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Research Paper

Prediction of crop coefficients from fraction of ground cover and height: Practical application to vegetable, field and fruit crops with focus on parameterization

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ABSTRACT

The A&P approach, developed by Allen and Pereira (2009), estimates single and basal crop coefficients (K_c and K_{cb}) from the observed fraction of ground cover (f_c) and crop height (h). The practical application of the A&P for several crops was reviewed and tested in a companion paper (Pereira et al., 2020). The current study further addresses the derivation of optimal values for A&P parameter values representing canopy transparency (M_L) and stomatal adjustment (F_r), and tests the resulting model performance. Values reported in literature of M_L and F_r were analysed. Optimal M_L and F_r values were derived by a numerical search that minimized the differences between $K_{cb\ A\&P}$ with standard K_{cb} for vegetable, field, and fruit crops as tabulated by Pereira et al. (2021a, 2021b) and Rallo et al. (2021). Sources for f_c were literature reviews supplemented by a remote sensing survey. Computed K_{cb} and K_c for mid- and end-season together with associated parameters values were tabulated. To improve the usability of the M_L and F_r parameters a cross validation was performed, which consisted of the linear regression between K_{cb} computed by A&P and observed K_{cb} relative to independent data sets obtained from field observations. Results show that both series of K_{cb} match well, with regression coefficients very close to 1.0, coefficients of determination near 1.0, and root mean square errors (RMSE) of 0.06 for the annual crops and RMSE = 0.07 for the trees and vines. These errors represent less than 10% of most of the computed tabulated K_{cb}. The tabulated F_r and M_L of this paper can be regarded as defaults to support A&P field practice when observations of f_c and h are performed. Therefore, the A&P approach shows to be appropriate for use in irrigation scheduling and planning when f_c and h are observed using ground and/or remote sensing, hence supporting irrigation water savings.

1. Introduction

The Food and Agriculture Organization (FAO) two-step crop coefficient method, K_c-ET_o (Doorenbos and Pruitt, 1977; Allen et al., 1998), has been a successful and dependable means to estimate crop evapotranspiration (ET_c) and crop water requirements (Pereira et al., 2015a; Jensen and Allen, 2016). The method uses weather data to compute the grass reference evapotranspiration (ET_o) with the FAO Penman–Monteith ET_o equation (PM-ET_o equation, Allen et al., 1998) and a crop coefficient (K_c) that represents the relative rate of evapotranspiration from a specific crop and condition to that of the reference crop (ET_c/ET_o). The reference condition is ET from a clipped, cool season, well-watered grass with a height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, fully covering the ground. The calculation of ET_o has been standardized by FAO (Allen et al., 1998, 2006) and the American Society of Civil Engineers (ASCE-EWRI, 2005). Therefore, standard K_c values have to be computed using the standardized PM-ET_o equation. Using alternative reference ET equations is only acceptable for local practice.

The K_c-ET_o approach provides a simple, convenient and reproducible way to estimate ET from a variety of crops and climatic conditions (Allen et al., 1998; Pereira et al., 1999, 2015a; Jensen and Allen, 2016). Crop

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coefficient curves have been developed and reported for a wide range of agricultural crops (Allen et al., 1998, 2007; Jensen and Allen, 2016) and their standard values were recently updated for vegetable and field crops (Pereira et al., 2021a, 2021b), as well as for fruit tree and vine crops (Rallo et al., 2021). Standard K_c represents the relative fraction of ET_o that is governed by the amount, type and condition of a given crop type under standard, pristine conditions, and is regarded as generally transferable among regions, subject to adjustment for local climate, under the assumption that the ET_o accounts for nearly all weather-related ET_c variation. When a crop is cultivated under water and/or saline stress, or under specific management conditions differing from pristine conditions (well-watered, homogeneous crop without yield limitations from water stress, nutrient availability, salinity, pests or disease), the actual crop ET is affected relative to the potential ET_c, i.e., $ET_{c\ act} \leq ET_c$. Thus, a stress coefficient has to be considered as $ET_{c\ act} = (K_s\ K_c)\ ET_o$, $K_s = 1.0$ unless available soil water and/or salinity limits transpiration, in which case $K_s < 1.0$ (Allen et al., 1998; Minhas et al., 2020). In the case of tree and vine crops, ET_c and K_c values are assumed as standard when cropping conditions are nearly pristine but may involve some beneficial water stress aimed at maximizing crop yield and quality.

In addition to the single K_c, a dual K_c is proposed in FAO56 (Allen et al., 1998), i.e., $K_c = K_{cb} + K_e$ where K_{cb} refers to crop transpiration and K_e refers to the evaporation from the soil. The estimation of K_e from the fraction of ground covered or shaded by vegetation (f_c) is described in Allen et al. (1998). This partition is detailed by Allen et al. (2005a) and its modelling is described by Rosa et al. (2012). Adopting the dual K_c approach and the use of K_s results in Eq. (1):

$$K_{c\ act} = K_s K_{cb} + K_e \tag{1}$$

which shows that K_s applies only to K_{cb}, which represents the transpiration component.

The FAO segmented approach is commonly adopted to describe the K_c and K_{cb} curves, where the four linear segments represent the initial, development, mid-season and late-season periods. The FAO K_c curve requires knowledge of only three key values: $K_{c\ ini}$ for the initial period, $K_{c\ mid}$ during the midseason period, and $K_{c\ end}$ at the end of the late season (Doorenbos and Pruitt, 1977, Allen et al., 1998). However, many authors do not adopt the FAO K_c curve and do not distinguish mid- and end-season K_c in their reporting, e.g., defining K_c or K_{cb} as a non-linear function of time after planting, which may be appropriate for local use but limits the subsequent relevance and transferability of their research results to different locations.

The derivation of K_c and K_{cb} values from field data requires that ET_c is accurately determined as discussed in the recent K_c reviews (Pereira et al., 2021a, 2021b; Rallo et al., 2021). Those field-based ET_c measurements are appropriate for research purposes but are generally impractical for grower use due to complexity and expense. Nevertheless, as discussed in the companion paper (Pereira et al., 2020), K_c and K_{cb} values can be accurately estimated through their relationship with the ground fraction covered or shadowed by the crop canopy (f_c), the height (h) of the vegetation, and the relative amount of stomatal adjustment under moist soil conditions. This approach was initially proposed in FAO56, further developed by Allen and Pereira (2009), and was extensively tested in the companion paper (Pereira et al., 2020), where it is referred to as the A&P approach. However, it must be taken into consideration that K_{cb} and K_c values estimated with this approach ($K_{cb\ A\&P}$ and $K_{c\ A\&P}$) are not standard but actual values, since stress often occurs in practice, which affects f_c, crop h and the relative stomatal resistance. Nevertheless, when computations are performed using parameters obtained under optimal, pristine cropping conditions, the estimated $K_{cb\ A\&P}$ and $K_{c\ A\&P}$ may be considered to represent standard values.

The study by Allen and Pereira (2009) is often quoted when users compare K_{cb} from field research with paper tabulated K_{cb} values, e.g. for strawberries (Lozano et al., 2016), vineyards (Moratiel and Martínez-Cob, 2012; Picón-Toro et al., 2012; Poblete-Echeverría et al., 2017), and almond orchards (Stevens et al., 2012). More important, numerous studies report successful applications of the A&P approach to calculate K_{cb}, mainly for trees and vines. Applications when computing K_{cb} with remote sensing vegetation indices are also reported (Pôças et al., 2015, 2020). In various cases, parameters proposed by Allen and Pereira (2009) were not modified when the approach is used to estimate K_{cb}, e.g., in successful applications to vineyards (Fandiño et al., 2012; Cancela et al., 2015), olives (Conceição et al., 2017), almonds (Phogat et al., 2013), trellised tomato (Zheng et al., 2013) and bermudagrass subjected to cuts (Paredes et al., 2018). Studies relative to field crops generally did not report changes of the originally proposed parameters but, in some cases, equations were modified (Ding et al., 2013; Jiang et al., 2014). The A&P approach has been integrated with the SIMDualKc soil water balance model (Rosa et al., 2012) and has been successfully used with numerous crops, particularly when crop density plays an important role, as for water stressed rainfed maize (Wu et al., 2015), grasslands (Wu et al., 2016) and intercrop cultivation (Miao et al., 2016).

