Agricultural Water Management 250 (2021) 106645

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Review

# Updated single and dual crop coefficients for tree and vine fruit crops

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## ARTICLE INFO

Handling Editor - B.E. Clothier

*Keywords:*
$K_c$ and $K_{cb}$ values
Vineyards
Evergreen fruit trees
Deciduous fruit trees
Nut trees
Tropical fruit crops
Berries and hop

## ABSTRACT

The present study reviews the research on the FAO56 crop coefficients of fruit trees and vines performed over the past twenty years. The main objective was to update information and extend tabulated single ($K_c$) and basal ($K_{cb}$) standard crop coefficients. The selection and analysis of the literature for this review have been done to consider only studies that adhere to FAO56 method, computing the reference ET with the FAO Penman–Monteith $ET_o$ equation and field measuring crop ET with proved accuracy. The crops considered refer to vine fruit crops, berries and hops, temperate climate evergreen fruit trees, temperate climate deciduous fruit trees and, tropical and subtropical fruit crops. Papers satisfying the conditions expressed above, and that studied the crops under pristine or appropriate eustress conditions, were selected to provide for standard $K_c$ and $K_{cb}$ data. Preference was given to studies reporting on the fraction of ground cover ($f_c$), crop height (h), planting density, crop age and adopted training systems. The $K_c$ and $K_{cb}$ values obtained from the selected literature generally show coherence relative to the crop biophysical characteristics and reflect those characteristics, mainly $f_c$, h and training systems. The ranges of reported $K_c$ and $K_{cb}$ values were grouped according to crop density, particularly $f_c$ and h, and were compared with FAO56 (Allen et al., 1998) previously tabulated $K_c$ and $K_{cb}$ values, as well as by Allen and Pereira (2009) and Jensen and Allen (2016), which lead to define update indicative standard $K_c$ and $K_{cb}$ values. These values are aimed for use in crop water requirement computations and modeling for irrigation planning and scheduling, thus also aimed at supporting improved water use and saving in orchards and vines.

## Contents

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https://doi.org/10.1016/j.agwat.2020.106645
Received 6 February 2020; Received in revised form 6 November 2020; Accepted 10 November 2020
Available online xxxx
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## 1. Introduction

Irrigation is the main user and consumer of water, exceeding by far the demand for other uses (de Fraiture, 2007; Pereira et al., 2009). Nonetheless, there is growing water scarcity and a decline of water quality that pose diverse key challenges, such as increased competition for limited water resources, increased demands for food to nourish an ever-growing population, reduced water supply reliability, climate change and climate uncertainty and droughts, decline in critical ecosystems services, competition for land use, and less participatory water resources governance. Hence, agriculture faces increased difficulties and challenges aiming at providing for worldwide sustainable food security while preserving natural and man-made ecosystems and landscapes. As reviewed by Pereira (2017), high water use performance and productivity, as well as water conservation and saving in irrigation are among the required solutions.

Institutional interventions, policies and new technologies are essential and there is an increasing focus on irrigation management performance to achieve the sustainable use of water for food production. However, the lack of basic information on crop water needs is one of the causes of inadequate water use and poor irrigation management (Abuzar et al., 2013). Therefore, research should contribute to improving the knowledge of crop water requirements and their use in irrigation management.

Recent advances in sensors, communications and information technologies progressively allow the implementation of tools to support irrigation and water management decisions, namely supported by the “internet of things” as recently reviewed by García et al. (2020) and, focusing on irrigation, by Jovanovic et al. (2020) and Pereira et al. (2020a, 2021c). Despite new tools to support irrigation management, the knowledge of crop water requirements is paramount. Evapotranspiration (ET) is commonly measured with a variety of instruments and field procedures which have well-defined requirements for accuracy, as discussed in other papers for the current special issue (Pereira et al., 2021a,b). Crop ET is typically computed or modeled by using weather data and a panoply of computational procedures, more often adopting the FAO56 method (Allen et al., 1998). This method uses the simple $K_c$-$ET_o$ approach, which considers the product of a crop coefficient ($K_c$) by the grass reference evapotranspiration ($ET_o$). The latter represents the actual evaporative demand of the atmosphere while $K_c$ represents an integration of the effects of the main characteristics that distinguish the grass reference from the crop in terms of the energy balance (Allen et al., 1998; Pereira et al., 1999). Adopting the $K_c$-$ET_o$ approach is simple but requires the application of accurate measurements and computations, particularly when deriving $K_c$ values for a crop using field observations (Allen et al., 2011; Pereira et al., 2021a,b), or their prediction from the field observed fraction of ground cover and height (Allen and Pereira, 2009; Pereira et al., 2020b). The method is particularly challenging for woody and incomplete cover crops, as it is the case of fruit trees and vines.

To be considered standard, crop coefficients must be obtained from accurate ET field measurements, as well as with $ET_o$ computed with the FAO-PM (Allen et al., 1998) or the ASCE-PM (ASCE, 2005) equations. From its development, adopting fixed grass parameters for aerodynamic and surface resistance, it resulted that crop coefficients, despite computed empirically, should be interpreted in terms of relating the aerodynamic and surface resistances of the considered crop with those of the grass reference crop (Pereira et al., 1999). This is particularly challenging for vines and fruit trees due to the enormous difference of the canopy architecture and the incomplete ground cover. Other methods may be used to calculate $ET_c$ (Pereira et al., 2020a), namely by remote sensing (Courault et al., 2005), in many cases not making use of standard crop coefficients.

The definition of standard crop coefficient implies its determination under non-water or other stress conditions; otherwise it refers to actual evapotranspiration ($ET_{c\ act}$), namely under water stress conditions. However, research on tree and vine crops is demonstrating that the best crop management does not correspond to the full satisfaction of crop water demand, but to the adoption of controlled water stress at given phases of the crop cycle (Ferreira et al., 2012; Cammalleri et al., 2013a; Lobos et al., 2016; Rallo et al., 2017), herein called eustress conditions (Paço et al., 2019). Accurate standard, transferable and updated $K_c$ values obtained from the literature review require that related ET data collection, ET models and related model calibrations, as well as experimental set-ups were exempt of biases caused by experimental flaws (Allen et al., 2011). Following the methodology adopted in studies focused on vegetable and field crops (Pereira et al., 2021a,b), the selected references were checked to ensure that sufficient descriptions of ET measurement practices, crop management and related production environment were provided. They were also checked to detect possible computational flaws and shortcomings in data handling, as well as in model calibration and validation. In addition, the possible influence of advection was considered (e.g. Wang et al., 2019) since related $K_c/K_{cb}$ values are then of local value only, thus not transferable. Nonetheless, for several crops, the collected information was scarce.

Tree and vine fruit crops are heterogeneous, sparse vegetated surfaces with complex canopies, requiring different methodological approaches to determine and update crop coefficients, when compared with homogeneous vegetation fully covering the soil, like vegetables and field crops. The objective of this paper, addressing particularly this group of crops, consists of reviewing standard updated single and basal $K_c$ values for tree and vine fruit crops obtained under near-pristine eustress conditions, using the available $K_c$ and $K_{cb}$ information for tabulating indicative standard $K_c$ and $K_{cb}$ values. Thus, the current review intends to identify the main results of recent research on standard $K_c$ and $K_{cb}$ values, to assess their range and the way they were obtained. These standard values are further summarized and tabulated. Section 2 is focused on the basic concepts underlying the derivation of $K_c$ values, including a brief discussion on $K_c$ concepts and on the $K_c$ curve, as well as on the factors influencing $K_c$ values and limiting their transferability. Section 3 describes the methodologies used to select crop coefficient data. Section 4 consists of a literature review on the derivation of $K_c$ and $K_{cb}$ from field research, including the related ancillary data, whereas Section 5 provides updated indicative values of standard $K_c$ and $K_{cb}$ for tree and vine fruit crops. Conclusions and recommendations are reported in Section 6.

## 2. Requirements for accuracy on deriving $K_c$ from field studies

### 2.1. Limitations and requirements for the transferability of crop coefficients

Crop evapotranspiration, $ET_c$ (mm $d^{-1}$), adopting the FAO56 method, is estimated by multiplying the grass reference evapotranspiration, $ET_o$ (mm $d^{-1}$), by a crop coefficient, $K_c$ (dimensionless):

$$ET_c = ET_o K_c \tag{1}$$

$ET_o$ is defined as the evapotranspiration of a grass reference crop which is a hypothetical crop with height of 0.12 m, a surface resistance of 70 s $m^{-1}$ and an albedo of 0.23, closely resembling an extensive surface of green grass of uniform height, actively growing and adequately watered, and well covering the ground (Allen et al., 1998). The daily $ET_o$ is computed with the PM-$ET_o$ equation (Eq. (2)), obtained by parameterizing the Penman–Monteith combination equation for that grass crop (Allen et al., 1998; Pereira et al., 1999), fixating the corresponding aerodynamic and surface resistance terms. Daily grass reference evapotranspiration is then obtained with the following equation:

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

where $\Delta$ is the slope of the saturation vapor pressure–temperature curve at mean air temperature (kPa °C$^{-1}$), ($R_n$ – G) is the available energy at the vegetated surface (MJ m$^{-2}$ d$^{-1}$), $\gamma$ is the psychrometric constant (kPa °C$^{-1}$), T is mean daily air temperature (°C), $u_2$ is mean daily wind speed (m s$^{-1}$) at 2 m height and ($e_s$ – $e_a$) is the vapor pressure deficit (VPD) of the atmosphere (kPa). Because the PM-ET$_o$ equation considers only vertical fluxes of heat and vapor, advective heat energy fluxes are not considered in ET$_o$. Thus, ET$_o$ incorporates most of the weather and related energy effects and then represents the evaporative demand of the atmosphere. Since K$_c$ is the ratio between ET$_c$ and ET$_o$ (Eq. (1)), its variations should mainly be attributed to the specific crop characteristics and for a limited extent to the climate, which enables the transfer of standard K$_c$ values between locations and climates when local and/or regional advection is excluded.

Apart from the PM-ET$_o$ equation, other alternative processes have been tested to calculate reference evapotranspiration, either with full weather data sets or limited data sets. Processes with full data sets are an attempt to simplify the calculation procedure, which is advantageous, but have the tendency to overlook the conceptual framework (Pereira et al., 2015). For limited data sets, the Hargreaves–Samani equation (Hargreaves and Samani, 1985) and the FAO PM temperature method have been widely used; consolidated methodologies are discussed and described by Paredes et al. (2020), as well as the use of reanalysis weather data and of geostationary satellite products (Paredes et al., 2021). However, the use of alternative approaches requires the scrutiny of input data and ET$_o$ results since processes are not linear. For scientific research studies, intending to derive time and space transferable crop coefficients, the PM-ET equation (2) should be used.

The crop coefficient, K$_c$, represents an integration of the effects of three primary characteristics that distinguish any crop from the reference one: crop height, that affects roughness and aerodynamic resistance ($r_a$); bulk crop-soil surface resistance ($r_s$), which relates to leaf area, the fraction of ground covered by the vegetation ($f_c$), leaf age and condition, degree of stomatal control, and soil surface wetness; and albedo of the crop-soil surface influencing the net radiation, that is determined by the fraction of ground covered by vegetation and soil surface wetness (Allen et al., 1998).

Two K$_c$ approaches are considered (Allen et al., 1998): one consists of a time-averaged single K$_c$, which includes multi-day effects of evaporation from the soil in addition to plant transpiration, whereas the second refers to the dual K$_c$, i.e. the sum of the basal crop coefficient (K$_{cb}$) and the soil evaporation coefficient (K$_e$). These coefficients represent, respectively, the ratios between crop transpiration (T$_c$) or soil evaporation (E$_s$) and ET$_o$. In the latter approach, therefore, $K_c = K_{cb} + K_e$ with $K_{cb} = T_c/ET_o$ and $K_e = E_s/ET_o$. Various authors have developed models or procedures for partitioning ET into T$_c$ and E$_s$. However, the FAO56 approach has been successfully used, mainly after the paper of Allen et al. (2005), even implemented in models such as SIMDualK$_c$ (Rosa et al., 2012), whose applications to peach (Paço et al., 2012), vineyards (Fandiño et al., 2012), papaya (Chaterlán et al., 2012b) and olives (Paço et al., 2014, 2019) are reported herein.

For transferability purposes, FAO56 (Allen et al., 1998) adopted the concept of standard K$_c$ and potential ET$_c$, which refer to pristine cropping and well-watered conditions and are distinct of actual field conditions, often not optimal due to insufficient (or non-uniform) irrigation, crop density, salinity, agronomic practices and soil management. The tabulated K$_c$ refer, therefore and exclusively, to the standard K$_c$. However, for tree and vine crops, as referred in Section 1, K$_c$ refer to adopting crop-specific eustress practices.

Under water stress conditions, ET$_c$ gives place to the actual crop ET (ET$_{c\ act}$), with K$_c$ replaced by the actual K$_{c\ act}$ or, using the dual approach, by $K_sK_{cb} + K_e$:

$$ET_{c\ act} = K_sET_c = K_sK_cET_o = (K_sK_{cb} + K_e)ET_o \quad (3)$$

where K$_s$ (0 – 1.0) is the stress coefficient, which depends upon the sufficiency of available soil water to maintain the crop ET rate. Adopting this concept eases a consistent estimation and transferability of measured standardized K$_c$. Therefore, it avoids the need to define multiple K$_c$ values for the same crop depending upon related water management, because factors influencing crop management are numerous and cause values for K$_{c\ act}$ to vary widely, contrary to standard K$_c$. Plot level use of crop coefficient-based simulations can be backed up by soil and plant water status measurements to detect water stress conditions (e.g., leaf or stem water potential).

Evapotranspiration relies on the amount of energy available at a surface, resulting from the energy balance of that surface: net radiation flux (R$_n$) minus soil heat flux (G), minus sensible heat flux (H) will result in the term of latent heat flux ($\lambda$E), or the energy available to the evaporation process. Thus, there are physical limits imposed for such process. Since available energy is dependent on this energy balance process, upper limits to crop coefficient values are observed: 1.2 in sub-humid regions and 1.2–1.4 in arid regions (both relative to grass reference). Higher values might result from errors in ET measurement, weather data for ET$_o$ calculation or data processing procedure (Allen et al., 2011; Pereira et al., 2021a).

Awareness of such upper limits of K$_c$ is important since their transfer to different conditions in time and space are only possible when recurring to indicative standard values of K$_c$ that are bounded by such limits. Furthermore, the conditions where measurements were acquired or those from where K$_c$'s are meant to be applied must be considered. For application in small and isolated areas of vegetation, K$_c$ can exceed the limits for grass reference (1.2–1.4), while for large areas or small areas surrounded by vegetation with similar roughness and soil water status, K$_c$'s must stick to values equal or smaller than those limits (Allen et al., 2011).

The concepts of standard K$_c$ and potential crop ET and related terminology are progressively being accepted by the users communities (Pereira et al., 2015). However, the standard K$_c$ and K$_{cb}$ values for tree and vine crops vary with the fraction of ground cover and height (Allen and Pereira, 2009; Jensen and Allen, 2016) due to crop age and crop management, particularly crop training (Pereira et al., 2021b,c). However, these values can be considered standard if they are obtained under optimal, pristine cropping conditions (Pereira et al., 2021b,c). According to these authors, another aspect to consider is that orchard and vine crops do not achieve full canopy cover, resulting in an upper limit of K$_c$ close to 1.2, unless in the presence of advection.

The present review has shown that satisfactorily accurate reported K$_c$ and K$_{cb}$ values for the same crop show significant dissimilarity among locations due to differences in cultivar, soil properties, irrigation method and strategy, soil-crop management practices and orchard management and training (Minacapilli et al., 2009; Cammalleri et al., 2013a; Marsal et al., 2014a; Pereira et al., 2020b). Thus, while it is difficult and challenging to develop standard K$_c$ and K$_{cb}$, and while site-specific K$_c$ and/or K$_{cb}$ values are needed when it is required for research objectives to produce more robust and accurate crop coefficients, it is possible to orient the development of standard K$_c$ and K$_{cb}$ on the basis of crop density as estimated by the fraction of ground cover, or the fraction of ground shaded or the fraction of intercepted photosynthetic active radiation. A most common value of the fraction of ground cover can be attributed to each crop, relative to the growing stage (initial, mid- or end-season) (Pereira et al., 2021b,c). Likewise, for the same crop, it is possible to link different values of ground cover to the respective K$_c$ or K$_{cb}$. For most crops it is possible to derive crop coefficients from f$_c$ and h, as demonstrated in Pereira et al. (2020b), although for orchards larger errors are expected due to varied training practices and differences of crop varieties. Therefore, bearing in mind specificities of woody crops, and departing from the most common value for $f_c$ of a given crop, it is possible to infer correspondent standard $K_c$ or $K_{cb}$.

