	0.80–1.50	0.40	0.40	0.60–1.20	0.30	0.40
Melon, cantaloupe (<i>Cucumis melo</i>)	n/r	n/r	n/r	n/r	0.90–1.50	0.30	0.45	0.60–1.20	0.30	0.40
Okra (<i>Abelmoschus esculentus</i>)	0.60	0.90	n/r	0.40	n/r	n/r	n/r	0.60–0.80	0.90	0.40
Pumpkin, winter squash (<i>C. pepo</i>)	0.90	n/r	n/r	n/r	1.00–1.50	0.40	0.35	0.90–1.50	0.40	0.40
Squash, Zucchini (<i>Cucurbita pepo</i>)	0.50	0.55	0.99	0.50	0.60–1.10	0.30	0.50	0.60–1.10	0.50	0.50
Strawberries (<i>Fragaria × ananassa</i>)	n/r	n/r	0.80	n/r	0.20–0.30	0.20	0.20	0.30–0.50	0.20	0.25
Tomato (<i>Solanum lycopersicum</i>)										
Processing	1.00	0.70	0.95	0.30	0.70–1.50	0.60	0.40	0.60–1.20	0.70	0.40
Fresh market	0.60	1.25	0.85	0.30	0.70–0.50	2.00	0.40	0.60–1.20	0.70*	0.40
Watermelon (<i>Citrullus lanatus</i>)	n/r	n/r	0.80	n/r	0.80–1.50	0.40	0.40	0.80–1.50	0.40	0.40
Herbs, spices and special vegetable crops										
Basil (<i>Ocimum basilicum</i>)	0.30	0.40	1.00	0.10	n/r	n/r	n/r	0.30–0.60	0.40	0.30
Black cumin (<i>Nigella sativa</i>)	0.60	n/r	n/r	0.30	n/r	n/r	n/r	0.50–0.80	0.40	0.40
Coriander (<i>Coriandrum sativum</i>)	0.60	0.13	n/r	0.10	n/r	n/r	n/r	0.30–0.50	0.30	0.30
Lemon balm (<i>Melissa officinalis</i>)	n/r	0.15	0.80	n/r	n/r	n/r	n/r	0.30–0.50	0.50	0.40
Mint (<i>Mentha spicata</i>)	n/r	n/r	n/r	n/r	0.40–0.80	0.60–0.80	0.40	0.40–0.80	0.40	0.40
Oregano (<i>Origanum vulgare</i>)	n/r	n/r	n/r	n/r	n/r	n/r	n/r	0.30–0.50	0.30	0.35
Parsley (<i>Petroselinum crispum</i>)	n/r	n/r	n/r	n/r	n/r	n/r	n/r	0.30–0.50	0.30	0.30
Pineapple (<i>Ananas comosus</i>)	n/r	1.15	n/r	n/r	0.30–0.60	0.60–1.20	0.50	0.30–0.60	1.20	0.50
Saffron (<i>Crocus sativus</i>)	0.60	n/r	n/r	n/r	n/r	n/r	n/r	0.50–0.80	0.20	0.30

* $h_{\max} = 1.50$ m when cultivated with a trellis system.

$Z_{r \max}$ – 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 the initial, mid- and end-season stages, respectively; n/r – not reported.

ET equation leads to over- or under-estimation errors in using the K_c - ET_0 approach. It is recommended that research using a different ET equation should consider the ratio between ET_0 equations when using K_c values that refer to the PM- ET_0 , thus, allow the ability to convert K_c values.

The best use of the K_c - ET_0 method implies using the segmented FAO K_c curve, i.e., with accepting the definition of the four crop growth stages and the definition of three K_c values: $K_{c \text{ ini}}$, $K_{c \text{ mid}}$ and $K_{c \text{ end}}$. Using time averaged K_c values or non-linear K_c functions with time are difficult to use predictably because the corresponding values are site-focused. The FAO K_c curve is also difficult to use predictably due

to inter-annual weather variability inducing variable durations of the crop growth stages. However, this difficulty may be overcome when expressing those duration in terms of cumulative growth degree days. This consists of an area of research already initiated for various field crops and that should be extended to vegetable crops.

The review reported herein provided a set of updated tables for $K_{c \text{ mid}}$ and $K_{c \text{ end}}$, as well as $K_{cb \text{ mid}}$ and $K_{cb \text{ end}}$ season for a great number of vegetable crops, exceeding those previously tabulated in FAO56. The new tabulated values refer to the PM ET_0 reference equation and the standard sub-humid climate with $RH_{\min} = 45\%$ and $u_2 = 2$ m s^{-1} . The K_c values principally refer to drip irrigation without the use of mulches,

plastic tunnels, or greenhouses. The review allowed us to observe that results comparing impacts of irrigation methods on the single and basal crop coefficients for vegetables are not very consistent, likely because many variables are considered. Further research is required for various crops and with consideration of the relationships between soil evaporation, transpiration, fraction of soil wetted, fraction of ground cover by the crop. Hopefully, future research will focus on a few of the relevant variables in such a way that K_c and K_{cb} values could be easily recognized and related results more readily transferred to other locations.

The impacts of mulches on K_c and K_{cb} values could not be developed through this review and consist of another area where further needs of research were clearly identified. First, it is necessary to produce research focusing on high accuracy ET estimation, including through well-developed energy balance and water balance methods; second, it is required that impacts of mulches focus on the dynamics of soil evaporation and plant transpiration with consideration of the fraction of ground cover. In fact, there are numerous studies relative to mulches, mainly plastic ones, as for a recent special issue of this Journal entitled “Plastic Mulching Effects on Water Use Efficiency, Crop Growth, and Soil Health in Northwestern China”. To overcome difficulties resulting from the fact that studies refer to multiple issues, it is recommended that studies relative to mulch impacts on water use include a focus on the base ET processes and dynamics.

Today’s vegetable farm-irrigators face climate change challenges and related environmental consequences, such as decreasing water availability. Thus, it is apparent that increasing the irrigation water savings in these crops will play a major role in irrigated-agriculture’s adaption to climate change effects. It cannot be emphasized more clearly that the upper limits of potential crop evapotranspiration must be recognized in the irrigation management practice. Despite some limitations of the current review, it is recommended that researchers and practitioners use the updated K_c and K_{cb} values to determine those ET limits when planning or developing irrigation scheduling programs. When using FAO56 procedures, it is of utmost importance to apply the PM-ET_o equation for reference evapotranspiration and to ensure climatic parameters are correctly measured and scrutinized. Avoiding the use of high K_c values, let say above 1.25, which have no physical justification for these crops, can lead to saving irrigation water. Moreover, the use of drip irrigation systems for vegetables is a means to apply frequent irrigation from mid-season on without increased evaporation consequences. Thus, well-planned and highly efficient irrigation scheduling should result using FAO56 ET estimation along with properly managed drip irrigation.

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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