Direct computation of K_{cb} with the A&P approach often requires the numerical search of the empirical parameters relative to canopy transparency to solar radiation (M_L) and to the effects of stomatal adjustment (F_r), e.g., in applications to peach (Paço et al., 2012) and olive (Paço et al., 2019; Conceição et al., 2017; Puppo et al., 2019), including to non-irrigated, water stressed olive groves (Santos et al., 2012). Applications also include crops not previously considered such as Chinese tamarisk (Li et al., 2015). An application to perennial crops aimed at water resources balance studies is reported for California by Devine and O'Geen (2019). Studies relative to orchards demonstrate the need for modifying the empirical equation by defining the impacts of stomatal adjustment, which is adopted in this study on basis of research reported by Taylor et al. (2015, 2017) for orange orchards, and Mobe et al. (2020) for apples.

The A&P approach has been adopted by the Satellite Irrigation Management Support (SIMS) for use with remote sensing data for mapping crop ET in California and the western United States (US). That application to vegetable, field and fruit tree and vine crops with the SIMS system shows its usability for wide area mapping of crop ET and for delivery of data and information for irrigation management to farmers (Melton et al. 2012, 2020). Crop specific tests using SIMS compared with ground-based ET measurements were performed to evaluate system accuracy (Melton et al., 2018; Wang et al., 2021).

The companion paper (Pereira et al., 2020) discussed the feasibility of the practical use of the A&P approach and tested the use and variability of the parameters M_L and F_r used in the computations for several vegetable, field, tree and vine crops, with f_c and h obtained from ground and remote sensing observations. That study also revised approaches used to derive f_c and h using ground and remote sensing observations.

The objectives of the current study, considering the reviews and tests reported in the companion paper (Pereira et al., 2020), consist of providing for the usability of the A&P approach in the field by practitioners using available f_c and h data, as well as to parameterize the approach for a wide variety of crops. The aims include tabulating values for K_{cb} and related computation parameters, and performing their cross validation with independent data sets to assess the accuracy of K_{cb} estimation. It is expected that the tabulated parameters will facilitate the use of the A&P approach in the practice of ET-based irrigation management and will support increased adoption of data-driven irrigation, with associated advances in on-farm water use efficiency.

This article is organized into the following sections designed to assist the reader in locating information that is relevant to their intended use and practical application. The Section 2 describes the computational approach, Section 3 presents a summary of the data and parameterization of the A&P, as well as of the procedures used, while Section 4 consist of the presentation of the tabulated parameters and the K_c and K_{cb} values computed with the A&P approach, concluding with the cross validation of the tabulated parameters for vegetable, field crops and vine and fruit tree crops. Section 5 provides conclusions and recommendations.

2. Estimating K_{cb} from the fraction of ground cover and crop height

For expanses of vegetation large enough that an equilibrium boundary is established so that general one-dimensional equations such as the Penman–Monteith equation (Monteith, 1965) apply, a maximum upper limit on ET is established due to the law of conservation of energy. Therefore, for large expanses of vegetation (larger than about 500 to 2,000 m^2), the K_c development process has upper limits for K_c of 1.2–1.3 for the grass reference. However, under conditions of "clothesline effects" (where vegetation height exceeds that of the surroundings) or "oasis effects" (where vegetation has higher soil water availability than the surroundings), the peak K_c values may exceed those limits. Caution is required when extrapolating ET measurements from small vegetation plots to large stands or regions because estimation errors of ET may occur.

Following the A&P approach, the basal K_{cb}, because it primarily represents transpiration, depends upon the amount of vegetation and can be expressed as a function of a density coefficient, K_d, as:

$$K_{cb} = K_{c\ min} + K_d\left(K_{cb\ full} - K_{c\ min}\right) \tag{2}$$

where K_{cb} is approximated for conditions represented by the density coefficient, K_d, $K_{cb\ full}$ is the estimated basal K_c during peak plant growth for conditions having nearly full ground cover (or LAI > 3), and $K_{c\ min}$ is the minimum basal K_c for bare soil (0.15 under typical agricultural conditions). Examples of application to several crops are given by Pereira et al. (2020). For tree crops having grass or other ground cover, Eq. (2) takes a different form to consider transpiration by the active ground cover, thus:

$$K_{cb} = K_{cb\ cover} + K_d\left(\max\left[K_{cb\ full} - K_{cb\ cover},\ \frac{K_{cb\ full} - K_{cb\ cover}}{2}\right]\right) \tag{3}$$

where $K_{cb\ cover}$ is the K_{cb} of the active ground cover in the absence of tree foliage. The second term of the max function reduces the estimate for $K_{cb\ mid}$ by half the difference between $K_{cb\ full}$ and $K_{c\ cover}$ when this difference is negative. This accounts for impacts of shading by vegetation when $K_{cb} < K_{cb\ cover}$ due to differences in stomatal conductance. Eq. (3) applies to estimate K_{cb} during any period. Two application examples are provided by Fandiño et al. (2012) and Cancela et al. (2015). As described by Allen and Pereira (2009), the approach of Eq. (3) can be similarly applied to estimate a single K_c coefficient.

The value for $K_{cb\ full}$ represents a general upper limit on $K_{cb\ mid}$ for vegetation having full ground cover and LAI > 3 under full water supply. $K_{cb\ full}$ can be approximated as a function of mean plant height and adjusted for climate following Allen et al. (1998):

$$K_{cb\,full} = F_r\left(min(1.0 + k_h h, 1.20) + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right) \tag{4}$$

where u_2 is average daily wind speed (m s^{-1}) at a height of 2 m above ground level during the growth period, RH_{min} (%) is average daily minimum relative humidity during the growth period, and h is the mean plant height (m) during midseason. Eq. (4) suggests that an upper bound for $K_{cb\ full}$ is 1.20 prior to climatic adjustment. Effects of crop height are considered through the sum $1 + k_h$ h, with $k_h = 0.1$ for tree and vine crops, as well as tall field crops, and $k_h = 0.2$ for short crops and vegetables (Pereira et al., 2020). Eq. (4) produces increases in $K_{cb\ full}$ with plant height and when local climates are more arid or windier than standard climate conditions. The parameter F_r applies an empirical downward adjustment ($F_r \leq 1.0$) if the vegetation exhibits more stomatal adjustment on transpiration than is typical of most annual agricultural crops. F_r is near 1.0 for annual crops cultivated under non-stressed, pristine conditions and decreases when crops are water or salinity stressed. For trees and vines, F_r is high when crops exhibit great vegetative vigor and decreases by effect of pruning and training, as well as limited water supply. Examples are provided in the companion paper (Pereira et al., 2020). Adopting the Allen et al. (1998) definition for F_r, considering the variability of leaf resistance from annual to perennial crops, it is assumed:

$$F_r = \frac{\Delta + \gamma(1 + 0.34\quad u_2)}{\Delta + \gamma\left(1 + 0.34\quad u_2\dfrac{r_l}{r_{typ}}\right)} \tag{5}$$

where r_l and r_{typ} are, respectively, the mean leaf resistance and the typical leaf resistance [s m^{-1}] for the vegetation in question, Δ is the slope of the saturation vapor pressure vs. air temperature curve, kPa $°C^{-1}$, and γ is the psychrometric constant, kPa $°C^{-1}$, both relative to the period when $K_{cb\ full}$ is computed. The original version of that equation was established with a fixed $r_{typ} = 100$ s m^{-1}, a common value for annual crops. The F_r equation is rewritten to cover a wider range of typical leaf resistances for a variety of crops, including the perennials. Important to note that F_r applies to $K_{cb\ full}$ in the direct calculation of actual or standard K_{cb} (Eqs. (2) and (3)) as adopted by Allen and Pereira (2009) and Pereira et al. (2020), while K_s applies to convert standard K_{cb} into $K_{cb\ act}$ when performing a soil water balance to a stressed crop (e.g., Rosa et al., 2012; Wu et al., 2015, 2016; Giménez et al., 2017; Minhas et al., 2020).