Research reporting field derived crop coefficients, and showing diverse objectives, used quite different methodologies with variable accuracy, often with the aim to obtain $K_c$ values only for local use, and therefore not transferable. Results are frequently published without sufficient information relative to the methods and instruments used, or about the crop itself, the cropping practices or training. When the published material had serious limitations to transferability, it was not used in this review. Main limitations are referred to:

1. Not adopting the standard PM-$ET_o$ equation as defined in FAO56. Because $K_c$ is defined as the ratio $ET_c/ET_o$, if the $ET_o$ equation changes, the $K_c$ also changes as a function of the ratio between the selected $ET_o$ equation and PM-$ET_o$; the transferability of the research results is then not possible unless that ratio is well known.
2. Using a $K_c$ curve such as a function of time or a function of LAI, thus different from the standard segmented FAO $K_c$ curve, which defines $K_c$ (and $K_{cb}$) values for the initial, mid-season and end-season, respectively $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$. Then, only approximate estimations of $K_{c\ mid}$ and $K_{c\ end}$ can be made from the reported graphical data or, often more difficult, from tabulated information.
3. Using non-standard cultivation conditions, namely aimed at controlling soil evaporation ($E_s$) using mulch, which produces specific $K_c$ values. Reported changes in $K_c$ are very often insufficient to properly recognize standard $K_c$ values.
4. Adopting deficit irrigation practices that deviate from eustress conditions. Then $K_c$ results refer to local $K_{c\ act}$ and cannot be directly transferred.

### 2.2. Field data measurement and accuracy requirements

As evapotranspiration is dependent on the available energy at a crop surface, limits apply to the process, yielding crop coefficient values for grass reference, for tree crops, more likely to be below 1.2 (as reported above, Section 2.1). Higher values might result from errors in ET measurement, data processing and/or the effects of advection (Pereira et al., 2021a,b); hence, field data acquisition processes must respect well defined requirements. Field data sets used to derive $K_c$ or $K_{cb}$ are usually obtained using techniques based on soil water balance, the Bowen ratio energy balance (BREB) method, the eddy covariance method (EC), scintillometry, sap flow methods, remote sensing energy balance or vegetation indices derived from satellite information. The requirements for data quality acquired by these methods are extensively described in Allen et al. (2011) and reviewed by Pereira et al. (2021a,b) and herein summarized.

Techniques that recur to soil water balance methods calculate ET as the remaining term when water stored in the soil is added to rainfall, irrigation and capillary rise, and subtracted of drainage or deep percolation and surface runoff. The main sources of error in this calculation normally arise from the quantification of drainage/deep percolation and/or capillary rise. Other difficulties may arise from the different patterns of soil water extraction by the roots, namely for heterogeneous stands, as sampling processes may not represent adequately the stand. These techniques must take into account: (i) a comprehensive characterization of soil hydraulic properties, (ii) representativeness of data in spatial and temporal terms, (iii) appropriate sensor calibration, (iv) differential spatial wetting by irrigation, (v) deep percolation and capillary rise, (vi) root water extraction patterns, relevant in the case of trees and, (vii) inappropriate sampling or readings.

The BREB method relies on the surface energy balance equation and requires measurements of air temperature and vapor pressure gradients at a certain level above the evaporating surface, having the advantages of being able to be used in water stressed stands, as long as some conditions are respected, of almost eliminating turbulent transfer coefficients and of not requiring wind speed and surface measurements. Nevertheless, it requires some caution in its application, since the accuracy of the method relies strongly on $R_n$ and G measurements and on an adequate fetch for the establishment of the equilibrium boundary layer. Also, the adoption of BREB in tree stands implies that gradients measurement are performed at a height above the canopies sufficient to avoid individual tree effects. Main requirements for BREB data quality must then include: (i) large enough fetch to allow for the establishment of a suitable equilibrium boundary layer, (ii) adequate positioning of sensors above the canopy avoiding the roughness sublayer, (iii) representative measurement of $R_n$ and G, (iv) multiple $R_n$ and G measurement points for heterogeneous or sparse crops.

The EC method presents a relatively simple theoretical framework, although its implementation requires complex and expensive sensors, capable of high frequency measurement, and extended data processing and treatment. It entails the knowledge of vertical wind speed and fluctuations around the mean of air temperature and humidity in vertical fluxes of sensible and latent heat, sampling statistically turbulent eddies. The main advantage of the EC method is to provide a direct measurement of ET in actual conditions, either potential or not. Recurring to the EC method implies respecting the following data quality requirements: (i) large enough fetch and adequate elevation of sensors, as with BREB, (ii) application of the required corrections, including coordinate rotation if the sensor measuring vertical wind speed is not set parallel to surface, (iii) recognition of advection situations and taking of corrective actions, (iv) correct data for lack of closure of energy balance equation, when needed.

Scintillometry is another method that, although not able to measure ET directly, allows its estimation as a residual term, by measuring sensible heat flux. The sensor (scintillometer) detects small oscillations in air density caused by temperature, humidity and pressure, in the form of slight fluctuations in the refractive index of air. It has the advantage of integrating large areas information along a certain direction, but still relies on $R_n$ and G measurements for calculating ET, requiring accurate representative measurements of $R_n$ and G (Allen et al., 2011).

The transpiration component in ET can be obtained independently by sap flow methods. These methods use heat as a tracer to measure the flow of water in the xylem of plants. They are more frequently oriented to applications in woody plants, although there are also solutions applicable to herbaceous plants. Although most methods require calibration to produce accurate quantitative results, these methods generally follow well the transpiration dynamics. Several factors can influence the data quality of sap flow measurements and must be observed: (i) a calibration is required for each new application, (ii) being a plant-based process, implies scaling from plant to stand level, dealing with measurement representativeness, (iii) an accurate estimate of conductive xylem area is needed (Allen et al., 2011).

Remote sensing data can be used to calculate ET but these processes produce estimates and not measurements, as with remote sensing energy balance data, and should be considered accordingly (Pôças et al., 2020; Pereira et al., 2021a,b). They are, however, becoming largely used for $K_c$ and ET calculation. Satellite-based energy balance methods have the disadvantage of being time consuming and requiring specialized skills, but they can be a way of calibrating less complex methods which recur to vegetation indices. Vegetation indices derived from satellite information require ground data for validation and they are related to crop coefficients in ET actual conditions, therefore often not standard (Pereira et al., 2021a,b).

Inaccuracies in measuring crop ET and in computing $ET_o$ often results in high $K_c$ values, commonly indicating that the corresponding energy use would largely exceed the energy available at the surface for evaporation (Allen et al., 2011; Pereira et al., 2021a,b). Although values of $K_c$ above 1.3 may be observed for a few occasional days following a rainfall event, or over quite short periods, such high values cannot be accepted as averages for large periods such as a month or the entire mid-season. Problems for transferability also result from conditions where $K_c$ experiments are developed, managed and data are handled, e.g., small size experimental plots, inadequate setting and management of lysimeters, the reduced fetch of BREB and EC systems, and poor estimation of soil water fluxes and inadequate calibration of soil water balance (SWB) models. When using remote sensing, adopting non-calibrated vegetation indices or energy balance models are causes for inaccuracies. These subjects were reviewed by Allen et al. (2011), Evett et al. (2012a,b) and Pereira et al. (2021a,b). When the accuracy of crop ET measurements cannot be accepted then, it is not possible to use/transfer the reported $K_c$ values. This is summarized as follows:

1. Inaccuracies in performing the soil water balance (e.g. Evett et al., 2012c) such as insufficient characterization of the soil hydraulic properties, non-consideration of the full root zone depth, inadequate spacing and/or frequency of measurements, inaccuracies in measuring the soil water content and/or the irrigation water and rainfall, poor estimation of deep percolation and/or capillary rise, rough computational approaches, and/or using an inadequately calibrated and validated model.
2. Using lysimeters with poor setting and management (Allen et al., 1991a,b; Grebet and Cuenca, 1991; López-Urrea et al., 2006; Evett et al., 2016), namely having differences in cropping conditions inside and outside of the lysimeter that relates to vigor and growth of vegetation, the poor setting of the lysimeter without similar surrounding vegetation causing local advection or clothesline effects, insufficient fetch to establish an equilibrium boundary layer of air, lack of consideration of the area effectively used by the crop for ET.
3. Measuring ET with the BREB method or the EC systems with insufficient fetch, less representative measurement of net radiation, insufficient elevation of instruments above the canopy, lack of adjustments for the effects of advection, and/or poor correction of data for the energy balance closure error (Payero et al., 2003; Allen et al., 2011; Alfieri et al., 2012; Evett et al., 2012b; Kutikoff et al., 2019).
4. The use of remote sensing vegetation indices (VIs) to estimate crop coefficients is now well established, mainly with the Normalized Difference Vegetation Index (NDVI, Hunsaker et al., 2005a,b; Pôças et al., 2020) and the soil adjusted vegetation index (SAVI, Glenn et al., 2011). However, inaccuracies in deriving $K_c$ or $K_{cb}$ from a VI result from improper calibration of the index and from insufficient identification of the pixels that correspond to the crop growing under an approximately pristine condition (Hunsaker et al., 2005a,b, and 2007). Remote sensing energy balance is less used to derive $K_c$ values, and similar difficulties to those using VI approaches also occur. However, good results on $K_c$ values estimated with energy balance have been reported (Paço et al., 2014; Pôças et al., 2014).

The FAO56 method (Allen et al., 1998) proposes that, when local climate conditions deviate from the standard reference (wind velocity=2 m $s^{-1}$ and minimum relative humidity=45%) the $K_c$ and $K_{cb}$ values for mid- and end-seasons are adjusted to the reference climate. However, the equations proposed in FAO56 were developed for field and vegetable crops, which are full or near full cover crops, and were not intended for tree and vine crops, because these are incomplete cover crops and have large to very large heights, thus having a different aerodynamic behavior from that of the former (Pereira, personal communication); thus, adjustments for climate were not applied in the current study.

### *2.3. Crop coefficients derived from field measurements in the presence of advection*

If the ET term of the surface energy balance equation results in a value higher than $R_n$ – G, the surface is receiving sensible heat downwards, instead of just losing it by convection to the atmosphere. Therefore, a larger amount of energy will be available for the process of evapotranspiration. However, there is an upper boundary to ET, imposed by limitations in aerodynamic transfer and equilibrium forces over a vegetated surface (Allen et al., 2011). Then, similarly as referred in Section 2.1, limits apply and $K_c$ must be less than or equal to 1.2 (grass reference, Allen et al., 2011), except in the presence of advection. In the past two decades, numerous studies have been published in this research area without considering advection impacts (Pereira et al., 2021b) and care must be taken when there is insufficient information relative to the methods employed or measurement conditions. Advection conditions can though limit transferability of crop coefficients, either because they were determined under advection conditions or they are to be applied in such conditions.

Advection conditions can result from the small dimension of the stand under analysis, not providing adequate conditions for the development of a boundary layer in equilibrium with the surface, or by favoring a “clothesline effect”, where vegetation in the stand is somehow more exposed to atmosphere drive than the surrounding vegetation (Allen et al., 2011; Pereira et al., 2021a). Advection can also result from measurement errors in the field, for example when lysimeters are not correctly set, causing local and micro-scale advection or a “clothesline effect” (Pereira et al., 2021a), or when, in EC systems, fetch conditions are not observed or data quality selection criteria against wind direction/fetch not applied. Under advection, H decreases to very small values, given the downward advective H flux, and $\lambda$E becomes larger than the term $R_n$-G. Therefore, it is expected that, under advection conditions and over small stands of vegetation, ET would reach a much larger value (Allen et al., 2011), which is not the case for large stands, where limits apply for $K_c$ (1.2, grass reference, Allen et al., 2011). Advection effects on ET of woody crops are rarely reported in literature. However, since trees and vines do not attain full crop development due to pruning and training, in the absence of advection, $K_c$ values should not surpass 1.2 (Pereira et al., 2021a,b). However, under advective conditions much larger transpiration and larger evaporation values are observed (Kool et al., 2018; Wang et al., 2019); nevertheless, too much large $K_c$ values were also reported without signaling the occurrence of advection.

## 3. Information on selection methodologies

### *3.1. Methods adopted to select the papers*

Insufficiencies and inaccuracies referred in the previous section limit the transferability of reported $K_c$ values; thus, to update the tabulated $K_c$ it was necessary to operate a careful literature selection. In fact, 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, often, monthly values. Crop growth stages are sometimes defined differently than in FAO56. These limitations impede to adequately identify the $K_c/K_{cb}$ values for the mid- and the end-season. Information provided in some papers, despite sufficient to achieve the objectives of the research, could be inadequate for the transferability of the reported $K_c$ to environments different from that where the investigation was carried out. These limitations obliged a careful review of published material to check when the proposed $K_c$ or $K_{cb}$ were limited to local interest and/or represented non-standard experimental conditions, thus contrasting to $K_c$ resulting from near-pristine or eustress cropping practices. The studies were therefore selected when:

- Adopted the PM-ET$_o$ equation (Allen et al., 1998) or the ASCE-ET$_o$ equation (ASCE, 2005). Therefore, studies reporting reference ET values obtained with grass lysimeters, empirical equations, pan evaporation or similar were excluded;
- Presented data referred to two or more seasons; only exceptionally studies were considered with one-year of data but with different treatments, so that it was possible to understand if the results were or not occasional as for a few studies presenting one-year data for tropical fruit trees, which represented the only available data source;
- Adopted the FAO $K_c$ curve or a $K_c$-time curve that allowed to identify $K_c$ or $K_{cb}$ for the mid-season and, sometimes, for the end season. When that identification was not possible or when the $K_c$ curve was provided as a function of LAI or similar, the studies were excluded.
- Relative to the field methods using BREB or EC systems, the papers reporting upon the upwind fetch conditions and the energy balance closure were considered, otherwise they were excluded;
- Studies using SWB methods describing the terms of the balance and/or providing for the accuracy associated with the model calibration and validation were selected; otherwise, papers not properly reporting deep percolation or referring to SWB interesting only for the upper soil layers were not considered.
- Studies using lysimeters were accepted when there were adequate setting and management of the lysimeters, namely avoiding “oasis” and “cloth-line” effects, and the evaporative surface was corrected if the tree/vine canopy exceeded the lysimeter surface.
- Studies using remote sensing were considered when a calibration/validation was performed.
- Studies reporting $K_c$ values greater than 1.25 were excluded, since such high values are frequently induced by advection situations or sensor malfunctioning.
- Also, studies reporting $K_{cb\ end} > K_{cb\ mid}$ and $K_{cb} > K_c$ were excluded.
- Finally, papers where crops were evidently stressed were excluded, such when $K_c$ values were low relative to studies referring to the same or a similar crop, or heavy deficit irrigation was practiced.

As a consequence of the criteria assumed, it was possible to select some papers that were used as reference to other studies or, at least, to approach reasonable quality conditions.

### 3.2. Methods adopted to select updated ranges of $K_c/K_{cb}$ values

Standard values were established considering:

(i) ranges of new $K_c/K_{cb}$ values collected in literature from the past twenty years;
(ii) prior information on tabulated $K_c/K_{cb}$ values from Allen et al. (1998), Allen and Pereira (2009), and Jensen and Allen (2016);
(iii) crop density based upon ground cover fraction, which varies with the crop and with training. Thus, the term crop density is not exclusively related to plant spacing but, in a broader sense, encompasses plant density/sparsity/dimensions, including height, and at last, the fraction of ground cover and plant spacing, but not exclusively.

## 4. Review on single and dual $K_c$ for tree and vine crops

Information relative to crop coefficient ($K_{c\ mid}$ and $K_{c\ end}$) and basal crop coefficient ($K_{cb\ mid}$ and $K_{cb\ end}$) and related ancillary data collected from the selected studies were tabulated after grouping the crops into: (1) Vine fruit crops, berries and hops; (2) Temperate climate evergreen fruit trees; (3) Temperate climate deciduous trees; and (4) Tropical and sub-tropical fruit crops. Values for the initial period ($K_{c\ ini}$), often characterized by a short duration and dependent mainly from the rainfall regime, were not considered. Users are advised to follow the recommendations in FAO56 and guiding values provided by Allen and Pereira (2009) and Jensen and Allen (2016).

The collected data included in this review consider information regarding the age of the orchard, the planting density (number of trees, vines or shrubs per hectare), and various crop biophysical characteristics such as the training system, crop height (h) and ground cover fraction ($f_c$). Alternatively to $f_c$, some studies adopted other indices that may serve as indicators of the ground surface covered by the canopies, such as the fraction of intercepted photosynthetic active radiation ($f_{IPAR}$) (Intrigliolo et al., 2009; Girona et al., 2011; Marsal et al., 2013) and the shaded fraction of soil ($f_{shad}$) (Stevens et al., 2012). The crop coefficient presented in the tables from 1 to 4 correspond to the average of the different experimental years. However, whenever it was possible to relate $K_c$ or $K_{cb}$ with $f_c$, results are presented for every single experimental year.