The original F_r Eq. (5) was developed to empirically consider the effects of stomatal adjustment, on $K_{cb\ full}$ and, therefore, on K_{cb}, in response to water stress (Allen et al., 1998) since stomatal closure causes a decrease of transpiration, thus of K_{cb} and K_c. Stomatal adjustment processes were quite well known for annual crops (Monteith, 1965; van Bavel and Ehrler, 1968; Hsiao, 1973; Szeicz et al., 1973; Jarvis and McNaughton, 1986; Chaves, 1991; McNaughton and Jarvis, 1991). It was also known that stomatal adjustment processes varied among crops and throughout the crop cycle, and that leaf aging favors stomatal closure in response to water stress relative to younger leaves (Jordan et al., 1975). Stomatal adjustment in fruit trees and grapevine was less well known but, despite leaf resistances are much higher, it the process is coherent with that of annual crops (Cohen and Cohen, 1983; Chaves and Rodrigues, 1987; Steinberg et al., 1989; Winkel and Rambal, 1990). The effect of stomatal adjustment processes on transpiration could therefore be characterized by empirical adjustment of F_r, Eq. (5) was developed previously using a default r_{typ} value of 100 s m^{-1} but default F_r values were indicated by Allen and Pereira (2009) for tree and vine crops.

F_r serves to adjust $K_{cb\ full}$ for considering effects of stomatal adjustment in relation to typical leaf resistance associated with a given crop type and growth stage. This adjustment is particularly important for perennials, which have a F_r behavior different from annuals as referred by Allen and Pereira (2009). The standard value for F_r is 1.0 for annuals before leaf senescence, i.e. when r_l is close to r_{typ}. F_r decreases during the late season, when senescence develops and stomatal closure increases. For perennials F_r not only decreases during the late season but is smaller than 1.0 when pruning and training reduce the vigor of the plant.

Good results were obtained assuming that the F_r values are estimated with empirical consideration of stomatal adjustment for various annual and perennial crops (Pereira et al., 2020), thus not measuring stomatal resistances. However, different approaches may have to be used when dealing with various orchards of the same crop but having different varieties, planting spacings and f_c values. Mobe et al. (2020), using observed apple r_l, found that F_r was over-estimated when using the ratio $r_l/100$ proposed by Allen et al. (1998) and by Allen and Pereira (2009). Thus, they replaced the 100 s m^{-1} value with a resistance parameter representing the minimum unstressed canopy resistance for apple trees. Following this adjustment, $K_{cb\ A\&P}$ was able to match the K_{cb} derived from eddy covariance (EC) measurements over the 12 orchards evaluated in the study. The earlier studies by Taylor et al. (2015, 2017) relative to citrus orchards and the Mobe et al. (2020) modification of F_r originated the current change in Eq. (5). Using a numerical search procedure focusing on F_r, not requiring to observe r_l and r_{typ}, it was possible to find F_r values for various crop stages (Allen and Pereira, 2009; Pereira et al. 2020). This empirical approach may however be tested when r_l could be measured.

A density coefficient K_d used in Eqs. (2) and (3) describes the increase in K_c with increases in the amount of vegetation. Where estimates of the fraction of ground surface covered by vegetation, f_c, are available, the K_d is estimated as (Allen and Pereira, 2009):

$$K_d = \min\left(1, \quad M_L f_{c\ eff}, \quad f_{c\ eff}^{\left(\frac{1}{1+h}\right)}\right) \tag{6}$$

where $f_{c\ eff}$ is the effective fraction of ground covered or shaded by vegetation [0.01–1] near solar noon, M_L is a multiplier on $f_{c\ eff}$ describing the effect of canopy density on shading and on maximum relative ET per fraction of ground shaded [1.0 – 2.0], and h is the mean vegetation height (m). The $f_{c\ eff}$ parameter is often observed as the shaded area near noon, between 11.00 and 15.00, or as the fraction of intercepted light, or the intercepted photosynthetic active radiation as reviewed by Pereira et al. (2020). Estimation of $f_{c\ eff}$ for row crops was described by FAO56 and for trees was provided by Allen and Pereira (2009). As with SIMS, remotely sensed vegetation indices, such as the normalized difference vegetation index (NDVI), can be used to estimate f_{c_eff} for agricultural crops (Johnson and Trout, 2012; Melton et al., 2012).

The M_L multiplier on $f_{c\ eff}$ in Eq. (6) imposes an upper limit on the relative magnitude of transpiration per unit of ground area as represented by $f_{c\ eff}$ (Allen et al. 1998). It is expected to usually range from 1.0 to 2.0, depending on the canopy density and thickness, and will have a low value when the canopy transparency to solar radiation is higher. The value for M_L should be modified to fit the specific vegetation and the respective crop stage as reported by Allen and Pereira (2009) and Pereira et al. (2020), as well as by several users as analyzed in Section 3.1.

As proposed by Allen and Pereira (2009), where LAI ($m^2\ m^{-2}$) can be observed or estimated, K_d can be alternatively estimated as:

$$K_d = \left(1 - \quad e^{[-0.7LAI]}\right) \tag{7}$$

where LAI is defined as the leaf area per area of ground surface averaged over a large area with consideration of only one side of 'green', healthy leaves active in vapor transfer and 0.7 is a common value for the light extinction coefficient (k_{ex}) used for annual crops, e.g. for maize (Ding et al., 2013; Jiang et al., 2014) and tomato (Zheng et al., 2013). However, the extinction coefficient changes with the crop type, crop density, LAI, and over the course of the growing season (e.g. Flenet et al., 1996; Zhang et al., 2014). A different exponent in Eq. (7) may be used if more appropriate information is available for the specific crop considered or a numerical search is performed, as reported for applications to shrubs ($k_{ex} = 0.46$, Li et al., 2015) and vineyards ($k_{ex} = 0.32$, Zhao et al., 2018).

3. Methods, data and parameterization of the A&P approach

3.1. Parameterization of the A&P approach

Requirements for parameterization of the A&P approach refer to the parameter F_r used in the calculation of $K_{cb\ full}$ (Eqs. (4) and (5)) and M_L used in the computation of the density coefficient K_d (Eq. (6)). Both K_d and $K_{cb\ full}$ are used when computing K_{cb} for any crop with or without active ground cover (Eqs. (2) and (3)). It has been observed (Pereira et al., 2020) that F_r plays a primary role, particularly for trees and vines.

The selection of F_r and M_L values is performed through a numerical search for the values of the parameters that make $K_{cb\ A\&P}$ to match the tabulated $K_{cb\ TAB}$ values. The $K_{cb\ A\&P}$ are those computed with the A&P approach and the $K_{cb\ TAB}$ are those tabulated by Pereira et al. (2021a, 2021b) and Rallo et al. (2021). The procedure consists of:

1. Selecting initial values for F_r and M_L.
2. Computing crop $K_{cb\ A\&P}$ for observed/known values of f_c and h and comparing the resulting $K_{cb\ A\&P}$ with the standard tabulated $K_{cb\ TAB}$ for the same crop.
3. Repeating the computations using an iterative numerical search where the initial F_r values are progressively changed, but are constrained by the limits of F_r (maximum is 1.0 and minimum is 0.25), and comparing the resulting $K_{cb\ A\&P}$ with $K_{cb\ TAB}$ values for the same crop, progressively decreasing the differences between both values until that difference is negligible.
4. When a F_r value is selected, the calculations are performed with the F_r value obtained in the previous calculation set, now changing M_L within its interval (1.0–2.0, however with a smaller minimum of 0.3 for the initial phase of annual crops), aiming at minimizing the difference between $K_{cb\ A\&P}$ with $K_{cb\ TAB}$.
5. If increasing or decreasing M_L leads to increases in the difference between $K_{cb\ A\&P}$ and $K_{cb\ TAB}$, then the last value for M_L is retained, as well as the F_r used in the calculation; however, if the difference decreases, a new run must be conducted until an M_L value is found that minimizes the difference. The value selected for F_r in Step 3 should remain fixed throughout Steps 4 and 5, but it may be required to apply again the numerical search focusing F_r.
6. The procedure ends when the difference $K_{cb\ A\&P}$-$K_{cb\ TAB}$ is minimized and values for both M_L and F_r are selected.

The target standard $K_{cb\ TAB}$ values for vegetable, field, tree and vine crops have been reviewed and updated in three papers of the current Special Issue (Pereira et al., 2021a, 2021b; Rallo et al., 2021). Ancillary data published in these papers, as well as f_c and h data published in Allen and Pereira (2009), were used to define the fraction of ground cover and crop height used with the current application of the A&P approach. To better represent actual conditions in production agriculture, f_c values obtained from a remote sensing (RS) survey described below in Section 3.2 and Table 5 were also considered. The f_c data have considerable variability for both the mid- and late-season, because f_c is strongly dependent on various facets of crop management. Nevertheless, it was possible to select for each crop a f_c value that is assumed to represent the most common f_c values at the initial, mid- and end-seasons, and to associate these values with crop heights to compute $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ for every vegetable, field, tree and vine crop when these data were not available in the referenced review papers. A precise approach to compute $f_{c\ eff}$ from raw f_c data, as proposed by Allen and Pereira (2009), could not be adopted because it was not possible to establish a well-defined sun angle. Thus, the raw f_c values were used as the best estimator of $f_{c\ eff}$. It is, however, assumed that in practice, in the field, ground and remote observations of f_c may be performed accurately as already reviewed in the companion paper (Pereira et al., 2020).

In the A&P approach, K_{cb} (Eqs. (2) and (3)) depends upon the definition of a $K_{c\ min}$ value, the estimation of $K_{cb\ full}$ (Eq. (4)) and the estimation of K_d (Eqs. (6) or (7)). For all annual crops, $K_{c\ min}$ was set to 0.15 following the recommendations of Allen et al. (1998) and Allen and Pereira (2009). For perennial crops, a value of $K_{c\ min} = 0.05$ was adopted for all orchard and vine crops to avoid the situation where computations of $K_{cb\ mid}$ could be larger than $K_{cb\ full}$.

K_d was estimated from M_L, $f_{c\ eff}$ and h (Eq. (6)). The parameter M_L is a multiplier on $f_{c\ eff}$ describing the effect of canopy density on shading and on maximum relative ET per fraction of ground shaded, considered to represent the transparency of the crop canopy to solar radiation; it is expected to usually range from 1.5 to 2.0 during mid-season, when f_c is high, and varies with the canopy density and thickness. In contrast, M_L is low when the canopy transparency to solar radiation is higher, for example, during the initial crop stages when f_c is small. Thus, low M_L value are assumed in the initial crop development stage while, in contrast,

Table 1
Values of the M_L parameter retrieved from literature for vegetable, field crops, and pastures.

Crop	*Crop stages*	M_L
Vegetable crops		
Artichoke	Mid-season	$2.0^{a,1}$
Broccoli	Mid-season	$2.0^{a,1}$
Lettuce	Mid-season	$2.0^{a,1}$
Cantaloupe melon	Mid-season	$2.0^{a,1}$
Onion	Development	$2.0^{b,2}$
	Mid-season	$2.0^{a,1,b,2}$
	Late-season	$2.0^{b,2}$
Strawberries	Mid-season	$2.0^{a,1}$
Tomato, on trellis	Mid-season	$2.0^{a,2,b,4}$
	End-season	$2.0^{b,4}$
Oil and fiber crops		
Canola	Development	$2.0^{b,8}$
	Mid-season	$2.0^{b,8}$
	Late-season	$2.0^{b,8}$
Sunflower	Development	$2.0^{b,9,10}$
	Mid-season	$2.0^{b,9,10}$
	Late-season	$2.0^{b,9,10}$
	End-season	$2.0^{b,9,10}$
Cotton	Mid-season	$1.5^{b,11}$
	Late-season	$1.5^{b,11}$
	End-season	$1.5^{b,11}$
Pasture		
Bermuda grass	Growth	$1.5^{b,19}$
	Cutting	$1.5^{b,19}$
Grain legumes		
Beans	Mid-season	$2.0^{a,1}$
Peas (industry)	Mid-season	$2.0^{b,5}$
	End-season	$2.0^{b,5}$
Soybean	Mid-season	$2.0^{b,6,7}$
	Late-season	$2.0^{b,6,7}$
	End-season	$2.0^{b,6,7}$
Cereals		
Barley	Mid-season	$2.0^{b,12}$
	Late-season	$2.0^{b,12}$
	End-season	$2.0^{b,12}$
Wheat (winter & spring)	Initial	$2.0^{b,13,14}$
	Development	$2.0^{b,13,14}$
	Mid-season	$2.0^{b,13,14}$
	Late-season	$2.0^{b,13,14}$
	End-season	$2.0^{b,13,14}$
Maize, grain	Mid-season	$2.0^{b,13\text{-}16}$
	Late-season	$2.0^{b,13\text{-}16}$
	End-season	$2.0^{b,13\text{-}16}$
Maize, grain, stressed	Mid-season	$1.5^{b,17,18}$
	Late-season	$1.5^{b,17,18}$
	End-season	$1.5^{b,17,18}$
Maize, silage	Mid-season	$2.0^{b,15}$
	Late-season	$2.0^{b,15}$
	End-season	$2.0^{b,15}$

Field data from: 1 - Grattan et al. (1998); 2 – López-Urrea et al. (2009a); 3 - Hanson and May (2006); 4 - Zheng et al. (2013); 5 - Paredes et al. (2017); 6 – Wei et al. (2015); 7 - Giménez et al. (2017); 8 - Sanchéz et al. (2015); 9 - López-Urrea et al. (2014); 10 - Miao et al. (2016); 11 - Cholpankulov et al. (2008); 12 – Pereira et al. (2015b); 13 - Zhao et al. (2013); 14 - Zhang et al. (2013); 15 - Martins et al. (2013); 16 - Paredes et al. (2014); 17 - Wu et al. (2015); 18 - Giménez et al. (2016); 19 - Paredes et al. (2018).
Sources: a – Allen and Pereira, 2009; b – Pereira et al., 2020.

a high M_L, close to 2.0, was assumed for the mid-season to increase the effects of f_c. In addition, a lower value was considered for the end-season, when f_c is generally decreased relative to the mid-season.

Values of M_L for annuals and perennials retrieved from the literature are presented in Tables 1 and 2, respectively. During the mid-season, M_L values ranged 1.5–2.0. Those values should depend on the leaf cutout type, insertion angle of the leaves, number of overlapping leaf layers (canopy architecture), which directly influence the crop canopy transparence to solar radiation. In this approach, crops with more vertical production training systems, or with less leaf density or with leaves of very small dimension, were consider having lower M_L values. Crops with leaves still active at harvest such as the evergreen were suggested to have $M_{L\ mid} = M_{L\ end}$. However, the effect of the M_L value on K_d depends upon the effect of the exponent $1/(1 + h)$ of $f_{c\ eff}$ in Eq. (6), which decreases when h increases. The use of diverse M_L values in the range from 1.5–2.0 do not influence K_d for crops with $h < 3.0$ and $f_c > 0.60$. Thus, for the considered vegetable crops, grain legumes, fiber, oil and sugar crops, and cereals, the values of M_L reported do not induce changes in K_d values for the mid- and end-season. In contrast, for the initial stage, where f_c is around 0.10, low M_L values were selected since using large M_L values would excessively increase K_d.