### 4.1. Vine fruit crops, berries and hops

A total of nineteen studies suitable to update the FAO56 crop coefficients were retained for vineyards, one for kiwi (*Actinidia deliciosa* A. Chev), two for passion fruit (*Passiflora edulis* Sims), three for highbush blueberries (*Vaccinium corymbosum* L.), and one for hop (*Humulus lupulus* L.). Table 1 presents the list of these selected studies and reported single and basal crop coefficients as well as related ancillary data.

Vineyards were divided into table- and wine grapes, with nine and ten suitable studies, respectively for each group (Table 1). The works referring to vineyards used different approaches to measure $ET_{c\ act}$ from field observations. Two studies used weighing lysimeter (Williams et al., 2003; López-Urrea et al., 2012), while only one used a drainage lysimeter (Netzer et al., 2009). Four works applied EC systems to measure actual, $ET_{c\ act}$ (Villagra et al., 2011; Carrasco-Benavides et al., 2012; Er-Raki et al., 2013; Marras et al., 2016). Villagra et al. (2014) combined the use of EC with the SWB. The EC technique was associated with sap flow measurements for the determination of crop transpiration in the studies by Poblete-Echeverría et al. (2012) and Poblete-Echeverría and Ortega-Farias (2013). Ferreira et al. (2012) measured ET with EC and its components, plant transpiration and soil evaporation, using respectively the sap flow technique and microlysimeters. Other studies (Moratiel and Martínez-Cob, 2012) used the surface renewal (SR), and the BREB to estimate crop ET (Teixeira et al., 2007). Parry et al. (2019) combined the use of SR with weighing lysimeter measurements to estimate vineyards ET. Fandiño et al. (2012) and Cancela et al. (2015) used the SWB for estimating vineyards ET. Phogat et al. (2020) adjusted the standard $K_{cb}$ values from FAO56 taking into account local meteorological variables and crop biophysical characteristics. One work used sap flow measurements exclusively (Suvočarev et al., 2013) and another sap flow in combination with a whole canopy gas exchange system to measure the transpiration and to derive the $K_{cb}$ of table and wine grape (Intrigliolo et al., 2009).

The most common irrigation method in both table and wine grapes is surface drip irrigation and subsurface drip irrigation. However, one study used micro-sprinkler irrigation in addition to drip irrigation (Teixeira et al., 2007). Rainfed is also common in wine grapes (Ferreira et al., 2012). Other studies used both drip irrigation and rainfed conditions (Fandiño et al., 2012; Cancela et al., 2015). The studies on vineyards were conducted in different countries (i.e. Australia, Chile, USA, Spain, Italy, Brazil, México, Portugal and Israel), which include the primary producing vine areas and new emerging producing regions.

Generally, the $K_c$ and $K_{cb}$ values resulted higher in table grapes compared to wine grapes, which are related to the different training system employed. The $K_c$ and $K_{cb}$ values reported for table and wine grapes are generally related to $f_c$. At the same time, the different $K_c$ and $K_{cb}$ values reported by various studies are coherent with the varieties, age, training and irrigation systems, soil cover and crop management.

**Table 1**

Published $K_c$ and $K_{cb}$ for the mid and end-season relative to vine fruit crops, berries, and hops.

| Crop and author | Age (years) | Density (plants/ha) | Training system | Height (m) | $f_c$[a] | $K_{c\ mid}$ | $K_{c\ end}$ | $K_{cb\ mid}$ | $K_{cb\ end}$ |
|---|---|---|---|---|---|---|---|---|---|
| **Table grapes (*Vitis vinifera*)** | | | | | | | | | |
| Williams et al. (2003) | 4–7 | 1324 | Horizontal trellis | 1.70 | 0.60 | 1.00 | 0.80 | – | – |
| Teixeira et al. (2007) | 2 | 714 | Horizontal trellis | 1.80 | – | 0.91 | 0.80 | 0.77 | 0.62 |
| Netzer et al. (2009) | 2–8 | 1430 | Open gable trellis | 2.00 | 0.80 | 1.10 | – | – | – |
| Villagra et al. (2011) | 8–9 | 1633 | Overhead trellis | – | 0.95 | 1.05 | 0.80 | – | – |
| Moratiel and Martínez-Cob (2012) | 8 | 1429 | Y shape gable | 2.20 | 0.90 | 0.80 | – | 0.65 | – |
| Suvočarev et al. (2013) | 9 | 1429 | Overhead trellis | – | 0.90 | – | – | 0.65 | – |
| Er-Raki et al. (2013) | Mature | 2662 | Y trellis | 2.20 | 0.62 | 0.55 | 0.25 | – | – |
| | Mature | 1462 | Y trellis | 2.20 | 0.62 | 0.55 | 0.30 | – | – |
| Villagra et al. (2014) | 8–9 | 1633 | Overhead trellis | 2.00 | 0.95 | 1.05 | 0.70 | – | – |
| Parry et al. (2019) | 25 | 1325 | T trellis | 2.00 | 0.46 | 0.84 | – | – | – |
| **Wine grapes (*Vitis vinifera*)** | | | | | | | | | |
| Intrigliolo et al. (2009) | 2 | 1352 | VSP trellis[c] | – | 0.30 | – | – | 0.50 | – |
| Carrasco-Benavides et al. (2012) | 8–9 | 2667 | VSP trellis[c] | – | 0.28–0.31 | 0.56 | 0.46 | – | – |
| Fandiño et al. (2012) | Mature | 2222 | Pergola | 2.00 | 0.55 | – | – | 0.60 | 0.46 |
| Ferreira et al. (2012) | Mature | 3030 | VSP trellis[c] | 1.70 | 0.35 | – | – | 0.70 | 0.20 |
| | Mature | 3333 | Espalier double Guyot | 1.60 | 0.20 | – | – | 0.50 | 0.30 |
| López-Urrea et al. (2012) | 8–10 | 2222 | VSP trellis | 1.70 | 0.45 | 0.75 | – | 0.69 | – |
| | | | | | 0.33 | 0.51 | – | 0.46 | – |
| | | | | | 0.40 | 0.72 | – | 0.67 | – |
| Poblete-Echeverría et al. (2012) | 9 | 1600 | VSP trellis[c] | 2.00 | 0.30 | 0.80 | 0.50 | 0.60 | 0.40 |
| Poblete-Echeverría and Ortega-Farias (2013) | 8–9 | 2667 | VSP trellis[c] | – | 0.30 | 0.62 | – | 0.53 | – |
| Cancela et al. (2015) | 15 | 3800 | VSP trellis[c] | 2.00 | 0.25–0.30 | – | – | 0.80 | 0.60 |
| | 70 | 4200 | VSP trellis | 1.50 | 0.25 | – | – | 0.75 | 0.60 |
| Marras et al. (2016) | 15 | 5952 | Guyot | 2.00 | 0.50 | 0.80 | 0.50 | – | – |
| Phogat et al. (2020)[b] | 12–16 | 2020 | – | 1.50 | 0.50 | – | – | 0.70 | 0.55 |
| **Kiwi (*Actinidia deliciosa*, A. Chev.)** | | | | | | | | | |
| Silva et al. (2008) | Mature | 400 | Pergola | 2.00 | – | – | – | 0.70 | – |
| **Passionfruit (*Passiflora edulis* Sims.)** | | | | | | | | | |
| Souza et al. (2009) | Young | 1000 | – | – | – | 1.25 | – | – | – |
| Nogueira et al. (2014) | – | 1000 | Vertical trellis | 1.80 | – | 1.00 | – | – | – |
| **Highbush blueberries (*Vaccinium corymbosum*)** | | | | | | | | | |
| Dourte et al. (2010) | 8 | 3500 | Vase | – | – | 0.84 | – | – | – |
| Bryla (2011) | Mature | | – | <2.00 | >0.70 | 1.00 | 0.85 | – | – |
| Lobos et al. (2016) | 6-7 | 3333 | – | – | – | 0.52 | – | – | – |
| | 27 | 3704 | | | | 0.49 | | | |
| **Hop (*Humulus Lupulus* L.)** | | | | | | | | | |
| Fandiño et al. (2015) | 5 –7 | 1667 | Hedgerow | 6.00 | 0.10 | 1.02 | 0.85 | 0.97 | 0.83 |

[a] Includes the ground cover fraction ($f_c$), the fraction of intercepted PAR ($f_{IPAR}$), the ground shaded fraction ($f_{shad}$), and the percentage of intercepted solar radiation at noon (ISR). [b] Average of three vineyards. [c] VSP trellis means Vertical shoot positioned trellis.

Teixeira et al. (2007) determined the $K_c$ values for micro-sprinkler irrigated table and drip irrigated wine grapes in the semiarid region of the São Francisco river basin (Brazil). The study reported higher crop coefficients for table than wine grapes which may relate with both the irrigation method and training. Phogat et al. (2020) reported similar $K_{cb}$ values for three different locations in South Australia.

Moratiel and Martínez-Cob (2012) measured the evapotranspiration of a table grape located in Zaragoza (Spain), which grew under netting with black plastic mulch. Therefore, crop coefficients were adjusted to take into account the reduction of $ET_c$ caused by the netting and the black plastic mulching. In the same experimental location, Suvočarev et al. (2013) adjusted the $K_{cb}$ for the netting effects using a reduction coefficient similar to the one used by Moratiel and Martínez-Cob (2012).

Two articles presented the FAO56 basal crop coefficient curve and the crop growth stages data (Fandiño et al., 2012; Cancela et al., 2015). Both studies performed in Galicia (Spain) calibrated and validated the soil water balance model SIMDualK$_c$ (Rosa et al., 2012) and obtained both the single and the basal crop coefficients for vineyards with active ground cover in the inter-row spacing.

Silva et al. (2008) studied the water requirements of kiwi in a mature orchard located in Guimarães (Portugal) irrigated with micro-sprinklers. In the study, crop evapotranspiration was measured with the EC method, the crop transpiration using sap flow sensors, and the soil evaporation and cover crop transpiration with micro-lysimeters.

The selected studies on passionfruit were set in Brazil in young drip-irrigated orchards. In both studies the SWB was used to determine $ET_c$ (Souza et al., 2009; Nogueira et al., 2014).

Dourte et al. (2010) studied the water requirements of southern mature highbush blueberries (interspecific hybrids of *Vaccinium corymbosum* L., *V.virgatum* Aiton and *V. darrowi* Camp) in Florida (USA), based on the SWB approach combining data from drainage lysimeter and soil moisture measurements; overhead impact sprinklers were used for irrigation. Bryla (2011) estimated the $K_c$ of highbush blueberries (*V. corymbosum*) using $ET_c$ data provided by the Pacific Northwest Co-operative Agricultural Weather Network (AgriMet) and weather-based estimates of $ET_o$ from the CIMIS (California Irrigation Management Information System) website. Lobos et al. (2016) validated the $K_c$ values reported in FAO56 using midday stem water potential measurements. The studies were developed in drip irrigated orchards from two experimental areas in Maule Region, Chile, and Michigan, USA. The difference observed among the $K_c$ values reported in these studies could be due to the different approaches employed to carry out the experiments as well as with the diverse irrigation and crop management conditions.

Regarding hops (*Humulus lupulus* L.*),* only one study was available (Fandiño et al., 2015) which was performed in Galicia (Spain) using the soil water balance approach to calibrate and validate the SIMDualK$_c$ model and thus, to estimate crop ET under diverse irrigation management conditions (rainfed and drip irrigation).

**Table 2**
Published $K_c$ and $K_{cb}$ for the mid and end-season relative to temperate climate evergreen fruit trees.

| Crop and author | Age (years) | Density (plants/ha) | Training system | Height (m) | $f_c$[a] | $K_{c\ mid}$ | $K_{c\ end}$ | $K_{cb\ mid}$ | $K_{cb\ end}$ |
|---|---|---|---|---|---|---|---|---|---|
| **Clementine (*Citrus* × *clementina*)** | | | | | | | | | |
| Castel (2000) | Mature | 433 | – | 2.30 | 0.37 | 0.55 | – | – | – |
| Rana et al. (2005) | 10 | 400 | Vase | 4.10 | – | 1.20 | 0.80 | – | – |
| **Lime (*Citrus* × *aurantiifolia*)** | | | | | | | | | |
| Marin and Angelocci (2011) | 7 | 179 | – | 4.50 | 0.38 | 0.69 | – | 0.41 | – |
| **Mandarine (*Citrus reticulate* Blanco)** | | | | | | | | | |
| Maestre-Valero et al. (2017) | Mature | 555 | – | 2.80 | 0.66 | 0.51 | – | – | – |
| **Orange (*Citrus sinensis* L. Osbeck)** | | | | | | | | | |
| Snyder and O'Connell (2007) | 33–37 | 282 | Hedge prune | 4.00–4.50 | 0.66–0.70 | 1.00 | – | – | – |
| Er-Raki et al. (2009) | 13 | 667 | – | 3.15 | 0.70 | 0.60 | 0.50 | 0.55 | 0.45 |
| | 15 | 204 | – | 3.30 | 0.30 | 0.55 | 0.60 | 0.50 | 0.40 |
| Villalobos et al. (2013) | 7 | 417 | – | 2.30 | 0.27 | – | – | 0.40 | – |
| Consoli and Vanella (2014) | Mature | 454 | Vase | 3.70 | 0.40 | 0.71 | – | – | – |
| Rallo et al. (2017) | Mature | 400 | Vase | 2.50 | 0.40 | – | – | 0.56 | 0.61 |
| Taylor et al. (2017a) | 14 | 800 | – | 3.30 | 0.88 | – | – | 0.80 | 0.35 |
| Peddinti and Kambhammettu (2019) | 8 | 400 | – | 2.50–3.00 | 0.70 | 0.78 | 0.80 | 0.57 | 0.63 |
| **Olives (*Olea europaea* L.)** | | | | | | | | | |
| ***Traditional*** | | | | | | | | | |
| Testi et al. (2004) | 3 | 408 | Vase | 2.90 | 0.25 | 0.35 | – | – | – |
| Cammalleri et al. (2013b) | 25 | 250 | Vase | 3.50 | 0.35 | 0.65 | – | 0.59 | – |
| ***Intensive*** | | | | | | | | | |
| Martínez-Cob and Faci (2010) | 8 | 556 | Hedgeprune | 3.50 | 0.33 | 0.48 | 0.97 | – | – |
| Puppo et al. (2019) | 1 | 727 | – | 2.90 | 0.30 | – | – | 0.25 | 0.15 |
| | 2 | | – | | 0.50 | – | – | 0.40 | 0.22 |
| ***Super-intensive*** | | | | | | | | | |
| López-Olivari et al. (2016) | 5–6 | 1333 | Hedgerow | 3.20 | 0.30 | 0.56 | 0.45 | 0.35 | 0.25 |
| Paço et al. (2019) | 5 | 1975 | Hedgerow | 3.00–4.00 | 0.38 | 0.71 | 0.84 | 0.48 | 0.43 |

[a] Includes the ground cover fraction ($f_c$), the fraction of intercepted PAR ($f_{IPAR}$), and the ground shaded fraction ($f_{shad}$).

### 4.2. *Temperate climate evergreen fruit trees*

This group of orchards includes citrus (*Citrus* spp.) and olives (*Olea europaea* L.). A total of eleven articles were selected for citrus and six articles were retained for olives with diverse tree densities. Table 2 presents the list of these selected studies and reported single and basal crop coefficients as well as the related ancillary data.

The articles selected for citrus included studies on clementine (*Citrus × clementina*) (Castel, 2000; Rana et al., 2005), lime (*Citrus × aurantiifolia*) (Marin and Angelocci, 2011), mandarine (*Citrus reticulate* Blanco) (Maestre-Valero et al., 2017), and orange (*Citrus sinensis* L. Osbeck) (Snyder and O'Connell, 2007; Er-Raki et al., 2009; Villalobos et al., 2013; Consoli and Vanella, 2014; Rallo et al., 2017; Taylor et al., 2017a; Peddinti and Kambhammettu, 2019). In general, the $K_c$ and $K_{cb}$ values reported in the studies were comparable and related to the ancillary data (Table 2).

Different methodologies were used to estimate ET for the *Citrus* spp. group. The EC technique was used by Consoli and Vanella (2014) and Maestre-Valero et al. (2017), and it was associated with soil water balance (FAO56) by Rana et al. (2005) and Er-Raki et al. (2009). Castel (2000) used the SWB approach combining data from drainage and weighing lysimeters. Moreover, sap flow (SF) measurements were used by Marin and Angelocci (2011), Villalobos et al. (2013) and Taylor et al. (2017a) to provide accurate evaluations of tree transpiration. Snyder and O'Connell (2007) applied the surface renewal method to measure $ET_{c\ act}$. The FAO56 dual crop coefficient approach was applied through soil water balance models in two studies; Rallo et al. (2017), who derived $K_{cb}$ values for orange using the soil water balance (FDR soil water content measurements) and ecophysiological indicators. Peddinti and Kambhammettu (2019) used the SIMDualK$_c$ water balance model, which was calibrated and validated with soil water content data determined with electrical resistivity tomography (ERT).