A smaller range of M_L values was adopted for orchards and vines; however, it was observed that the computation of K_d was highly determined by h in the exponent $1/(1 + h)$ of $f_{c\ eff}$. For perennials, the selected M_L values impacted K_d when $f_c < 0.60$, i.e., for, low and medium density and young orchards. This is the case of olive orchards, wine grapes and table grapes trained with a T trellis.

As referred before, the parameter F_r (≤ 1.0) applies an empirical downward adjustment if the vegetation exhibits more stomatal adjustment on transpiration than is typical of most agricultural crops, i.e., when the leaf resistance r_l is greater than the typical leaf resistance (Eq. (5)). Values of F_r used in previous studies are presented in Table 3 for vegetable and field crops, and in Table 4 for fruit trees and vines. Values for vegetable and field crops correspond to nearly pristine, non-stressed cropping conditions, i.e., when stomatal adjustment is small or not occurring and F_r values at mid-season are equal or close to 1.0. When crops (vegetable) are harvested green and the late-season is very short, stomatal adjustment is very limited or does not typically occur; thus, F_r values at the end-season are also equal or close to 1.0. In contrast, for field crops harvested dry or nearly dry, stomatal adjustment occurs during the late-season with the result that F_r decreases to near 0.30 by the end -season. Low F_r values, ranging from 0.20 to 0.45, were obtained for the end-season of crops drying in the field (Pereira et al., 2020). For silage, where stomatal adjustment is limited at harvesting, an intermediate value of $F_r = 0.65$ was used for the end season.

For trees and vines, the F_r assumed was almost always a value < 1.0 (Table 4). The variability of the reported values and the use of numerical search make it difficult to explain the results published in the literature. Results for wine grapes show that there is an influence of the training and management of the vineyard, as well as an influence of the varieties on stomatal adjustment, thus on F_r (Souza et al., 2005; Rodrigues et al., 2008; Costa et al., 2012). Results also show the influence of management, namely irrigation management, since higher F_r values refer to training with pergola trellis in case of wine grapes, and to overhead trellis systems in vineyards for table grapes, where supplemental irrigation is adopted. There is a great variability of F_r values for citrus and olives (Table 4), that is associated with irrigation management and crop varieties. F_r values are smaller for olives because these trees present an important stomatal adjustment in response to water stress (Fernández et al., 1997; Moriana et al., 2002; Tognetti et al., 2009; Fernández, 2014; Perez-Martin et al., 2014). In terms of management, the low F_r values reported indicate that applied irrigation in orchards used in the studies cited was far from the full satisfaction of crop water requirements despite the fact that production was high, i.e. the beneficial deficit irrigation in olives is large. Citrus also present strong stomatal adjustment to cope with water stress since a heavy beneficial deficit irrigation is often practiced (Obiremi and Oladele, 2001; Poggi et al., 2007; Ribeiro and Machado, 2007). In contrast, a small beneficial deficit irrigation is practiced with pome trees, stone fruit trees and nut trees, which is due to commonly managing irrigation using partial root drying, thus resulting a in smaller stomatal adjustment (O'Connell and Goodwin, 2007a, 2007b) and resulting F_r values close or equal to 1.0 through the mid-season (Table 4). It is important to note that temperate deciduous trees have a large daily variability in both K_{cb} and stomatal conductance (Villalobos et al., 2013). However, almond trees show stomatal adjustment during summer (Romero and Botía, 2006; Rouhi et al. 2007; Karimi et al., 2015; Espadafor et al., 2017), with F_r values of

Table 2
Values of the M_L parameter retrieved from literature for vines and fruit trees.

Crop	*Crop stages*	*M_L*
Wine grapes		
With bare soil (Vertical shoot positioned trellis)	Initial	$1.1^{b,1}$-1.5^{a}
	Development	$1.3^{b,1}$
	Mid-season	1.5^{a}-$1.8^{b,1}$
	End-season	1.5^{a}
With ground cover (Pergola trellis)	Initial	$1.5^{b,2}$
	Development	$1.5^{b,2}$
	Mid-season	$1.5^{b,2}$
	Late-season	$1.5^{b,2}$
With mulch (Vertical shoot positioned trellis)	Development	$1.5^{b,3}$
	Mid-season	$1.5^{b,3}$
	Late-season	$1.5^{b,3}$
Table grapes	Initial	1.5^{a}
	Mid-season	1.5^{a}
	End-season	1.5^{a}
Citrus	Initial	1.5^{a}
	Development	$1.2^{b,4}$-1.5^{a}
	Mid-season	$1.2^{b,4}$-$1.5^{a,c}$
	End-season	1.5^{a}
Olives		
Intensive, Hedgerow	Non-growing	$1.5^{b,d}$
	Initial	$1.5^{b,d,f}$
	Development	$1.5^{b,d}$
	Mid-season	$1.5^{b,d,f,g}$
	Late-season	$1.5^{b,d}$
	End-season	$1.5^{b,d,f}$
Rainfed	Mid-season	1.8^{e}
Apples	Initial	2.0^{a}
	Mid-season	1.5^{h}-2.0^{a}
	End-season	2.0^{a}
Pears	Initial	2.0^{a}
	Development	$1.5^{b,4}$-2.0^{a}
	Mid-season	$1.5^{b,4}$-2.0^{a}
	End-season	2.0^{a}
Almonds	Initial	1.5^{a}
	Mid-season	1.5^{a}
	End-season	1.5^{a}
Apricot	Initial	1.5^{a}
	Mid-season	1.5^{a}
	End-season	1.5^{a}
Cherry	Initial	2.0^{a}
	Mid-season	2.0^{a}
	End-season	2.0^{a}
Peach	Initial	1.5^{a}
	Mid-season	$1.4^{b,i}$-1.5^{a}
	End-season	1.5^{a}
Plums	Initial	1.5^{a}
	Mid-season	1.5^{a}
	End-season	1.5^{a}
Walnut	Initial	1.5^{a}
	Mid-season	1.5^{a}
	End-season	1.5^{a}

Field data from: 1 – López-Urrea et al., 2012, 2 – Fandiño et al., 2012, 3 - Cancela et al., 2015, 4 – Rosa (2019).
Sources: a – Allen and Pereira, 2009; b – Pereira et al., 2020; c – Taylor et al. 2015; d – Paço et al., 2019; e - Santos et al., 2012; f – Puppo et al., 2019; g – Conceição et al., 2017; h – Mobe et al., 2020; i – Paço et al., 2012.

< 1.0. During late season, leaves start yellowing, stomata close and leaf conductance decreases, resulting in lower values for F_r by the end-season (Table 4).

The complexity of abiotic factors and the differences among crop varieties or species referred above demonstrate that the parameterization of F_r can only be performed with a numerical search procedure; when this procedure cannot be applied, users may adopt the M_L and F_r values presented in this study, particularly those given in next sections for a variety of annual and perennial crops, which were obtained applying a numerical search procedure whose initial values of the searched parameters are those in Tables 1–4.

The estimation of the parameters M_L and F_r used in the A&P approach is subject to error. Pereira et al. (2020) evaluated crop coefficients for a wide range of crops calculated using the A&P approach driven with f_c and h against results from prior studies that derived K_c and K_{cb} values from field measured data with simultaneously observed f_c and h. Comparisons of K_{cb} values computed with the A&P method against results from these studies produced regression coefficients close to 1.0 and coefficients of determination ≥ 0.92, except for orchards. Expected errors and/or challenges with orchards are higher due to effects of pruning, training and crop varieties.

3.2. *Single and basal crop coefficients*

The numerical search to determine M_L and F_r values using the A&P approach described in Section 3.1 focused on evaluation of K_{cb} values only. Inclusion of corresponding K_c values in Tables 6–10 is also valuable for practical use, and the approach used to calculate the corresponding K_c values for each crop type is described below.