Drip irrigation was the most common method; however, two works were carried out under surface irrigation (Er-Raki et al., 2009; Peddinti and Kambhammettu, 2019), and thus presented higher $K_c$ values. Most of the experimental studies were carried out in Mediterranean countries (e.g. Italy, Spain, Morocco), which are among the most important production regions for citrus, while three studies were performed outside this region, one in Brazil (Marin and Angelocci, 2011), one in India (Peddinti and Kambhammettu, 2019) and the other in South Africa (Taylor et al., 2017a).

Rana et al. (2005) reported the highest $K_{c\ mid}$ for citrus, which might be due to a high stomatal conductance, or to the favorable observed climatic conditions (high wind speed and vapor pressure deficit). Er-Raki et al. (2009) and Peddinti and Kambhammettu (2019) reported $K_{c\ end}$ values higher than the $K_{c\ mid}$ values which may be associated with the rainfall conditions during late autumn and winter, typical to the climate of the investigated areas. The highest $K_{cb\ mid}$ value was reported in the study with the highest $f_c$ (Taylor et al., 2017a); but the same study presented the lowest $K_{cb\ end}$ which relates with the stomatal control performed by the citrus trees under high climatic demand conditions.

In the last decades, the research activity on olive water requirement has been concentrated on irrigation management strategies, as well as on the crop response to water saving in terms of agronomic and/or eco-physiological features. The EC technique was applied in two studies (Testi et al., 2004; Martínez-Cob and Faci, 2010), and was associated with SF measurements in Cammalleri et al. (2013b) and López-Olivari et al. (2016). Puppo et al. (2019) used drainage lysimeters combined with soil water content measurements for estimating $ET_{c\ act}$. The soil water balance model SIMDualK$_c$ was calibrated and validated using sap flow based sensors in the study by Paço et al. (2019), which was the only study considering the direct calculation of the crop coefficient and derived the $K_c$ curve following the FAO56 approach.

The irrigation method used in all the olive studies was drip irrigation. The majority of the studies were carried out in the Mediterranean basin, which is the leading producing region for olives. Two of the selected studies were performed in south America countries, one in southern Uruguay characterized by a sub-humid climate (Puppo et al., 2019) while the other was performed in a location in Chile, characterized by a Mediterranean climate (López-Olivari et al., 2016).

The $K_c$ and $K_{cb}$ values observed in the different studies are coherent with the range of densities of the olive orchard (from traditional to super-intensive) and the $f_c$ values. Thus, the smallest $K_{c\ mid}$ was observed by Testi et al. (2004), which may be due to the young age of the trees, low $f_{c,}$ and the traditional olive orchard features, located in Córdoba (Spain). The highest $K_{c\ mid}$ values were those of Paço et al. (2019), which corresponded to a super-intensive orchard located in South Portugal, with the highest $f_c$ value, and managed with a high irrigation frequency. To note that the $K_{c\ end}$ was higher than $K_{c\ mid}$ in the studies by Martínez-Cob and Faci (2010) and Paço et al. (2019) which relates with the high autumn precipitation events, typical of the Mediterranean countries, that coincide with the olive end season.

The highest $K_{cb\ mid}$ among the examined studies was the one indicated in a traditional olive orchard by Cammalleri et al. (2013b), although the value resulted similar to that suggested by Allen et al. (1998); this high $K_{cb\ mid}$ value may be due to the combined effect of the age of the orchard (twenty-five years-old) with large size trees and highly developed canopy.

### *4.3. Temperate climate deciduous fruit trees*

Table 3 presents the list of the studies on deciduous fruit trees that were selected and the reported single and basal crop coefficients as well as the related ancillary data. Only two studies were available for apricot **(***Prunus armeniaca* L.**)**, which used different methods for measuring ET and T: one adopted SWB (Kaya et al., 2013) and the other a SF technique (Villalobos et al., 2013). The study by Kaya et al. (2013) was conducted in Turkey and presented the $K_c$ values for the three development stages of drip irrigated apricot orchards. These values are coherent with the $f_c$ and density of mature apricot orchards. The study by Villalobos et al. (2013) took place in the region of Murcia, Spain, and presented the value of $K_{cb}$ for the mid-season.

One work was selected for cherries **(***Prunus avium* L.**)** (Table 3), performed in a micro-sprinkler irrigated young orchard in Hungary, which used sap flow measurements to estimate cherry $K_{cb}$ (Juhász et al., 2013).

Regarding peach trees **(***Prunus persica* (L.) Batsch**)**, five studies were retained with the experiments conducted in a variety of climates and regions (Table 3). Ayars et al. (2003) and Marsal et al. (2014a) implemented their experiments in California, USA, while du Sautoy et al. (2013) in Pretoria, South Africa, Villalobos et al. (2013) in Cordoba, Spain, and Paço et al. (2012) in Southern Portugal. Several approaches were used to estimate $ET_{c\ act}$ with the studies by Ayars et al. (2003), du Sautoy et al. (2013) and Marsal et al. (2014a) used weighing lysimeters, and Paço et al. (2012) used EC. Villalobos et al. (2013) used sap flow to measure crop T. In the study by Paço et al. (2012) the ET components, crop T and Es, were also measured using SF and micro-lysimeters, respectively. Ayars et al. (2003) reported the highest $K_c$ values in a dense orchard ($f_c = 0.70$) irrigated with micro-sprinklers. Marsal et al. (2014a) presented the highest $K_{cb\ mid}$ values in a mature orchard with tall trees and high $f_c$, whereas the lowest $K_{cb}$ values were indicated by Paço et al. (2012) due to the smallest $f_c$ and the young age of trees.

Only one work was available for plum (*Prunus domestica* L.) (Table 3) which used SWB (Samperio et al., 2014). The study was conducted in Badajoz (Spain) in drip irrigated orchards, and considered two different plum varieties, namely an early-maturing (cv. "Red Beaut") and a late-maturing (cv. "Angeleno"). The reported $K_c$ values are consistent with the crop varieties and their biophysical characteristics.

For the apple crop (*Malus domestica* L.), eight studies were retained which generally derived the single crop coefficient ($K_c$); exceptions were the studies by Marsal et al. (2014a) and Gush et al. (2019) that reported the basal crop coefficient ($K_{cb}$). Weighing lysimeters were used by Girona et al. (2011) and Marsal et al. (2013, 2014a). Gong et al. (2007) combined the use of SWB and SF for estimating $K_c$ and $K_{cb}$ values respectively. Volschenk (2017) used the SWB approach to derive $K_c$ for the three crop development stages. The studies by Gush et al. (2019) and Zanotelli et al. (2019) used the EC method for measuring ET; the latter study also measured trees transpiration with sap flow sensors. Dragoni et al. (2005) measured tree transpiration with sap flow measurements. The most common irrigation system in the apple orchards was drip irrigation, whereas micro-sprinkler irrigation was used in two studies (Volschenk, 2017; Gush et al., 2019) and one used overhead sprinkler irrigation (Zanotelli et al., 2019). The examined studies were carried out in different climates and regions. Four of them were implemented in the Mediterranean countries, while the others in South Africa (Volschenk, 2017; Gush et al., 2019), USA (Dragoni et al., 2005), and China (Gong et al., 2007). The research by Girona et al. (2011) and Marsal et al. (2013, 2014a) were based on the same experimental field in Lleida (Spain), but used different methods to determine the fraction cover. The $K_c$ values indicated in these studies correspond to different experimental years and thus to different $f_c$. The studies included for apple crop reported a wide variability of $K_{c\ mid}$, which could be due to the diverse training systems resulting in diverse $f_c$ and tree height.

Two works were selected for the pear (*Pyrus* L.) tree (Girona et al., 2011; Marsal et al., 2014b). Both studies were developed in Spain and used weighing lysimeters to determine $ET_{c\ act}$. The study by Girona et al. (2011) indicated the relationship between $f_c$ values and the correspondent $K_{c\ mid}$.

There is a need to update nut trees crop coefficients, especially considering the modern cultivars and production systems. There is a lack of studies for hazelnut (*Corylus avellana* L.), pecan (*Carya illinoinensis* L.), pistachio (*Pistacia vera* L.) and walnuts (*Juglans regia* L.), while more studies were conducted for almonds (*Prunus dulcis* (Mill.) D. A. Webb). Five experimental studies (Stevens et al., 2012; Espadafor et al., 2015; García-Tejero et al., 2015; Bellvert et al., 2018; López-López et al., 2018) on $K_c$ and $K_{cb}$ have been included for almond. Field weighing lysimeter containing one almond tree instrumented with sap flow sensors, was the methodology used by López-López et al. (2018). García-Tejero et al. (2015) used drainage lysimeters combined with soil moisture probes. Micrometeorology technique (EC) and SWB modeling were associated to assess the crop coefficients in two studies (Stevens et al., 2012; Bellvert et al., 2018). The modeling approach assumed that the fraction of crop-intercepted radiation ($f_{IPAR}$) is the major determinant of $K_{cb}$. Espadafor et al. (2015) used the sap flow method to measure crop transpiration. The studies were done under drip irrigation, with the exception of the study presented by Stevens et al. (2012) in which the orchard was irrigated with micro-sprinklers. The study by Bellvert et al. (2018) was performed in a mature orchard located in Madera (CA, USA) reporting the highest $K_{cb\ mid}$ and $K_{c\ mid}$ values, which relates with the orchard presenting the highest ground cover ($f_{IPAR} = 0.85$). A slightly smaller $K_{c\ mid}$ value was reported by García-Tejero et al. (2015) in a non-mature orchard located in Sevilla (Spain). Similar $K_{c\ mid}$ values were reported by Stevens et al. (2012) in a mature and high-yielding almond orchard located in Loxton (Australia). But these authors reported an effect of advection due to the surrounding area characterized by different physical properties from those of the studied orchard, which may have increased the $K_c$ value. The experimental $K_{cb}$ indicated by Espadafor et al. (2015) was the lowest for almond orchards, which was related to the young age of the orchard and the lowest $f_c$.

Two studies were retained for hazelnut trees (Mačkić et al., 2016; Ortega-Farias et al., 2020). The study by Mačkić et al. (2016) was conducted in a micro-sprinkler hazelnut orchard in the Pannonia plain, Serbia, and used the SWB to measure ET. Ortega-Farias et al. (2020) used EC to determine the $K_c$ of a drip irrigated hazelnut orchard from the Maule Region, Chile. Higher $K_c$ values were reported by Mačkić et al. (2016), probably due to the higher planting density and the irrigation method employed.

Three works studied the ET of pecans (*Carya illinoinensis* L.) using micrometeorological techniques (Simmons et al., 2007; Samani et al.,

**Table 3**
Published $K_c$ and $K_{cb}$ for the mid and end-season relative to temperate climate deciduous trees.

| Crop and author | Age (years) | Density (plants/ha) | Training system | Height (m) | $f_c$[a] | $K_{c\ mid}$ | $K_{c\ end}$ | $K_{cb\ mid}$ | $K_{cb\ end}$ |
|---|---|---|---|---|---|---|---|---|---|
| **Stone fruit trees** | | | | | | | | | |
| **Apricot (*Prunus armeniaca* L.)** | | | | | | | | | |
| Kaya et al. (2013) | 4–8 | 156 | Vase | – | 0.80 | 0.95 | 0.56 | – | – |
| Villalobos et al. (2013) | 10 | 156 | – | 3.90 | 0.52 | – | – | 0.80 | – |
| **Cherry (*Prunus avium* L.)** | | | | | | | | | |
| Juhász et al. (2013) | 4–7 | 1250 | Central leader | 4.00–5.00 | – | – | – | 0.85 | – |
| **Peach (*Prunus persica* L. Batsch)** | | | | | | | | | |
| Ayars et al. (2003) | 3–7 | 1134 | Vase | 3.00–4.50 | 0.70 | 1.10 | 0.75 | – | – |
| du Sautoy et al. (2013) | Young | 2222 | Central leader | 1.80 | – | 0.90 | 0.50 | 0.60 | 0.20 |
| | | | | 2.50 | | 0.95 | 0.50 | 0.70 | 0.16 |
| Paço et al. (2012) | 2–3 | 1000 | Central leader | 3.00 | 0.29 | – | – | 0.44 | – |
| Villalobos et al. (2013) | 15 | 615 | Vase | – | 0.54 | – | – | 1.00 | – |
| Marsal et al. (2014a) | Mature | 1134 | Perpendicular V system | 4.10–5.00 | 0.75 | – | – | 1.05 | – |
| | | | | | 0.80 | | | 1.10 | |
| **Plum (*Prunus domestica* L.)** | | | | | | | | | |
| Samperio et al. (2014) | 4–9 | 417 | Vase | 2.50–4.60 | $0.65^{+}$ | 0.95 | 0.60 | – | – |
| | | | | | $0.90^{++}$ | 1.10–1.20 | 0.75–0.90 | | |
| **Pome fruit trees** | | | | | | | | | |
| **Apple (*Malus domestica* Borkh)** | | | | | | | | | |
| Dragoni et al. (2005) | 8 | 1280 | Conical, with central leader | 2.5 –3.0 | – | – | – | 0.80 | – |
| Gong et al. (2007) | 8 | 1042 | – | 2.0–2.7 | – | 1.10 | 0.50 | – | – |
| Girona et al. (2011) | 4–6 | 1563 | Modified central leader | 3.00–3.60 | 0.29 | 0.48 | – | – | – |
| | | | | | 0.34 | 0.65 | | | |
| | | | | | 0.40 | 0.77 | | | |
| | | | | | 0.41 | 0.93 | | | |
| | | | | | 0.46 | 1.04 | | | |
| Marsal et al. (2013) | 4-10 | 1563 | Modified central leader | 3.00 | 0.35 | 0.55 | – | – | – |
| | | | | 3.30 | 0.39 | 0.60 | – | – | – |
| | | | | 3.65 | 0.45 | 0.70 | – | – | – |
| | | | | 3.61 | 0.50 | 0.95 | – | – | – |
| | | | | 3.61 | 0.60 | 1.05 | – | – | – |
| | | | | 3.00 | 0.63 | 0.80 | – | – | – |
| | | | | 4.40 | 0.66 | 0.85 | – | – | – |
| | | | | 4.10 | 0.63 | 1.00 | – | – | – |
| Marsal et al. (2014a) | Mature | 1563 | Modified central leader | 3.00–4.10 | 0.70 | – | – | 1.00 | – |
| | | | | | 0.65 | | | 1.00 | |
| Volschenk (2017) | 13 | 1481 | Central leader | >3.50 | – | 0.80 | 0.40 | – | – |
| Gush et al. (2019) | 12 | 2000 | – | 5.10 | – | 0.76 | 0.17 | 0.60 | 0.10 |
| Zanotelli et al. (2019) | 13–15 | 3333 | Spindle bush | 3.50–4.00 | 0.70 | 1.01 | 0.84 | – | – |
| **Pear (*Pyrus* L.)** | | | | | | | | | |
| Girona et al. (2011) | 4–6 | 1563 | Modified central leader | 2.00-3.00 | 0.28 | 0.87 | – | – | – |
| | | | | | 0.27 | 1.05 | – | – | – |
| | | | | | 0.35 | 1.00 | – | – | – |
| | | | | | 0.38 | 1.00 | – | – | – |
| Marsal et al. (2014b) | Mature | 1563 | Modified central leader | 3.30–3.60 | 0.60 | – | – | 0.85 | – |
| | | | | | 0.65 | | | 0.90 | |
| **Nut trees** | | | | | | | | | |
| **Almond (*Prunus dulcis* Mill.)** | | | | | | | | | |
| Stevens et al. (2012)[b] | 8–9 | 286 | Central leader | 5.50 | 0.65 | 1.12 | – | – | – |
| Espadafor et al. (2015) | 3 | 238 | Vase | 4.80 | 0.35 | – | – | 0.45 | 0.40 |
| | 4 | | | | 0.50 | – | – | 0.60 | 0.40 |
| García-Tejero et al. (2015) | 4 | 238 | – | – | – | 1.15 | 0.45 | – | – |
| Bellvert et al. (2018) | 18 | 249 | Vase | – | 0.85 | 1.20 | 0.75 | 0.95 | 0.60 |
| López-López et al. (2018) | 5–7 | 238 | Vase | 4.80 | 0.55 | – | – | 0.75 | 0.50 |
| | | | | | 0.59 | – | – | 0.90 | 0.65 |
| | | | | | 0.55 | – | – | 1.00 | 0.65 |
| **Hazelnut (*Corylus avellana* L.)** | | | | | | | | | |
| Mačkić et al. (2016) | Young | 833 | Vase | 1.70 | – | 0.93 | 0.80 | – | – |
| Ortega-Farias et al. (2020) | 17–18 | 333 | – | 4.70 | – | 0.80 | | | |

(*continued on next page*)

2011; Taylor et al., 2017b). The studies of Simmons et al. (2007) and Samani et al. (2011) were carried out in New México (USA), both under flood irrigation. The study by Taylor et al. (2017b) was performed in an orchard located in Cullinan (South Africa) which was irrigated with micro-sprinklers. The work by Samani et al. (2011) allowed to assess a strong relation between $K_c$ and $f_c$.