For vegetable and field crops, $K_{c\ mid}$ and $K_{c\ end}$ values were determined from $K_{cb\ mid}$ and $K_{cb\ end}$ as performed in FAO56 (Allen et al., 1998). $K_{c\ mid}$ values were calculated by adding 0.05 to $K_{cb\ mid}$ values, while $K_{c\ end}$ was obtained by adding 0.05 or 0.10 to $K_{cb\ end}$ values, with the additive value of 0.05 for crops harvested green, thus also following the estimation approaches used by Pereira et al. (2021a, 2021b) when computing $K_{c\ end}$ from the $K_{cb\ end}$ values. For trees and vines, $K_{c\ mid}$ was also computed when adding 0.05 to $K_{cb\ mid}$ while $K_{c\ end}$ was obtained by adding a specific value, in the range 0.05–0.40, to $K_{cb\ end}$. This simple procedure used in FAO56 (Allen et al., 1998) can be modified when the user knows the expected behavior of the crop at the end of the season.

As described by Pereira et al. (2021a, 2021b) and Rallo et al. (2021), $K_{c\ ini}$ values were not tabulated in those studies focused on updating K_c values for vegetable and field crops, and tree and vine crops. During the initial crop stage of annuals, the ground cover is very small, as well as h. As a result, the variability of $K_{c\ ini}$ relates to soil evaporation and factors controlling it, such as the frequency of wettings by rainfall, the frequency and depth of irrigation applications, the fraction of soil wetted by irrigation (which relates with the irrigation method) and the presence of plastic mulches, plastic tunnels, organic mulching, or soil residue management. With such a variety of influencing factors, it is not possible to tabulate values for $K_{c\ ini}$ and it was not possible to derive related values from the reviewed papers. For deciduous trees and vines, the initial phase also has small f_c, values, and the variability of $K_{c\ ini}$ is similar to that described for annuals. In contrast, for evergreen crops f_c is much higher and the role of soil evaporation is reduced; however, there is little information on $K_{c\ ini}$ reported for those tree crops.

The rice crop is an exception because when flooded, or when the soil is kept close to saturation, $K_{c\ ini}$ does not vary as it does for other cereal crops. Therefore, the approach used by Pereira et al. (2021b) was adopted herein. As a result, differences between $K_{c\ ini}$ and $K_{cb\ ini}$ values for rice are the same as those determined by Pereira et al. (2021b).

FAO56 provided indicative $K_{c\ ini}$ values corresponding to the most common conditions, i.e., a standard sub-humid climate where minimum relative air humidity equals 45% and wind speed is of 2 m s^{-1}, surface irrigation was used, and the soil was maintained bare. The FAO56 tabulated $K_{c\ ini}$ and $K_{cb\ ini}$ values were provided as indicative values having large errors than tabulated standard $K_{c\ mid}$ and $K_{c\ end}$ values as well as the $K_{cb\ mid}$ and $K_{cb\ end}$. Therefore, due to the variability of conditions determining crop ET during the initial crop period, we did not include $K_{c\ ini}$ values. Instead, the computational procedures proposed in FAO56 (Allen et al., 1998) and by Allen et al. (2005b) are recommended. Simple models can be used for that purpose.

For the dual K_c approach, the value $K_{cb\ ini} = 0.15$ is the recommended default value for annuals since it represents average conditions from bare soil with fraction of ground cover $f_c \leq 0.10$. It is assumed to include ‘‘diffusive’’ or residual evaporation from soil for potentially long periods following a wetting (Allen et al., 2005a). However, under dry conditions with long periods between wettings, or during the

Table 3

Values of the F_r parameter retrieved from literature for vegetable, field crops, and pastures.

Crop	*Crop stages*	F_r
Vegetable crops		
Artichoke	Mid-season	1.00[a,1]
Broccoli	Mid-season	1.00[a,1]
Lettuce	Mid-season	1.00[a,1]
Cantaloupe melon	Mid-season	1.00[a,1]
Onion	Development	1.00[b,2]
	Mid-season	1.00[a,1,b,2]
	Late-season	1.00[b,2]
Strawberries	Mid-season	1.00[a,1]
Tomato, on trellis	Mid-season	1.00[a,2,b,4]
	End-season	0.80[b,4]
Oil and fiber crops		
Canola	Development	0.30-1.00[b,8]
	Mid-season	1.00[b,8]
	Late-season	1.00-0.20[b,8]
Sunflower	Development	0.30-0.90[b,9,10]
	Mid-season	1.00[b,9,10]
	Late-season	1.00-0.30[b,9,10]
	End-season	0.30[b,9,10]
Cotton	Mid-season	1.00[b,11]
	Late-season	1.00-0.35[b,11]
	End-season	0.35[b,11]
Pasture		
Bermuda grass	Growth	1.00[b,19]
	Cutting	1.00[b,19]
Grain legumes		
Beans	Mid-season	1.00[a,1]
Peas (industry)	Mid-season	1.00[b,5]
	End-season	1.00[b,5]
Soybean	Mid-season	1.00[b,6,7]
	Late-season	1.00-0.30[b,6,7]
	End-season	0.30[b,6,7]
Cereals		
Barley	Mid-season	1.00[b,12]
	Late-season	1.00-0.30[b,12]
	End-season	0.30[b,12]
Maize, grain	Mid-season	1.00[b,13-16]
	Late-season	0.30-1.00[b,13-16]
	End-season	0.30[1]-0.45[b,3,13-16]
Maize, stressed	Mid-season	0.90[b,17,18]
	Late-season	0.90-0.27[b,17,18]
	End-season	0.27[b,1,17,18]
Maize, silage	Mid-season	1.00[b,15]
	Late-season	1.00-0.65[b,15]
	End-season	0.65[b,15]
Wheat (winter & spring)	Development	0.80-1.00[b,13,14]
	Mid-season	1.00[b,13,14]
	Late-season	1.00-0.30[b,13,14]
	End-season	0.30[b,13,14]

Field data from: 1 - Grattan et al. (1998); 2 – López-Urrea et al. (2009); 3 - Hanson and May (2006); 4 - Zheng et al. (2013); 5 - Paredes et al. (2017); 6 – Wei et al. (2015); 7 - Giménez et al. (2017); 8 - Sanchéz et al. (2015); 9 - López-Urrea et al. (2014); 10 - Miao et al. (2016); 11 - Cholpankulov et al. (2008); 12 – Pereira et al. (2015b); 13 - Zhao et al. (2013); 14 - Zhang et al. (2013); 15 - Martins et al. (2013); 16 - Paredes et al. (2014); 17 - Wu et al. (2015a); 18 - Giménez et al. (2016); 19 – Paredes et al. (2018).

Sources: a – Allen and Pereira (2009). b – Pereira et al. (2020).

Table 4

Values of the F_r parameter retrieved from literature for fruit trees and vines.

Crop	*Crop stages*	F_r
Wine grapes		
With bare soil	Initial	0.65[b,1,a]
(Vertical shoot positioned trellis)	Development	0.65[b,1]
	Mid-season	0.65[a,b,1]
	End-season	0.43[a]
With ground cover	Initial	0.90[b,2]
(Pergola trellis)	Development	0.90[b,2]
	Mid-season	0.90[b,2]
	Late-season	0.85[b,2]
With mulch	Development	0.20-0.70[b,3]
(Vertical shoot positioned trellis)	Mid-season	0.65-0.70[b,3]
	Late-season	0.50-0.53[b,3]
Table grapes	Initial	0.95[a]
(Overhead trellis)	Mid-season	0.95[a]
	End-season	0.51[a]
Citrus	Initial	0.71[a]
	Development	0.65-0.75[b,4]
	Mid-season	0.71[a]-.75[b,4]
	End-season	0.94[a]
Olives	Non-growing	0.49[d]-0.55[b]
(Intensive, hedgerow)	Initial	0.32[f]-0.55[b]
	Development	0.55[b]-0.65[b]
	Mid-season	0.43[f]-0.65[b]
	Late-season	0.55[b]-0.65[b]
	End-season	0.35[f]-0.53[d]
Olives (Rainfed)	Mid-season	0.67[e]
Apples	Initial	0.95[a]
	Mid-season	0.95[a]
	End-season	0.75[a]
Pears	Initial	0.95[a]
	Development	0.95[b,4]
	Mid-season	0.95[a,b,4]
	End-season	0.75[a]
Almonds	Initial	0.81[a]
	Mid-season	0.81[a]
	End-season	0.81[a]
Apricot	Initial	1.00[a]
	Mid-season	1.00[a]
	End-season	0.71[a]
Cherry	Initial	0.95[a]
	Mid-season	0.95[a]
	End-season	0.75[a]
Peach	Initial	1.00[a]
	Mid-season	1.00[a,b,i]
	End-season	0.71[a]
Plums	Initial	1.00[a]
	Mid-season	1.00[a]
	End-season	0.71[a]
Walnut	Initial	0.90[a]
	Mid-season	0.90[a]
	End-season	0.52[a]

Field data from: 1 – López-Urrea et al., 2012, 2 – Fandiño et al., 2012, 3 - Cancela et al., 2015, 4 – Rosa, 2019.

Sources: a – Allen and Pereira, 2009; b – Pereira et al., 2020; c – Taylor et al. 2015; d – Paço et al., 2019; e – Santos et al., 2012; f – Puppo et al., 2019; g – Conceição et al., 2017; h – Mobe et al., 2020; i – Paço et al., 2012.

non-growing season, $K_{cb\ ini}$ can be set much lower, even close to 0. In contrast, the evaporation coefficient K_e should be computed taking into consideration all the factors affecting soil evaporation as detailed by Allen et al. (2005a). Nevertheless, the values of $K_{c\ ini}$ tabulated in FAO56, in Allen and Pereira (2009), and in Jensen and Allen (2016) are recommended indicative values for trees and vines.

3.3. *Fraction of ground cover from remote sensing in California*

When combined with information on crop height, information on expected maximum f_c values can be useful in calculating maximum expected K_{cb} values for a range of crops using the A&P approach. Determination of a representative, average crop height, h, is typically less difficult than estimation of average f_c at field scales. To provide a characterization of typical, expected maximum f_c values for a range of crops, the Satellite Irrigation Management Support (SIMS, Melton et al., 2012, 2020) framework conducted an analysis using Landsat satellite data, combined with field boundary and crop type information for all irrigated lands in California obtained from the California Agricultural Commissioners and Sealers Association (CACASA) database for 2016. SIMS combines satellite-based measurements of NDVI and f_c with the A&P approach and a soil water balance model to provide support for mapping of crop coefficients and crop evapotranspiration across the western U.S. SIMS was developed to increase access to satellite-derived ET data by agricultural producers to inform irrigation management. California was selected as the site for this analysis since more than 400

Table 5
75th and 95th percentiles of the fraction of ground cover (f_c) surveyed by SIMS in California in 2016 using Landsat data.

Crop Type	n*	f_c	
		75th	95th
Vegetables and field crops			
Alfalfa, spring	26094	0.92	0.94
Alfalfa, summer	26091	0.89	0.93
Asparagus	494	0.90	0.94
Barley	1820	0.89	0.94
Blueberries	498	0.73	0.83
Broccoli	1237	0.88	0.93
Cabbage	269	0.82	0.90
Caneberries	1448	0.73	0.86
Cantaloupe	407	0.86	0.91
Carrot	1369	0.87	0.92
Cauliflower	152	0.84	0.90
Celery	65	0.82	0.89
Chickpea	78	0.89	0.97
Clover/Wildflowers	743	0.86	0.91
Corn	17654	0.88	0.92
Cotton	6560	0.87	0.90
Cucumber	561	0.81	0.90
Dry Bean	2198	0.86	0.93
Eggplant	260	0.69	0.84
Garlic	348	0.87	0.94
Herbs	1031	0.85	0.93
Honeydew Melon	857	0.84	0.90
Lettuce	775	0.85	0.90
Mint	59	0.97	0.99
Oat	6136	0.91	0.95
Onion	1082	0.86	0.92
Hay/Non-Alfalfa	4312	0.89	0.94
Pea	247	0.85	0.97
Pepper	211	0.86	0.94
Potato	1531	0.88	0.96
Pumpkin	443	0.83	0.91
Radish	78	0.74	0.88
Rice	9843	0.97	0.99
Rye	1009	0.92	0.96
Safflower	1016	0.90	0.95
Small Grains	128	0.79	0.88
Sod/Grass Seed	1035	0.84	0.93
Spring Wheat	11704	0.90	0.95
Squash	983	0.80	0.90
Strawberries	4826	0.81	0.91
Sudan grass	770	0.86	0.91
Sugar beets	420	0.86	0.89
Sunflower	990	0.89	0.93
Tomatoes	6071	0.88	0.93
Triticale	174	0.88	0.94
Vetch	67	0.79	0.89
Trees and vines			
Almonds	23493	0.77	0.83
Apples	1714	0.80	0.86
Apricots	844	0.76	0.83
Cherries	2729	0.83	0.88
Christmas Trees	359	0.76	0.84
Citrus	9307	0.74	0.84
Grapes	42445	0.72	0.82
Nectarines	2968	0.77	0.83
Oranges	10483	0.71	0.80
Other Tree Crops	578	0.83	0.89
Other Tree Fruit	10309	0.74	0.85
Peaches	6071	0.77	0.84
Pears	792	0.83	0.88
Pecans	234	0.82	0.89
Pistachios	3579	0.68	0.77
Plums*	3030	0.74	0.82
Pomegranates	948	0.63	0.77
Prunes	2419	0.77	0.85
Walnuts	13632	0.86	0.91

* n – number of surveyed fields

different crops are produced in the state, and detailed field boundaries and crop type information reported by famers were available for the state in 2016. While the SIMS framework was used to support the satellite data processing and computations, only the algorithms for calculation of f_c from NDVI were used for this analysis.

Atmospherically corrected surface reflectance data for 2016 for all of California were obtained from the collection of Landsat data on Google Earth Engine (Gorelick et al., 2017), including USGS Landsat Collection 1 for the Enhanced Thematic Mapper (ETM+) on Landsat 7 and the Operational Land Imager (OLI) on Landsat 8. Normalized Difference Vegetation Index (NDVI) data were first calculated for each scene from the Landsat surface reflectances using Earth Engine (Gorelick et al., 2017), with a total of more than 1,900 Landsat scenes processed for this analysis. Next, f_c was calculated from NDVI using Eq. (8) following Johnson and Trout (2012):

$$f_c = 1.26 * \mathrm{NDVI} - 0.18 \tag{8}$$

Johnson and Trout (2012) and Trout et al. (2008) found robust relationships between NDVI and f_c across a range of different crop types and canopy architectures. Eq. (8) was derived based on in-situ f_c measurements of 49 commercial fields and 18 major crop types (row crops, grains, orchard, vineyard) of varying maturity that were made on 11 Landsat overpass dates in the San Joaquin Valley of California from April to October. The studies found a strong linear relationship between NDVI and f_c ($r^2 = 0.96$, RMSE = 0.06).

A shapefile containing the 2016 field boundaries and crop type information for more than 200,000 individual irrigated agricultural fields was used to define field boundaries and the crop type for each field. The crop type information was reported by farmers during calendar year 2016 to the agricultural commissioners in each county in California as part of the pesticide use reporting process, and composited into a geospatial database by CACASA. For each field and each Landsat scene, the field average f_c value was calculated using all cloud-free pixels contained within each field boundary. Next, for each field, the maximum annual f_c value was selected from the satellite overpass dates that spanned the growing season for each crop type.