The studies performed in pistachio (*Pistacia vera* L.) orchards measured ET using SWB associated with plant-based measurements (Memmi et al., 2016) and micrometeorological measurements (Bellvert

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

| Crop and author | Age (years) | Density (plants/ha) | Training system | Height (m) | $f_c$[a] | $K_{c\ mid}$ | $K_{c\ end}$ | $K_{cb\ mid}$ | $K_{cb\ end}$ |
|---|---|---|---|---|---|---|---|---|---|
| **Pecans (*Carya illinoinensis* L.)** | | | | | | | | | |
| Simmons et al. (2007) | 34–35 | 106 | – | 12.80 | | 1.08 | 0.60 | – | – |
| Samani et al. (2011) | Mature | – | Vase | – | 0.40 | 0.78 | 0.50 | – | – |
| | | | | | 0.60 | 0.85 | 0.63 | – | – |
| | | | | | 0.73 | 0.95 | 0.70 | – | – |
| | | | | | 0.80 | 1.14 | 0.39 | – | – |
| Taylor et al. (2017b) | 37 | 123 | – | 13.0 | – | 1.00 | 0.60 | – | – |
| **Pistachio (*Pistacia vera* L.)** | | | | | | | | | |
| Memmi et al. (2016) | 12–14 | 238 | Vase | – | – | 0.93 | – | – | – |
| Bellvert et al. (2018) | 14 | 332 | Vase | – | 0.65 | 1.00 | 0.50 | 0.90 | 0.45 |
| **Walnut (*Juglans regia* L.)** | | | | | | | | | |
| Villalobos et al. (2013) | 7 | 156 | – | 6–7 | 0.66 | – | – | 1.05 | – |
| Brickner (2016) | Mature | 125 | – | – | – | 1.07 | – | – | – |
| Fulton et al. (2017) | Young | 233 | Vase | – | 0.75–0.88 | 1.00 | 0.37 | – | – |
| | Mature | 445 | | – | 0.88–0.91 | 1.03 | 0.58 | – | – |
| **Other fruit trees**<br>**Fig tree (*Ficus carica* L.)** | | | | | | | | | |
| Andrade et al. (2014) | 3 | 1667 | Vase | – | – | 0.60 | – | – | – |
| Souza et al. (2014) | V-young | 1660 | Vase | – | – | 0.49 | – | | – |
| **Persimmon (*Diospyros kaki*)** | | | | | | | | | |
| Kanety et al. (2014) | 9–11 | 417 | – | – | – | 0.95 | – | 0.56 | – |
| **Pomegranate (*Punica granatum* L.)** | | | | | | | | | |
| Intrigliolo et al. (2011) | 9 | 500 | Vase | – | 0.56 | 0.71 | 0.64 | – | – |
| Ayars et al. (2017) | 6 | 567 | Free, multiple branches | 3.00 | – | 1.00 | 0.40 | – | – |
| Zhang et al. (2017) | 3 | 567 | Bush-like | 3.00 | 0.25 | 0.44 | – | – | – |
| | 4 | 567 | – | – | 0.39 | 0.56 | – | – | – |
| | 5 | 567 | – | – | 0.71 | 0.83 | – | – | – |
| | 3 | 727 | Vase | 3.00 | 0.17 | 0.36 | – | – | – |
| | 4 | 727 | – | – | 0.41 | 0.48 | – | – | – |
| | 5 | 727 | – | – | 0.38 | 0.46 | – | – | – |

[a] Includes the ground cover fraction ($f_c$), the fraction of intercepted PAR ($f_{IPAR}$), and the ground shaded fraction ($f_{shad}$); [b] Corrected for advection effects by the authors; + 'Red Beaut'(early-maturing); ++ 'Angeleno' (late-maturing).

et al., 2018). The study by Bellvert et al. (2018) used in addition a modeling approach with vegetation indices (NDVI) to determine $K_{cb}$. The orchards were drip irrigated (Bellvert et al., 2018; Memmi et al., 2016). The study of Bellvert et al. (2018) was based in California (USA), while the other was developed in Ciudad Real (Spain) (Memmi et al., 2016). $K_{c\ mid}$ values in the two examined studies, presented comparable ranges, in relation to the orchard age and density.

Regarding walnuts, the studies by Villalobos et al. (2013), Brickner (2016) and Fulton et al. (2017) are proposed for updating the crop coefficients. The study by Villalobos et al. (2013) recurs to a sap flow technique (compensation heat pulse) to measure tree transpiration, along the mid-season, thus allowing to estimate the $K_{cb\ mid}$ value. In the study by Fulton et al. (2017), multiple years of data were collected that allowed to capture the temporal dynamic of $K_c$ and have encompassed a wide range of soils, cultivation practices, and stages of canopy development. EC and SR techniques were used to study a temporal series from 2011 to 2016 of ET from two mature and one young walnut orchards. Orchards were irrigated with micro-sprinklers and set in Sacramento Valley (CA, USA). The mature orchards presented similar $K_{c\ mid}$ values in both studies.

The water requirements of fig trees (*Ficus Carica* L.) were studied in Brazil by Andrade et al. (2014) and Souza et al. (2014) using the SWB approach in drip irrigated orchards. The experiment presented by Andrade et al. (2014) consisted of two irrigation treatments with different watering frequencies scheduled to avoid water stress. The $K_{c\ mid}$ resulted higher for the high irrigation frequency.

Kanety et al. (2014) reported the only work available for persimmon (*Diospyros kaki* L.). The study was performed in drip irrigated orchards located in Israel. The study employed sap flow measurements to measure crop transpiration and thus to estimate $K_{cb;}$ the $K_c$ value was derived from modeled $K_e$.

Three works focused on the evaluation of pomegranate (*Punica granatum* L.) water requirements (Intrigliolo et al., 2011; Ayars et al., 2017; Zhang et al., 2017). The study by Intrigliolo et al. (2011) used a combined methodology of leaf water potential and leaf gas exchange to estimate crop ET, while the other two studies used weighing lysimeters to determine crop ET. The studies were performed in drip irrigated orchards located in Alicante (Spain) (Intrigliolo et al., 2011) and in California (USA) (Ayars et al., 2017; Zhang et al., 2017). The article by Zhang et al. (2017) refers to a three years study in two orchards. The studies on pomegranate reported $K_c$ values that were strongly related with $f_c$.

### 4.4. *Tropical and subtropical fruit crops*

A small number of papers reporting $K_c/K_{cb}$ values for tropical fruit trees were found in the literature (see Table 4). Two studies were considered on avocado (*Persea Americana* Mill.), the first developed in Florida (Kiggundu et al., 2012) and the second in South Africa (Mazhawu et al., 2018). Two different approaches were used to measure crop ET: one study used the SWB (Kiggundu et al., 2012) while the other used EC (Mazhawu et al., 2018). In both studies, the orchards were irrigated with micro-sprinkler system. $K_{c\ mid}$ values are very distinct, which may relate with the age of the orchard, plant density, and tree height.

All the studies on banana (*Musa*) were carried out in Brazil. The methodology used to determine $ET_c$ was the soil water balance for all studies, which was associated with drainage lysimeters in the study by Conceição et al. (2018). Drip irrigation was used in three studies (Figueiredo et al., 2006; Montenegro et al., 2008; Conceição et al., 2018) and micro-sprinkler irrigation in two (Bassoi et al., 2004; Montenegro et al., 2008). All the studies reported very similar $K_{c\ mid}$ values.

**Table 4**
Published $K_c$ and $K_{cb}$ for the mid and end-season relative tropical and sub-tropical fruit crops.

| Crop and author | Age (years) | Density (plants/ha) | Training system | Height (m) | $f_c$[a] | $K_{c\ mid}$ | $K_{c\ end}$ | $K_{cb\ mid}$ | $K_{cb\ end}$ |
|---|---|---|---|---|---|---|---|---|---|
| **Avocado (*Persea americana* Mill.)** | | | | | | | | | |
| Kiggundu et al. (2012) | 2–3 | 370 | – | 2.00 | – | 0.75 | 0.50 | – | – |
| Mazhawu et al. (2018) | 4 | 357 | – | 3.80 | 0.50 | 1.10 | 0.80 | – | – |
| **Banana (*Musa* spp.)** | | | | | | | | | |
| Bassoi et al. (2004) | 1–3 | 1111 | – | – | – | 1.05 | – | – | – |
| Figueiredo et al. (2006) | – | – | – | – | 0.90 | 1.00 | – | – | – |
| Montenegro et al. (2008) | 1–2 | – | – | – | – | 1.05 | – | – | – |
| Albuquerque et al. (2013) | 2–3 | 1111 | – | – | – | 1.03 | – | – | – |
| Conceição et al. (2018) | 2–3 | – | – | – | – | 1.00 | – | | |
| **Cactus Pear (*Opuntia ficus-indica* L.)** | | | | | | | | | |
| Consoli et al. (2013) | 10 | 333 | Globe | 3.00 | 0.65 | 0.50 | 0.27 | – | – |
| **Cherimoya (*Annona cherimolia* Mill.)** | | | | | | | | | |
| Rodríguez Pleguezuelo et al. (2011) | 15 | 280 | Vase | – | – | 0.65 | 0.30 | – | – |
| Durán-Zuazo et al. (2019b) | 20 | 280 | Vase | – | – | 0.65 | 0.25 | – | – |
| **Coconut (*Cocus nucifera* L.)** | | | | | | | | | |
| Miranda et al. (2007) | 2–4 | 178 | – | – | 0.80 | 1.00 | – | – | – |
| Sousa et al. (2011) | 2–3 | – | – | – | – | 1.00 | – | – | – |
| **Coffee (*Coffea* sp. L.)** | | | | | | | | | |
| Marin et al. (2005) | 5 | 4000 | Hedgerow | 2.50 | – | 1.00 | – | 0.78 | – |
| Costa et al. (2019) | Young | – | – | – | – | 0.79 | 0.31 | – | – |
| | Mature | – | – | | | 1.12 | 0.68 | | |
| **Datepalm (*Phoenix dactylifera* L.)** | | | | | | | | | |
| Sperling et al. (2014) | 12 | 123 | – | 10.00 | – | 0.65 | 0.60 | – | – |
| Montazar et al. (2020) | 20 | 121 | – | 9.20 | 0.71 | 0.84 | 0.65 | – | – |
| **Guava (*Psidium guajava* L.)** | | | | | | | | | |
| Teixeira et al. (2003) | 2 | 303 | – | – | – | 0.87 | – | – | – |
| Singh et al. (2007a) | – | 400 | – | – | – | 0.72[b] | 0.55 | – | – |
| **Jujube (*Zizyphus jujuba* Mill.)** | | | | | | | | | |
| Hu et al. (2012) | 7–8 | 1667 | – | – | – | 0.90 | – | – | – |
| Sun et al. (2012) | 5 | 1111 | – | – | 0.60–0.65 | 0.82 | – | 0.55 | |
| **Mango (*Mangifera indica* L.)** | | | | | | | | | |
| Azevedo et al. (2003) | 7 | 250 | – | 5.20 | 0.85 | 0.72 | 0.20 | – | – |
| Teixeira et al. (2008) | 18 | 100 | – | 5.50 | – | 0.95 | – | – | – |
| Rodríguez Pleguezuelo et al. (2011) | 15 | 600 | – | 2.90 | – | 0.82 | 0.25 | – | – |
| Levin et al. (2018) | Mature | 156 | – | – | – | 0.76 | – | – | – |
| Durán-Zuazo et al. (2019a) | 15 | 600–630 | – | 2.90 | – | 0.70 | 0.15 | – | – |
| **Papaya (*Carica papaya* L.)** | | | | | | | | | |
| Chaterlán et al. (2012a) | Mature | 1851 | – | 3.00 | – | 1.10 | 0.90 | – | – |
| Chaterlán et al. (2012b) | Mature | 1851 | – | 3.00 | 0.82 | – | – | 1.00 | 0.60 |

[a] Includes the ground cover fraction ($f_c$), the fraction of intercepted PAR ($f_{IPAR}$), and the ground shaded fraction ($f_{shad}$). [b] With plastic mulch.

Only a study was available for cactus pear (*Opuntia ficus-indica* (L.) Mill.) (Consoli et al., 2013) which was performed in an orchard in Sicily, Italy. Crop $ET_{c\ act}$ was measured using the SR method.

Rodríguez Pleguezuelo et al. (2011) and Durán-Zuazo et al. (2019b) studied cherimoya (*Annona cherimola* Mill.) water requirements in the same experimental farm (Granada, Spain) and with the same methodology. Both studies used the SWB approach combining drainage lysimeters with soil moisture measurements. The trees were mature, planted in terraces and irrigated with a drip system. The estimated $K_c$ confirmed that for cherimoya trees the values are well replicated under similar field conditions and biophysical characteristics.

The two studies on coconut (*Cocus nucifera* L.) were carried out in Brazil using SWB (Miranda et al., 2007) and weighing lysimeters (Sousa et al., 2011). Both studies reported the same $K_c$ values, even if referred to different irrigation method, micro-sprinkler and drip irrigation respectively in Miranda et al. (2007) and Sousa et al. (2011).

The studies on coffee (*Coffea* spp.) were carried out in Brazil. The BREB and SF methods were used by Marin et al. (2005) to calculate $ET_c$, while the remote sensing Surface Energy Balance Algorithm for Land (SEBAL) was employed by Costa et al. (2019). Drip (Marin et al., 2005) and central pivot irrigation (Costa et al., 2019) were used. Differences in the reported $K_c$ values were coherent with the crop age, planting density and irrigation system used. Only $K_{cb\ mid}$ values were reported in Marin et al. (2005), which evidenced two behaviors depending on $ET_o$ rates with lower $K_{cb}$ values associated with high $ET_o$ rates (> 4 mm $d^{-1}$), while higher $K_{cb}$ values were obtained when $ET_o$ is low (<2 mm $d^{-1}$). These results may be attributed to differences in the stomatal adjustment of the coffee plant.

The studies on date palm (*Phoenix dactylifera* L.) were conducted in Israel (Sperling et al., 2014) and California, USA (Montazar et al., 2020). Sperling et al. (2014) used weighing lysimeters to calculate the $K_c$ of drip irrigated date palms with water of different salinity levels; however, only the $K_c$ value corresponding to the treatment without salinity stress was selected. Montazar et al. (2020) used a combination of SR and EC techniques to measure $ET_c$ in commercial mature date palms. The orchard was irrigated by drip system and occasionally with surface irrigation.

There are two studies (Teixeira et al., 2003; Singh et al., 2007a) focused on measuring $ET_{c\ act}$ and deriving $K_c$ values for guava (*Psidium guajava* L.). The study of Teixeira et al. (2003) was carried out in Petrolina, Brazil, in a micro-sprinkler irrigated guava orchard where crop ET was measured using the BREB method. Singh et al. (2007a) conducted their study in West Bengal, India, in guava orchards under drip irrigation and plastic mulch conditions. The $K_c$ values were based on unpublished reports and local studies conducted in India. Singh et al. (2007a) reported lower $K_c$ than Teixeira et al. (2003), which may be due to the reduction of soil evaporation derived from the plastic mulch.

Two studies determined the jujube (*Ziziphus jujuba* Mill.) water requirements. Hu et al. (2012) determined the $K_c$ of jujube using SWB in a drip irrigated orchard located in the Loess Plateau of China. Sun et al. (2012) study was performed in North China Plain in a furrow irrigated jujube mature orchard where crop ET was obtained from the sum of the SF and micro-lysimeters measurements. The different $K_c$ values between studies are coherent with the crop age and planting density.

The studies performed for mango (*Mangifera indica* L.) used diverse methods to estimate crop ET. Teixeira et al. (2008) used BREB; Azevedo et al. (2003) and Levin et al. (2018) used SWB while Rodríguez Pleguezuelo et al. (2011) and Durán-Zuazo et al. (2019a) used drainage lysimeters. Localized irrigation methods were used in all studies. Two studies were developed in Petrolina, Brazil (Azevedo et al., 2003; Teixeira et al., 2008), two in Granada, Spain (Rodríguez Pleguezuelo et al., 2011; Durán-Zuazo et al., 2019a) and one in Israel (Levin et al., 2018). The highest $K_{c\ mid}$ value of the set of studies was reported by Teixeira et al. (2008) in a low-density orchard with the tallest, more vigorous trees.

The studies on papaya (*Carica papaya* L.) ET reported in the literature were performed along one season in La Habana, Cuba and used the SWB approach in an orchard irrigated with drip irrigation (Chaterlán et al., 2012a,b). The same experimental data were used in both studies to calibrate and validate SWB models allowing to derive the papaya crop coefficients. One model adopts the single crop coefficient approach (WinISAREG) and the other uses the dual crop coefficient approach (SIMDualK$_c$), thus allowing to determine both $K_c$ and $K_{cb}$ values.

## 5. Indicative standard $K_c$ and $K_{cb}$ values

Ranges of values for experimental data of standard crop coefficients ($K_c$ and $K_{cb}$) based on the literature, reported in the previous section, are presented in Tables 5 to 8 for vine fruit crops, berries and hops; temperate climate evergreen fruit trees; temperate climate deciduous fruit tree crops and, tropical and subtropical fruit crops, respectively. These Tables also present previously published $K_c$ and $K_{cb}$ information for the same crops from FAO56 (Allen et al., 1998), computed from the fraction of ground cover and height, with the approach proposed by Allen and Pereira (2009), as well as the more recent update provided by Jensen and Allen (2016). Indicative updated values of the crop coefficients ($K_{c\ mid}$, $K_{c\ end}$, $K_{cb\ mid}$ and $K_{cb\ end}$) were obtained from the observed values and those proposed in the referred studies, and are tabulated in the same Tables 5 to 8.

Following the simplified procedure used in FAO56 (Allen et al., 1998), the computation of the indicative updated values of $K_{c\ mid}$ for all trees and vines resulted from adding 0.05 to $K_{cb\ mid}$. This approach is due to the fact that for all orchards it was considered that drip irrigation systems are generally used, thus with a small fraction of soil wetted by irrigation and, mostly, under the shadow of the canopies; then, only a limited amount of energy reaches the soil surface, thus limiting soil water evaporation. A diverse approach was used for $K_{c\ end}$ values because the added value to $K_{cb\ end}$ varied in the range 0.05–0.40, according to the $f_c$ value and the probability of occurrence of precipitation events by the end season. When $K_{cb\ mid}$ and/or $K_{cb\ end}$ were not available they were computed from $K_{c\ mid}$ and/or $K_{c\ end}$ by subtracting the same amounts. Further explanation is provided for each type of orchard.

Due to the wide range of variability of observed $K_c$ and $K_{cb}$ values, the indicative standard values were considered within a range of ±10%. When information was available, $K_c$ and $K_{cb}$ values refer to the crop density estimated from the fraction of ground cover ($f_c$), including young crops. In the cases where $f_c$ was not available in the cited papers, an $f_c$ indicative value for commercial orchards was retrieved from literature and the respective references are provided as Table footnotes. A similar procedure was followed for tree height and references used to find an indicative value are also listed in the Tables footnotes. For vine fruit crops and hops, the management and training system was considered, instead of density, given the larger variability in the crop geometry and the information available.

$K_c$ and $K_{cb}$ for vine fruit crops in Table 5 include table grapes, wine grapes, kiwi, highbush blueberries and hop. For table grapes, five different management and training classes were considered: young, overhead trellis, horizontal trellis, T trellis, and Y shape gable & Y trellis. The collected $K_{c\ mid}$ and $K_{c\ end}$ information for young plantations indicated higher values than those previously reported but the standard values do not reflect that increase since the information available was not enough to support an alteration. For overhead trellis system, reported data for $K_c$ confirmed previous tabulated data and were therefore kept within those ranges. $K_{cb\ mid}$ reported data were lower than previously tabulated data and the indicative standard value chosen is below the range higher limit. Data on previous standard values was inexistent for the horizontal trellis and Y gable system & Y trellis systems, therefore new indicative values were set based on reported data and bearing in mind the new indicative values for other training classes, maintaining a 5%–10% difference. The T trellis system had only a reported value for $K_{c\ mid}$ and this was used to adjust a lower standard value, and the remnant coefficients for this class were set accordingly.

Table grape crops tend to have higher density and vigor than wine grape crops, which reflects on higher standard $K_c$ and $K_{cb}$ values for table grapes. For wine grapes trained with vertical shoot positioned trellis (VSP) systems, the reported data confirmed the previously tabulated values, with a slight increase in $K_{cb\ end}$, hence indicative values were set accordingly. Scarce information was found for the pergola system and only for $K_{cb\ mid}$ and $K_{cb\ end}$ indicating lower values than the ones previously tabulated. This was accounted for in the new indicative values. For *Guyot*, there was no previous information, and only a reported value in literature, thus indicative values were set according to those of the other systems and crop geometry. As previously pointed out, the indicative standard values of $K_{c\ mid}$ and $K_{cb\ mid}$ for both wine and grape wine (Table 5) differ by 0.05 while $K_{c\ end}$ and $K_{cb\ end}$ differed by 0.10 when $f_c<0.30$, otherwise by 0.05.

Information from literature was available for kiwi relative to $K_{cb\ mid}$, while $K_{c\ mid}$ and $K_{cb\ mid}$ values were available in Allen et al. (1998), allowing to set indicative standard values for the mid-season. Standard values for the end-season were based on common values found for vines and on the crop characteristics. For example, $K_{c\ end}$ for kiwi (pergola system) is close to $K_{c\ mid}$ considering that harvesting occurs during the rainy season, hence the soil surface is often wetted by rainfall, thus allowing to maintain a high $K_c$ value. Regarding $K_{cb\ end}$, there is a slight difference relative to $K_{cb\ mid}$ since leaves are starting to senesce. Table 5 presents $K_c$ data for berries and hop based on the collected data and on the information from Allen et al. (1998) and Jensen and Allen (2016). Standard $K_{c\ mid}$ for berries was set at 0.95 (high density), resulting from the experimental values. $K_{c\ end}$, $K_{cb\ mid}$ and $K_{cb\ end}$ were retrieved from previous tabulated information since no newly reported data existed. For other densities, no previous information was available, and crop coefficients were set based on density differences.

Collected values of $K_{c\ mid}$ and $K_{c\ end}$ for hop were identical to those found in Allen et al. (1998); therefore, these values were kept. Collected value of $K_{cb\ mid}$ for hop was slightly lower than those found in Allen and Pereira (2009) and Jensen and Allen (2016); therefore, indicative value was also slightly decreased. The value for $K_{cb\ end}$ was similar to previous tabulated value and therefore was kept.

**Table 5**

Updated indicative standard values for single and basal crop coefficients relative to the mid- and end-season for vine fruit crops, berries and hops, including reviewed literature and previous tabulated values.

| Crop | Plant density and training system | $f_c$[a] | Plant height[a] | Literature reported $K_c$ and $K_{cb}$ | | | | Previous tabulated standard $K_c$ and $K_{cb}$ | | | | Indicative standard values (±10%) of $K_c$ and $K_{cb}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ |
| Table grapes | Young | 0.20–0.35 | 1.0–1.8 | 0.91 | – | 0.80 | – | 0.60[c] | 0.55[c] | 0.50[c] | 0.45[c] | 0.60 | 0.55 | 0.55 | 0.45 |
| | Overhead trellis | 0.90–0.95 | 2.0 | 1.05 | 0.65 | 0.70–0.80 | – | 0.85[d]–1.10[c] | 0.80[d]–1.05[c] | 0.45[d]–0.90[c] | 0.40[d]–0.80[c] | 0.95 | 0.90 | 0.70 | 0.65 |
| | Horizontal trellis | 0.60–0.70 | 1.7–1.8 | 1.00 | 0.77 | 0.80 | 0.62 | – | – | – | – | 0.90 | 0.85 | 0.80 | 0.70 |
| | T trellis | 0.40–0.50 | 2.0 | 0.84 | – | – | – | 0.95[c] | 0.90[c] | 0.75[c] | 0.70[c] | 0.80 | 0.75 | 0.60 | 0.55 |
| | Y shape* | 0.60–0.90 | 2.2 | 0.55–0.80 | 0.65 | – | – | – | – | – | – | 0.70 | 0.65 | 0.55 | 0.50 |
| Wine grapes | Young | 0.15–0.30 | 1.0–1.5 | – | – | – | – | 0.45[c] | 0.40[c] | 0.40[c] | 0.30[c] | 0.45 | 0.40 | 0.40 | 0.30 |
| | Pergola | 0.50–0.60 | 2.0 | – | 0.60 | – | 0.46 | 0.75[c] | 0.70[c] | 0.60[c] | 0.55[c] | 0.65 | 0.60 | 0.50 | 0.45 |
| | VSP+ | 0.25–0.45 | 1.5–2.0 | 0.56–0.80 | 0.46–0.80 | – | 0.20–0.60 | 0.70[d] | 0.65[d] | 0.45[d] | 0.40[d] | 0.70 | 0.65 | 0.45 | 0.40 |
| | Guyot | 0.15–0.50 | 1.5–2.0 | 0.50 | | – | | – | – | – | | 0.50 | 0.45 | 0.40 | 0.35 |
| Kiwi | Pergola | 0.80-0.90[b] | 2.0[b] | – | 0.70 | – | – | 1.05[d] | 1.00[d] | 1.05[d] | 1.00[d] | 0.95 | 0.90 | 0.90 | 0.80 |
| Highbush blueberries | Young | 0.20–0.30 | <1.0 | – | – | – | – | – | – | – | – | 0.40 | 0.35 | 0.30 | 0.20 |
| | Low | 0.30–0.50 | 1.5–1.8 | 0.49–0.52 | – | – | – | – | – | – | – | 0.50 | 0.45 | 0.35 | 0.25 |
| | Medium | 0.50–0.70 | 1.5–1.8 | 0.84 | – | – | – | – | – | – | – | 0.80 | 0.75 | 0.35 | 0.30 |
| | High | >0.70 | 1.8–2.0 | 1.00 | – | – | – | 1.05[d] | 1.00[d] | 0.50[d] | 0.40[d] | 0.95 | 0.90 | 0.40 | 0.35 |
| Hop | V trellis | 0.10–0.20 | 5.0–6.0 | 1.02 | 0.97 | 0.85 | 0.83 | 1.05[d] | 1.00[d] | 0.85[d] | 0.80[d] | 1.00 | 0.95 | 0.85 | 0.80 |

*- includes Y shape gable & Y trellis training systems. +VSP - Vertical shoot positioned trellis. [a]Observed $f_c$ and plant height values from Table 1. [b]Indicative values from McAneney et al. (1984) and Xue et al. (2019). [c]Ranges of values from Allen and Pereira (2009) and Jensen and Allen (2016). [d]Values for common crop system management from Allen et al. (1998).

**Table 6**

Updated indicative standard values for single and basal crop coefficients relative to the mid- and end-season, under temperate climate, for evergreen fruit tree crops including reviewed literature and previous tabulated values.

| Crop | Plant density | $f_c$[a] | Plant height[a] (m) | Ranges of literature reported $K_c$ and $K_{cb}$ | | | | Previous tabulated standard $K_c$ and $K_{cb}$ | | | | Indicative standard values (±10%) of $K_c$ and $K_{cb}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ |
| Citrus | Young | <0.25 | 1.0–1.5 | – | – | – | – | 0.50[b] | 0.45[b] | 0.50[b] | 0.45[b] | 0.40 | 0.35 | 0.60 | 0.35 |
| | Low density | 0.25–0.40 | 2.3–4.5 | 0.55 | 0.40–0.56 | – | 0.40–0.61 | 0.45[c]–0.50[b] | 0.40[c]–0.45[b] | 0.55[c]–0.50[b] | 0.45[c]–0.50[b] | 0.55 | 0.50 | 0.65 | 0.50 |
| | Medium density, short | 0.40–0.65 | <3.5 | 0.51–0.55 | – | | – | 0.60[c]–0.75[b] | 0.55[c]–0.70[b] | 0.65[c]–0.75[b] | 0.50[c]–0.70[b] | 0.60 | 0.55 | 0.70 | 0.55 |
| | Medium density, tall | 0.40–0.65 | >3.5 | 0.71 | – | – | – | – | – | – | – | 0.65 | 0.60 | 0.75 | 0.60 |
| | High density, short | >0.65 | 2.5–3.5 | 0.60–0.78 | 0.55–0.80 | 0.50–0.80 | 0.35–0.63 | – | 0.60–0.85 | – | 0.65–0.85 | 0.70 | 0.65 | 0.80 | 0.65 |
| | High density, tall | >0.65 | 4.0–4.5 | 1.00 | – | – | – | 0.65[c]–0.90[b] | 0.60[c]–0.85[b] | 0.70[c]–0.90[b] | 0.65[c]–0.85[b] | 0.90 | 0.85 | 0.95 | 0.85 |
| Olive | Young | 0.15–0.30 | 1.5–2.0 | – | – | – | – | 0.25[b] | 0.20[b] | 0.25[b] | 0.20[b] | 0.25 | 0.20 | 0.60 | 0.15 |
| | Traditional, low density | 0.15–0.20 | 2.5–3.0 | 0.35 | – | – | – | – | | | | 0.30 | 0.25 | 0.60 | 0.20 |
| | Traditional, medium density | 0.20–0.30 | 3.0–3.5 | 0.65 | 0.59 | – | – | 0.40[b] | 0.35[b] | 0.35[b] | 0.30[b] | 0.45 | 0.40 | 0.65 | 0.30 |
| | Intensive (hedge prune) | 0.30–0.40 | 2.5–3.5 | 0.48 | 0.25–0.40 | 0.97 | 0.15–0.22 | 0.60[b]–0.70[c] | 0.55[b]–0.65[c] | 0.55[b]–0.70[c] | 0.50[b]–0.65[c] | 0.45 | 0.40 | 0.70 | 0.35 |
| | Super-Intensive, medium density | 0.25–0.35 | 3.0–3.5 | 0.56 | 0.35 | 0.45 | 0.25 | – | – | – | – | 0.40 | 0.35 | 0.70 | 0.30 |
| | Super-intensive high density* | 0.35–0.45 | 3.0–4.0 | 0.71 | 0.48 | 0.84 | 0.43 | – | – | – | – | 0.50 | 0.45 | 0.75 | 0.40 |

*- typically hedgerow orchards. [a]Observed $f_c$ and tree height values from Table 2. [b]Ranges of values from Allen and Pereira (2009) and Jensen and Allen (2016). [c]Values for common crop system management from Allen et al. (1998).

**Table 7**
Updated indicative standard values for single and basal crop coefficients relative to the mid- and end-season, under temperate climate, for deciduous fruit tree crops including reviewed literature and previous tabulated values.

| Crop | Density | $f_c$[a,b,c,d,e,f] | Plant height[a,b,c,d,e,f] (m) | Literature reported $K_c$ and $K_{cb}$ | | | | Previous tabulated standard $K_c$ and $K_{cb}$ | | | | Indicative standard values (±10%) of $K_c$ and $K_{cb}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ |
| **Stone fruit trees** | | | | | | | | | | | | | | | |
| Apricot[a], Cherry[b] & Plum[a] | Young | 0.15–0.30 | 1.5–2.0 | – | – | – | – | 0.60[h]–0.70[h] | 0.55[h]–0.65[h] | 0.45[h]–0.55[h] | 0.40[h]–0.50[h] | 0.55 | 0.50 | 0.40 | 0.30 |
| | Low | 0.30–0.40 | 2.0–3.0 | – | – | – | – | 0.60[h]–0.70[h] | 0.55[h]–0.65[h] | 0.45[h]–0.55[h] | 0.40–0.50 | 0.60 | 0.55 | 0.45 | 0.35 |
| | Medium | 0.40–0.50 | 2.5–3.5 | – | – | – | – | 0.90[i] | 0.85[i] | 0.65[i] | 0.60[i] | 0.80 | 0.75 | 0.55 | 0.50 |
| | High | 0.50–0.60 | 2.5–4.0 | – | 0.80–0.85 | – | – | 1.00[h]–1.05[h] | 0.95[h]–1.00[h] | 0.70[h]–0.75[h] | 0.65[h]–0.70[h] | 0.90 | 0.85 | 0.60 | 0.55 |
| | Very high | >0.60 | 2.5–5.0 | 0.95–1.20 | 1.05–1.10 | – | – | 1.15[h]–1.20[h] | 1.10[h]–1.15[h] | 0.80[h]–0.85[h] | 0.75[h]–0.80[h] | 1.05 | 1.00 | 0.70 | 0.65 |
| Peach[a] | Young | 0.15–0.25 | 1.5–2.5 | 0.90–0.95 | 0.60–0.70 | – | 0.16–0.20 | 0.60[h] | 0.55[h] | 0.45[h] | 0.40[h] | 0.55 | 0.50 | 0.45 | 0.35 |
| | Low | 0.25–0.40 | 2.5–3.0 | – | 0.44 | – | – | 0.60[h] | 0.55[h] | 0.45[h] | 0.40[h] | 0.65 | 0.60 | 0.50 | 0.40 |
| | Medium | 0.40–0.60 | 2.5–3.5 | – | 1.00 | – | – | 0.90[i]–1.00[h] | 0.85[i]–0.95[h] | 0.65[i]–0.70[h] | 0.60[i]–0.65[h] | 0.90 | 0.85 | 0.65 | 0.60 |
| | High | >0.60 | 4.0–5.0 | 1.10 | 1.05–1.10 | 0.75 | – | 1.15[h]–1.20[h] | 1.10[h]–1.15[h] | 0.80[h]–0.85[h] | 0.75[h]–0.80[h] | 1.05 | 1.00 | 0.70 | 0.65 |
| **Pome fruit trees** | | | | | | | | | | | | | | | |
| Apple[a] | Young | <0.25 | 1.0–1.8 | – | – | – | – | 0.70[h] | 0.65[h] | 0.55[h] | 0.50[h] | 0.40 | 0.35 | 0.35 | 0.25 |
| | Low | 0.25–0.30 | 3.0–3.6 | 0.48 | | – | – | 0.70[h] | 0.65[h] | 0.55[h] | 0.50[h] | 0.50 | 0.45 | 0.40 | 0.30 |
| | Medium | 0.30–0.40 | 3.0–3.6 | 0.55–0.65 | – | – | – | 0.95[i] | 0.90[i] | 0.75[i] | 0.70[i] | 0.70 | 0.65 | 0.55 | 0.45 |
| | High | 0.40–0.50 | 3.0–3.6 | 0.76–1.04 | 0.60 | 0.17 | 0.10 | 1.05[h] | 1.00[h] | 0.75[h] | 0.70[h] | 0.90 | 0.85 | 0.65 | 0.45 |
| | Very high | >0.50 | 3.0–4.5 | 0.85–1.01 | 0.80–1.00 | 0.40–0.84 | 0.10 | 1.15[h] | 1.10[h] | 0.80[h] | 0.75[h] | 1.00 | 0.95 | 0.65 | 0.60 |
| Pear[a] | Young | <0.25 | 1.0–1.5 | – | | – | | 0.70[h] | 0.65[h] | 0.55[h] | 0.50[h] | 0.40 | 0.35 | 0.30 | 0.20 |
| | Low | 0.25–0.35 | 2.0–3.0 | 0.87–1.05 | – | – | – | 0.70[h] | 0.65[h] | 0.55[h] | 0.50[h] | 0.55 | 0.50 | 0.45 | 0.35 |
| | Medium | 0.35–0.40 | 2.0–3.0 | 1.00 | – | – | – | 0.95[i] | 0.90[i] | 0.75[i] | 0.70[i] | 0.85 | 0.80 | 0.65 | 0.60 |
| | High | 0.40–0.50 | 2.0–3.0 | – | 0.85–0.90 | – | – | 1.05[h] | 1.00[h] | 0.75[h] | 0.70[h] | 1.00 | 0.95 | 0.75 | 0.70 |
| | Very high | >0.50 | 3.3–3.6 | – | – | – | – | 1.15[h] | 1.10[h] | 0.80[h] | 0.75[h] | 1.10 | 1.05 | 0.85 | 0.80 |
| **Nut trees** | | | | | | | | | | | | | | | |
| Almond[a] | Young | 0.15–0.30 | 1.0–2.0 | – | – | – | – | 0.50[h] | 0.45[h] | 0.40[h] | 0.35[h] | 0.40 | 0.35 | 0.35 | 0.25 |
| | Low | 0.30–0.40 | 4.0–5.0 | – | 0.45 | – | 0.40 | 0.50[h] | 0.45[h] | 0.40[h] | 0.35[h] | 0.45 | 0.40 | 0.40 | 0.30 |
| | Medium | 0.40–0.50 | 4.0–5.0 | – | 0.60 | – | 0.40 | – | – | – | – | 0.65 | 0.60 | 0.50 | 0.40 |
| | High | 0.50–0.60 | 4.0–5.0 | – | 0.75–1.00 | – | 0.50–0.65 | 0.85[h]–0.95[i] | 0.80[h]–0.85[i] | 0.60[h]–0.75[i] | 0.55[h]–0.60[i] | 0.90 | 0.85 | 0.65 | 0.60 |
| | Very high | >0.60 | 4.0–5.5 | 1.12–1.20 | 0.95 | – | 0.60 | 1.00[h] | 0.95[h] | 0.70[h] | 0.65[h] | 1.05 | 1.00 | 0.75 | 0.70 |
| Hazelnut[c] | Young | 0.15–0.30 | 1.0–2.0 | | – | | – | – | – | – | – | 0.45 | 0.40 | 0.40 | 0.20 |
| | Low | 0.30–0.45 | 4.0–5.0 | 0.80 | – | – | – | – | – | – | – | 0.75 | 0.70 | 0.55 | 0.45 |
| | High | 0.45–0.60 | 1.5–2.0 | 0.93 | – | 0.80 | – | – | – | – | – | 0.95 | 0.90 | 0.65 | 0.55 |
| Pecan[a] | Young | 0.25–0.30 | 1.0–5.0 | – | – | – | – | – | – | – | – | 0.55 | 0.50 | 0.50 | 0.35 |
| | Low | 0.30–0.60 | 5.0–10.0 | 0.78 | – | 0.50 | – | – | – | – | – | 0.75 | 0.70 | 0.55 | 0.45 |
| | Medium | 0.60–0.70 | 7.0–11.5 | 0.85 | – | 0.63 | – | – | – | – | – | 0.85 | 0.80 | 0.60 | 0.55 |
| | High | >0.70 | 10.0–13.5 | 0.90–1.14 | – | 0.39–0.70 | – | – | – | – | – | 1.00 | 0.95 | 0.65 | 0.60 |

(*continued on next page*)

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

| Crop | Density | $f_c$[a,b,c,d,e,f] | Plant height[a,b,c,d,e,f] (m) | Literature reported $K_c$ and $K_{cb}$ | | | | Previous tabulated standard $K_c$ and $K_{cb}$ | | | | Indicative standard values (±10%) of $K_c$ and $K_{cb}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ |
| Pistachio[d] | Young, low | 0.15–0.30 | 1.5–2.0 | – | – | – | – | 0.50[h] | 0.45[h] | 0.40[h] | 0.35[h] | 0.45 | 0.40 | 0.35 | 0.25 |
| | Medium | 0.30–0.50 | | – | – | – | – | 0.85[h] | 0.80[h] | 0.60[h] | 0.55[h] | 0.80 | 0.75 | 0.55 | 0.50 |
| | High | >0.50 | 2.0–3.0 | 1.00 | 0.90 | 0.50 | 0.45 | 1.00[h]–1.10[h] | 0.95[h]–1.05[h] | 0.45[h]–0.70[h] | 0.40[h]–0.65[h] | 0.95 | 0.90 | 0.65 | 0.60 |
| Walnut[e] | Young, low | <0.30 | 1.0–2.0 | – | – | – | – | 0.55[h] | 0.50[h] | 0.40[h] | 0.35[h] | 0.50 | 0.45 | 0.45 | 0.25 |
| | Medium | 0.45–0.75 | 3.5–7.0 | – | 1.05 | – | – | 0.90[h] | 0.85[h] | 0.60[h] | 0.55[h] | 0.85 | 0.80 | 0.50 | 0.40 |
| | High | 0.75–0.85 | 3.5–7.0 | 1.00 | – | 0.37 | – | 1.10[i] | 1.05[i] | 0.65[i] | 0.60[i] | 0.95 | 0.90 | 0.55 | 0.50 |
| | Very high | >0.85 | 3.5–7.0 | 1.07 | – | 0.58 | – | – | – | – | – | 1.05 | 1.00 | 0.60 | 0.55 |
| **Other fruit trees** | | | | | – | | – | | | | | | | | |
| Fig tree[f] | Young, low | <0.30 | 1.0–1.5 | 0.49 | – | – | – | – | – | – | – | 0.45 | 0.40 | 0.35 | 0.25 |
| | Medium | 0.30–0.50 | 2.0–3.0 | 0.60 | – | – | – | – | – | – | – | 0.65 | 0.60 | 0.45 | 0.40 |
| Persimmon[g] | Young, low | 0.15–0.25 | 1.0–2.0 | – | – | | – | – | – | – | – | 0.50 | 0.45 | 0.40 | 0.30 |
| | Medium | 0.30–0.50 | 2.5–3.5 | 0.95 | 0.56 | – | – | – | – | – | – | 0.95 | 0.90 | 0.75 | 0.70 |
| Pomegranate[a] | Young | 0.15–0.25 | 1.0–2.0 | 0.36 | – | – | – | – | – | – | – | 0.35 | 0.30 | 0.30 | 0.20 |
| | Low | 0.25–0.35 | 2.5–3.5 | 0.44 | – | – | – | – | – | – | – | 0.50 | 0.45 | 0.40 | 0.30 |
| | Medium | 0.35–0.45 | 2.5–3.5 | 0.46–0.56 | – | – | – | – | – | – | – | 0.60 | 0.55 | 0.45 | 0.40 |
| | High | >0.45 | 2.5–3.5 | 0.71–1.00 | – | 0.40–0.64 | – | – | – | – | – | 0.85 | 0.80 | 0.60 | 0.55 |

[a] Observed $f_c$ and plant height values from Table 3. [b] Indicative $f_c$ and plant height values from Li et al. (2010) and Steiner et al. (2015). [c] Indicative $f_c$ and plant height values from Me et al. (2004), Olsen (2013) and Fischbach (2017). [d] Indicative $f_c$ and plant height values from Kallsen and Fanucchi (2008). [e] Indicative $f_c$ and plant height values from Lampinen (2014). [f] Indicative $f_c$ and plant height values from Kumar et al. (2014) and Hendricks et al. (1994). [g] Indicative $f_c$ and plant height values from Ballester et al. (2013). [h] Ranges of values from Allen and Pereira (2009) and Jensen and Allen (2016). [i] Values for common crop system management from Allen et al. (1998).

**Table 8**

Updated indicative standard values for single and basal crop coefficients relative to the mid- and end-season for tropical and sub-tropical fruit crops including reviewed literature and previous tabulated values.

| Crop | Density | $f_c$[a,b,c,d,e,f] | Plant height[a,b,c,d,e,f] (m) | Literature reported $K_c$ and $K_{cb}$ | | | | Previous tabulated standard $K_c$ and $K_{cb}$ | | | | Indicative standard values (±10%) of $K_c$ and $K_{cb}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ | $K_{c\ mid}$ | $K_{cb\ mid}$ | $K_{c\ end}$ | $K_{cb\ end}$ |
| Avocado[a] | Young, low | 0.10–0.20 | 1.0–2.0 | – | – | – | – | 0.65[g] | 0.60[g] | 0.60[g] | 0.50[g] | 0.65 | 0.55 | 0.60 | 0.45 |
| | Medium | 0.30–0.50 | 2.0–3.0 | 0.75 | – | 0.50 | – | 0.85–0.90 | 0.80[h]–0.85[g] | 0.75[h]–0.80[g] | 0.70[h]–0.80[g] | 0.80 | 0.75 | 0.70 | 0.60 |
| | High | >0.50 | 3.0–4.0 | 1.10 | – | 0.80 | – | 1.00[g] | 0.95[g] | 0.90[g] | 0.85[g] | 1.00 | 0.95 | 0.85 | 0.80 |
| Banana[b] | | | | | | | | | | | | | | | |
| 1st cycle | High | 0.80–0.95 | 2.0–2.5 | 1.00 | – | – | – | 1.10[h] | 1.05[h] | 1.00[h] | 0.90[h] | 1.05 | 1.00 | 0.95 | 0.90 |
| 2nd cycle | High | 0.75–0.85 | 2.0–2.5 | 1.00–1.05 | – | – | – | 1.20[h] | 1.10[h] | 1.10[h] | 1.05[h] | 1.15 | 1.05 | 1.10 | 1.00 |
| Cherimoya[c] | Medium | 0.50–0.65 | 2.5–4.0 | 0.65 | | 0.25 | | – | – | – | – | 0.65 | 0.60 | 0.55 | 0.45 |
| Coconut[d] | High | 0.70–0.80 | 7.0–15.0 | 1.00 | – | – | – | 0.95[g]–1.00[h] | 0.85[g]–0.90[h] | 0.95[g]–1.00[h] | 0.85[g]–0.90[h] | 0.95 | 0.90 | 0.90 | 0.85 |
| Coffee[e] | Young, low | 0.15–0.25 | 1.0–2.0 | 0.79 | – | 0.31 | – | – | – | – | – | 0.75 | 0.70 | 0.70 | 0.65 |
| | High | 0.40–0.60 | 2.5–3.5 | 1.12 | 0.78 | – | – | 0.95[h] | 0.90[h] | 0.95[h] | 0.90[h] | 0.95 | 0.90 | 0.95 | 0.90 |
| | Very High | >0.60 | 2.0–3.0 | 1.00 | – | 0.68 | – | | – | | – | 1.00 | 0.95 | 1.00 | 0.95 |
| Date palm[a] | Young, low | 0.15–0.25 | 8.0–10.0 | – | – | – | – | 0.55[g] | 0.45[g] | 0.55[g] | 0.45[g] | 0.50 | 0.45 | 0.55 | 0.45 |
| | Medium | 0.30–0.60 | 8.0–10.0 | 0.65 | | 0.60 | | 0.80[g]–0.95[h] | 0.70[g]–0.85[h] | 0.80[g]–0.95[h] | 0.70[g]–0.85[h] | 0.70 | 0.65 | 0.65 | 0.60 |
| | High | >0.60 | 10.0–15.0 | 0.84 | – | 0.65 | – | 0.95[g] | 0.85[g] | 0.95[g] | 0.85[g] | 0.85 | 0.80 | 0.75 | 0.70 |
| Guava[f] | High | >0.70 | 1.8–3.0 | 0.72–0.87 | – | 0.55 | – | – | – | – | – | 0.80 | 0.75 | 0.60 | 0.55 |
| Mango[a] | Young, low | 0.10–0.20 | 1.0–2.0 | – | – | – | – | 0.45[g] | 0.40[g] | 0.40[g] | 0.35[g] | 0.40 | 0.35 | 0.35 | 0.25 |
| | Medium | 0.30–0.70 | 2.5–3.0 | 0.70–0.82 | – | 0.15–0.25 | – | 0.75[g] | 0.70[g] | 0.60[g] | 0.55[g] | 0.75 | 0.70 | 0.60 | 0.55 |
| | High | >0.70 | 5.0–5.5 | 0.72–0.95 | – | 0.20 | – | 0.90[g] | 0.85[g] | 0.75[g] | 0.70[g] | 0.90 | 0.85 | 0.70 | 0.65 |
| Papaya[a] | High | >0.70 | 1.5–3.0 | 1.10 | 1.00 | 0.90 | 0.60 | – | – | – | – | 1.00 | 0.95 | 0.75 | 0.70 |

[a] Observed $f_c$ and plant height values from Table 4. [b] Indicative $f_c$ and plant height values from Turner et al. (2007) and Stevens et al. (2020). [c] Indicative $f_c$ and plant height values from Pinto et al. (2005), González et al. (2010). [d] Indicative $f_c$ and plant height values from Palaniswami et al. (2006) and Mohan et al. (2019). [e] Indicative $f_c$ and plant height values from Philpott et al. (2008) and Chemura et al. (2017). [f] Indicative $f_c$ and plant height values from Singh et al. (2007b) and Mushtaq et al. (2019). [g] Ranges of values from Allen and Pereira (2009) and Jensen and Allen (2016). [h] Values for common crop system management from Allen et al. (1998).

Standard $K_c$ and $K_{cb}$ values for temperate climate evergreen fruit tree crops (Table 6) include citrus and olive crops. For young citrus plantations, no information was found in literature and therefore previously tabulated values were considered to establish new indicative values, although following a water conservation perspective, since irrigation systems for this crop, as well as for other crops, have often evolved to localized irrigation systems, mirrored by a decrease in indicated crop coefficients. Low density citrus orchards presented reported values somehow higher than standard ones and this was taken in account in indicative values. For medium density short (h <3.5 m) citrus orchards, the collected $K_{c\ mid}$ was lower than the ones reported in Allen et al. (1998), Allen and Pereira (2009), and Jensen and Allen (2016); thus, the new indicative standard value was defined adopting the lower value in this range. No information existed on previous tabulated values $K_c$ for medium density tall (h >3.5 m) citrus orchards. A new indicative standard value was set considering a reported value and differences of 5%–10% among the various classes. This last procedure was adopted for $K_{cb\ mid}$, $K_{c\ end}$ and $K_{cb\ end}$ whenever previous tabulated information was not available. For high density, standard $K_{c\ mid}$ was set to 0.70 (short trees orchards) and to 0.90 (tall trees orchards) according to observed or observed/tabulated information, respectively. A similar approach was followed for $K_{cb\ mid}$, $K_{c\ end}$ and $K_{cb\ end}$. Citrus species are evergreen, presenting a similar foliage and ground cover in the mid and the end of the cycle, which originates close values of $K_{c\ mid}$ and $K_{c\ end}$, and also $K_{cb\ mid}$ and $K_{cb\ end}$, for every density. For citrus, differences between $K_{c\ end}$ and $K_{cb\ end}$ are different from the previously tabulated values because it is expected that wetting events by precipitation occur by the end season. $K_{c\ end}$ value was obtained by adding a specific value to $K_{cb\ end}$ which ranged 0.10–0.25. The specific value added decreased with $f_c$, thus a value of 0.25 was used for the young orchards and it decreased to 0.10 in case of the high-density orchards.

For olive, the four crop systems considered were young, traditional, intensive and super-intensive. Young and traditional systems have the smallest tree density and lower $f_c$, originating lower $K_c$ and $K_{cb}$ when compared with the other systems. The collected data for traditional olive orchards showed values of $K_{c\ mid}$ reaching a maximum of 0.65, which is larger than the $K_{c\ mid}$ indicated in Allen et al. (1998), Allen and Pereira (2009), and Jensen and Allen (2016). The value of $K_{c\ mid}$ for olive orchards with traditional systems (medium density) was then updated to 0.45. No observed data for $K_{c\ end}$ and $K_{cb\ end}$ was available in the literature for this kind of systems and new values were set considering differences of 5%–10% to adjacent classes. The newly reported value of $K_{cb\ mid}$ for these traditional systems (0.59, medium density) is higher than those previously reported (0.35) by Allen and Pereira (2009) and by Jensen and Allen (2016), so, standard $K_{cb\ mid}$ was set to 0.40.

Intensive olive orchards have higher tree density than traditional orchards and it was expected that they would have higher $K_c$ values. This was not confirmed for $K_{c\ mid}$, as a lower collected value was retrieved, also non-concordant with prior information. Given the special characteristics of hedgerow olive orchards in what concerns canopy shape, height and spacing, $K_c$ and $K_{cb}$ values were supposed to be larger in comparison with the other two systems. This was confirmed with collected data for $K_{c\ mid}$ and $K_{cb\ mid}$. For most of the olive systems, standard values for $K_{c\ end}$ are higher than $K_{c\ mid}$, as retrieved by the collected information since the end-season occurs during the rainy season in the Mediterranean climate types, thus when soil evaporation contribution to ET is high and, consequently, $K_c$ increases. Thus, differences between the indicative standard values of $K_{c\ end}$ and $K_{cb\ end}$ range 0.35–0.40 depending on the $f_c$ of the orchard.

Table 7 presents information on temperate climate deciduous fruit tree crops including stone fruit trees (apricot, cherry, plum and peach), pome fruit trees (apple and pear), nut trees (almond, hazelnut, pecan, pistachio and walnut) and other fruit trees such as fig tree, persimmon and pomegranate. Collected information for this group is abundant, mainly for $K_{c\ mid}$, although not covering all the densities, as for low-density orchards.

New information on the $K_{c\ mid}$ and $K_{cb\ mid}$ values for a first group of stone fruit trees (apricot, cherry and plum) was only available for very high-density orchards (and only one value of $K_{cb\ mid}$ for high density) and provided a range of values slightly lower (0.95–1.20) than those tabulated by Allen and Pereira (2009) and Jensen and Allen (2016). The standard $K_{c\ mid}$ was then set to 1.05. For other density classes, information was only available from the referred studies and in Allen et al. (1998), thus the standard values were established considering these previous studies. A similar procedure was followed to set standard $K_{cb\ mid}$, $K_{c\ end}$ and $K_{cb\ end}$. A similar approach was followed for peach, although more information was available.

For young apple orchards, values for crop coefficients were set with small differences to low density plantations. For low density, observed values of $K_{c\ mid}$ were smaller than the ones found in Allen and Pereira (2009) and Jensen and Allen (2016) but an indicative standard value was derived from those tabulated, bearing in mind orchard characteristics and differences to other density classes since reported information was scarce. $K_{c\ end}$ was derived from previously tabulated values, except for high and very high-density orchards, where literature data were used to establish the indicative values. For medium-density orchards the standard $K_{cb\ mid}$ value decreased compared to the previously indicated by Allen and Pereira (2009) and Jensen and Allen (2016), given the literature collected $K_{cb}$ values. The same occurred for high and very high-density apple orchards, where a standard value for $K_{c\ mid}$ is smaller, based on the values retrieved from experimental studies. The differences between $K_{c\ end}$ and $K_{cb\ end}$ values were 0.10 or 0.05 according to the $f_c$ values, with higher values for the lower $f_c$, which corresponded to the young and low density orchards.

Data collected in literature relative to $K_{c\ mid}$ of low-density pears orchards was higher than previously tabulated values, but the new indicative values do not reflect this change, since related information is scarce. In case of the medium density orchards $K_{c\ mid}$ values collected in literature and previously tabulated (Allen et al., 1998; Allen and Pereira, 2009; Jensen and Allen, 2016) were close, therefore standard values were similar to the existing information. For high density orchards the $K_{c\ mid}$ values reported in literature were lower than those in Allen and Pereira (2009) and Jensen and Allen (2016) thus, the standard $K_{c\ mid}$ values were lowered to accommodate this difference. There was no collected information available for $K_{c\ end}$ and $K_{cb\ end}$, thus, the standard value was derived from previous tabulated data (Allen et al., 1998; Allen and Pereira, 2009; Jensen and Allen, 2016).

For nut trees, no information was found for young orchards. From collected information in literature relative to low, medium and high densities of almond orchards, only information on $K_{cb}$ was available to update the previously tabulated values (Allen et al., 1998; Allen and Pereira, 2009; Jensen and Allen, 2016) which were taken into account to set the updated indicative values. Standard values were retained for $K_{c\ mid}$, considering the values for other classes. Very high-density orchards presented higher $K_{c\ mid}$ and similar $K_{cb\ mid}$ and $K_{c\ end}$, as compared to previously tabulated values. Differences between $K_{c\ mid}$ and $K_{cb\ mid}$ values for all the nut tree orchards were assumed equal to 0.05, while for $K_{c\ end}$ and $K_{cb\ end}$ differences range 0.10 to 0.05, with the highest value for young and low density orchards, as well as in a few cases of medium density orchards when the expected wetting events by precipitation are high during the end-season.

Collected $K_c$ values in literature for hazelnut were available for low and high densities and a reported $K_{c\ mid}$ was found for a low-density orchard. Since no prior information from tabulated values existed the experimentally derived $K_c$ and $K_{cb}$ values were used to support setting the new indicative values.

For pecan orchards there was no prior tabulated information on $K_c$ and $K_{cb}$ thus, the indicative standard values were derived from ranges given in literature for low to high densities, considering the growth habits and the crop cycle. As a deciduous tree, $K_{c\ end}$ and $K_{cb\ end}$ present an evident decrease since the plants senesce during the late-season stage.

No information was found for young plantations of pistachio, as well as relative to low and medium densities, hence standard values were set from the values previously tabulated (Allen and Pereira, 2009; Jensen and Allen, 2016), bearing in mind the new values reported in literature for high-density orchards. For high density pistachio plantations, the collected values for $K_{c\ mid}$ were close to those previously tabulated, leading to similar indicative values.

For walnut orchards with young trees, or low to medium densities, there was little or no information reported in literature; therefore, the indicative crop coefficient values were established mostly based on previous information, crop characteristics and maintaining reasonable differences to high and very high-density orchard $K_c/K_{cb}$ values. For high-density walnut orchards, collected $K_{c\ mid}$ values were slightly lower than the ones previously tabulated and the $K_{c\ mid}$ indicative values reflect this trend. The indicative standard $K_{c\ end}$ value results from the combination between the previously tabulated value with the lower value collected from the literature. For very high-density orchards there was no prior tabulated information and new indicative values were set based on literature reported values.

One of the least documented crops is the fig tree, with literature data available only for $K_{c\ mid}$ and without previously tabulated information. New values for $K_{c\ mid}$, $K_{c\ end}$, $K_{cb\ mid}$ and $K_{cb\ end}$ are suggested, based on observations and, for $K_{cb}$, bearing in mind that fig are deciduous trees and that tree spacing tends to be large. Similar situation in terms of available data was found for persimmon, where only $K_{c\ mid}$ and $K_{cb\ mid}$ values for medium density orchards are reported in literature. Indicative values were provided based on these values and on the crop characteristics. For pomegranate, there was no previous tabulated information, but it was possible to collect $K_{c\ mid}$ for all densities and $K_{c\ end}$ for the high density orchards. The standard $K_{c\ mid}$ value for all densities resulted from the corresponding adjustment. There was no new literature information on $K_{cb}$ and, in this case, standard values adopted were set bearing in mind expected differences relative to $K_c$ taking into consideration the diverse crop density classes.

Table 8 presents updated indicative values of crop coefficients for tropical and sub-tropical fruit crops: avocado, banana, cherimoya, coconut, coffee, date palm, guava, mango, and papaya. For mango and avocado, collected data refer only to $K_c$ for high and medium density because there was no information available for low densities. Therefore, standard $K_c$ values for low densities were set based on what was suggested by Allen and Pereira (2009) and Jensen and Allen (2016). For $K_{cb}$, no reported values were available in literature for both crops.

For the first cycle of the banana crop, $K_{c\ mid}$ values collected in literature were slightly lower than the ones reported in Allen et al. (1998) and in Jensen and Allen (2016); thus the standard value was slightly decreased. The standard $K_{cb\ end}$ value was set to a lower value than in Allen et al. (1998); in fact, a decrease in $K_{cb}$ by the end-season is in agreement with the status of the crop in that stage, when leaf senescence occurs and harvest is performed. From the first cycle to the second cycle, plant canopy shadow decreases due to a higher spacing between plants, thus soil evaporation increases inducing larger values for $K_c$ and $K_{cb}$. In the second cycle, collected $K_{c\ mid}$ values were somewhat smaller than those presented in Allen et al. (1998) and therefore the respective consolidate values were set to reflect this fact. No observed values were found for $K_{cb}$ thus, standard values were determined to bear in mind the information in Allen et al. (1998) and the occurrence of leaf senescence by the end of the cycle.

Information collected from literature on $K_{cb\ mid}$ was more limited and only available for coffee and papaya high-density plantations. $K_{cb}$ value for coffee collected from literature was lower than the tabulated by Allen et al. (1998), but the standard $K_{c\ mid}$ was set equal to that previous one, as reported information is scarce. For $K_{c\ mid}$, reported values helped fixing indicative values, considering the different density classes and crop ground cover and height. Only a small difference for $K_c$ or $K_{cb}$ values between the mid and end seasons is expected because, at the end of the cycle, the plant does not have a significantly different foliar coverage compared with the mid-season.

Standard $K_c$ and $K_{cb}$ for papaya were set based on newly collected information since no prior data existed. The same occurred for cactus pear, but existing information was not considered sufficient to derive indicative standard values.

The cherimoya crop had no prior tabulated information, but new collected values could be considered to set the standard ones. The same procedure was used with guava to set standard values for $K_c$. For $K_{cb}$, as no information at all existed, standard values were set considering those for $K_c$ and the crop characteristics: cherimoya is a briefly deciduous plant but most evergreen, and guava is evergreen, therefore lower $K_{c\ end}$ and $K_{cb\ end}$ for cherimoya were considered.

The $K_c$ values collected in literature relative to coconut orchards were similar to those previously reported in Allen et al. (1998). No other information was available in literature, thus the new standard values were kept within the range previously established. Information on $K_{cb}$ was available in Allen et al. (1998) and this was used as the standard value.

The collected $K_c$ values for date palm are somewhat lower than those presented in previously tabulated information. Accordingly, new indicative standard values were set to lower values. No $K_{cb}$ data could be retrieved from literature and new standard values were set considering previous information.

Data collection evidenced that field derived crop coefficients ($K_c$ and $K_{cb}$) as reported in the literature, are fairly variable among species and for the same tree or vine crop, thus making it difficult to define standard $K_c$ and $K_{cb}$ for each crop. Likely, the large range of data observed in the literature is linked to several factors such as crop variety, climate effects, the method used to determine crop ET, crop spacing, soil type and soil management, irrigation method and scheduling, crop age and agronomic practices. Moreover, crop density represented by the fraction of ground cover and crop training plays a major role as indicated by the former studies where $K_{cb}$ and $K_c$ were computed from the fraction of ground cover. Nevertheless, literature is often scarce in providing related information despite crop density and training are changing in recent times due to the mechanization of orchard operations, which includes pruning and harvesting. All the factors referred above led to setting $K_c$ and $K_{cb}$ values considering an interval of 10% relative to the indicative values provided.

## 6. Conclusions and future perspectives

The present study gathered information from field research performed using the FAO56 approach (Allen et al., 1998) for deriving the crop coefficients of fruit trees and vines over the past twenty years. This information was used to update the values of single ($K_c$) and basal ($K_{cb}$) crop coefficients previously tabulated in FAO56.

The $K_c$ and $K_{cb}$ values retained in this review were obtained in field studies that used the FAO56 grass reference $ET_o$ equation. The accuracy of $ET_c$ estimates was assured by selecting only studies that employed well designed and performed field studies such as eddy covariance, sap flow, soil water balance approaches and lysimetry. Conditions for transferability of reported data were therefore assumed. Nevertheless, because studies for the same crop are quite different in terms of crop varieties, crop and irrigation management, rainfall amounts and timings, and field methods, there is a great variability of reported $K_c$ and $K_{cb}$ for the same crop and similar training systems and fractions of ground cover. It was therefore necessary to assume that tabulated values are indicative and vary in a range of approximately 10%, which is referred in the Tables. Users may therefore select a larger or small value than the tabulated ones.

Single values for $K_c$ and $K_{cb}$ were provided in FAO56 for most crops corresponding to the most common crop system management. In the current review, considering the wide range of plants density, $f_c$ and h, as well as the tabulation of values according to $f_c$ as adopted in Allen and Pereira (2009) and Jensen and Allen (2016), the indicative standard tabulated $K_c$ and $K_{cb}$ values are assigned to various categories related with crop density: young orchard and low density, and medium, high and very high densities. Ranges of $f_c$ and h characterize those densities. That categorization for vine fruit crops was mainly related with the training systems.

The presently tabulated indicative values for $K_c$ and $K_{cb}$ agree with those tabulated in FAO56 but have the advantage of being tied to the crop density and training system, particularly with the fraction of ground cover. This allows users to select the indicative values according to the conditions prevailing in the considered orchards and vines. The current review allowed to propose indicative $K_c$ and $K_{cb}$ values for several fruit crops that were not considered in FAO56, nor in other previous publications, e.g. hazelnut, pecan, fig, persimmon, pomegranate, as well as a few tropical fruit crops such as cherimoya, guava, mango and papaya. Therefore, favorable conditions are created to better using the $K_c$-$ET_o$ method to compute crop water requirements of trees and vines as proposed in FAO56. The use of tabulated $K_c$ and $K_{cb}$ values is appropriate for a variety of applications, such as irrigation scheduling, in planning irrigation, namely using water balance or water-yield models.

The current review revealed that many $K_c$ research studies, not retained but published, did not report about the quality of input and output data, or reported very high $K_c$ values which were not justified by the local climate, but could result from advection and/or inaccuracies in field measurements and data handling. It is therefore recommended that appropriate scrutiny of results be commonly adopted from planning to end of experiments and data handling. The quality of research results is very important to base new approaches that may lead to improved production and resource conservation.

The review has shown that only few studies used appropriately calibrated and validated SWB simulation models despite their use eases to derive standard $K_c$ and $K_{cb}$ values including when water stress is greater than the reasonable eustress. It is recommended that more research is performed using SWB models in searching $K_c$ and $K_{cb}$ as well as for irrigation management purposes. The incorporation of remote sensing and big data in such modeling is a recommended area of research. Moreover, the use of forecasted weather data is also recommended aiming at real-time irrigation scheduling.

The impacts of active ground cover, cover crops, and mulches on $K_c$ and $K_{cb}$ values of fruit trees and vines consist of another area where further research is required. It is recommended to develop research on these domains in a broader perspective of better production and resource conservation, namely water saving.

It is important to recognize that current water scarcity and climate change call for water-saving, which may be achieved when adopting precision irrigation protocols, namely when supported by modeling. With that perspective, the $K_c$ and $K_{cb}$ indicative values were set in a conservative way, not increasing relative to the past but whenever possible decreasing since the use of drip irrigation, improved soil management and an appropriate adoption of eustress management allows higher yields in a combination with water saving and resources conservation.

## 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.

## Acknowledgments

The support of the Fundação para a Ciência e a Tecnologia, Portugal, through the research grant attributed to the research unit LEAF (UID/AGR/04129/2020) and to the third author (DL 57/2016/CP1382/CT0022) is acknowledged.

The research was carried out in the frame of “Progetto OP-Illuminati Frutta-Rallo” (University of Pisa, MIPAF-Regione Toscana), ATMOSMART-dimostratore tecnologico (University of Pisa) and “PRIN-2017-Provenzano” (University of Palermo).

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