For most annual crops, vineyards and tree crops, the maximum values from the period between May 1 and October 31 were used. These dates were selected to correspond with the timing of peak canopy cover for a range of crops, and also to minimize the influence of cover crops for vineyards and tree crops, since it is not possible to discriminate between the crop canopy and the cover crop at the spatial resolution of Landsat (30 m x 30 m). However, cover crops that may be present in the interrow for vineyards and orchards are typically mowed and rapidly senescing in California in May, well before the vine and tree canopies reach maximum f_c in mature orchards and vineyards. As such, cover crops were expected to have a minimal influence on the maximum annual f_c value calculated for each field. In cases where an irrigated cover crop persists throughout the summer, users would need to employ Eq. (3) to account separately for the K_{cb} for the cover crop and the K_{cb} for the vine or tree. For alfalfa and cereal crops, we selected the maximum values from the period between January 1 and October 31. We then collated the data from all fields by crop type and selected both the 75th and 95th percentile values for each crop type. We selected the 75th percentile value to represent an expected maximum f_c value for a typical, well-irrigated crop grown under near ideal conditions but with some heterogeneity across the field due to variability in soil conditions, distribution uniformity of irrigation, or the presence of pests or pathogens in isolated regions in the field. We selected the 95th percentile value to represent an expected upper limit on f_c for a well-irrigated crop grown under ideal conditions and with very little heterogeneity across the field. For perennial crops, the maximum f_c values are also representative of mature orchards and vineyards. Any crop types with fewer than 50 fields sampled were excluded from the analysis.

Table 5 reports the 75th and 95th percentile of the maximum annual f_c values ($f_{c\ 75}$ and $f_{c\ 95}$) measured using satellite data over California for each annual crop type. The number of fields (n) of each crop type included in the analysis and used to calculate $f_{c\ 75}$ and $f_{c\ 95}$ are also included in Table 1. These f_c values can be combined with direct measurements of h for specific fields, or typical maximum h values listed in Tables 2–4 below to support assessment of typical maximum K_{cb} values using the A&P approach. These values represent expected maximum values under ideal conditions, and lower K_{cb} values would be expected for immature orchard and vineyard crops, deficit irrigation, nutrient deficiencies, or due to the presence of plant pests and pathogens.

In the current study, f_c values between the tabulated $f_{c\ 75}$ and $f_{c\ 95}$ were used in combination with the $f_{c\ max}$ values tabulated in Pereira et al. (2021a, 2021b) and Rallo et al. (2021) relative to K_{cb} and K_c for vegetable, field crops and perennials, respectively, to estimate the indicative f_c values used to compute K_{cb} and K_c for these crops as presented in Section 4.

3.4. *Procedures used in computations*

Predicted values for K_{cb} and K_c computed with the A&P approach, as well as the computational parameters used, are presented and discussed in the following Sections and Tables 6–8 relative to vegetable crops, Tables 9–11 for field crops and Tables 12–15 relative to tree and vine crops. Computations, using the equations described in Section 2, were performed following the same approach for all crops. In particular:

1) The calculations assume the standard sub-humid climate adopted in FAO56, i.e., average minimum relative humidity $RH_{min} = 45\%$ and wind speed $u_2 = 2$ m s^{-1} which results in an upper bound of $K_{cb\ full} = 1.20$ (Eq. (4)).
2) The $f_{c\ eff}$ values for the mid-season resulted from combining observed f_c values collected from the literature, tabulated by Pereira et al. (2021a, 2021b) and Rallo et al. (2021), with the 75th and 95th percentile ($f_{c\ 75}$ and $f_{c\ 95}$) of remotely sensed f_c values tabulated in Table 5. Unreasonable values were discarded; generally, the values considered are intermediate between $f_{c\ 75}$ and $f_{c\ 95}$.
    a) For crops not having f_c values included in the above referred Tables, various additional sources were used:
        Artichoke - Grattan et al. (1998) and Visconti et al. (2014)
        Beans, dry - Grattan et al. (1998) and Kim et al. (2020)
        Beets, table - Gimenez et al. (2002) and Reid et al. (2020)
        Brussels sprout - Jones (1972) and Everaarts et al. (1998)
        Castor bean - Li et al. (2011) and Sadras et al. (2016)
        Flax and Linseed - Casa et al. (2000) and Kar et al. (2007)
        Lentils - Ayaz et al. (2004) and McKenzie and Andrews (2010)
        Millet - Corlett et al. (1992) and Bello and Walker (2016)
        Mustard - Kar et al. (2007) and Gupta et al. (2017)
        Okra - Agba et al. (2011) and Konyeha and Alatise (2013)
        Spinach - Gimenez et al. (2002) and Nomura et al. (2020)
    b) f_c values were not available for parsnip, rutabaga and turnip; thus, we assumed mid-season $f_{c\ max}$ similar respectively to radish and to table beet for the latter two.
    c) For crops that are not object of any study referring to f_c or LAI observations, the f_c values adopted herein, considering the personal knowledge of the authors, are assumed from comparing with similar crops. For example, values for rye and oats were selected based on comparison against values for wheat.
3) Crop heights were defined from those tabulated by Pereira et al. (2021a, 2021b) and Rallo et al. (2021), which resulted from combining observed values reported in the literature and referenced by the authors, with h values tabulated in FAO56.
4) K_c and K_{cb} values were tabulated for vegetable and tree and vine crops assuming they are irrigated with drip irrigation with pipes and wetted area shadowed by the crop, thus reducing evaporation of applied irrigation water. For the field crops, well managed sprinkler irrigation was considered to be the default irrigation type.
5) Cropping is assumed to be practiced with bare soil. Special practices such as the use of plastic films and organic mulches or small plastic tunnels were not considered due to the lack of information on the reductions in K_c associated with these practices. Brief notes on their effects on K_c were recently provided by Jovanovic et al. (2020).

Relative to the initial crop stage, there was a lack of base information for appropriate parameterization for tree and vine crops; therefore, related $K_{c\ ini}$ values were not computed. For the annual crops, the main assumptions are discussed in Section 3.2. The following may be relevant:

1) The $f_{c\ eff}$ values for the initial period were assumed equal to 0.05 for all annual crops since, by definition in FAO56 (Allen et al., 1998), f_c varies from 0 up to 0.10 during that stage.
2) The parameter M_L was set to 0.30 for sown crops and 0.40 for transplanted crops; these low M_L values correspond to a very open canopy, as occurs for small f_c values.
3) Because the young plants are assumed not to require stomatal adjustment at this stage, the value $F_r = 1.0$ was assumed for all annual crops.

These assumptions when considering the initial crop stage resulted in the common value of $K_{cb\ full} = 1.0$ and $K_{cb\ ini} = 0.15$, the latter in agreement with Allen et al. (1998, 2005a).

4. Results

4.1. *Vegetable crops*

For roots, tuber, bulb and stem crops (Table 6), it has been generally assumed that h does not change from the mid-season to the end-season, since crop senescence generally occurs over a short time period. However, this assumption is not true for various crops. The case of asparagus is likely the most evident because harvesting is performed when the crop reduces to the asparagus spears, which are much lower than the mid-season vegetation, in spite of the subsequent regrowth of the vegetative part of the crop after harvesting. Other exceptions include crops that have a longer late-season to allow the crop to dry out before harvesting. This is the case for garlic, onion, and long season potato.

$f_{c\ eff}$ is assumed not to change from mid- to end-season for crops having a very short late-season: carrots, celery, parsnip, radish and turnip. A small decrease in $f_{c\ eff}$ was considered for other crops having a short senescence period: beets for table, rutabaga and sweet potato. Changes in f_c and h may also be made by users based on their observations and the way in which the crop is managed, i.e. allowing for a longer or shorter senescence period.

The M_L values for both the mid- and end-season are all in the range of 1.5–2.0 because that value does not influence the K_d results (Eq. (6)). In contrast, the M_L value influences the computation of K_d relative to the initial crop stage, as already discussed in Section 3.4.

The F_r values selected for the mid-season were all very close or equal to 1.0 (Table 6), thus indicating that, likely, there was no stomatal adjustment since the roots, tuber, bulb and stem vegetable crops were considered not to be stressed and cropped under pristine conditions, and because values used are based on computation of the standard $K_{cb\ TAB}$. The numerical search procedure produced $F_r = 1.0$ for most of crops and $F_r < 1.0$ but close to 1.0 for asparagus, carrots, celery, garlic, radish, rutabaga and turnip.

All the end-season, values for F_r (obtained through a numerical search procedure) are all decreased relative to the mid-season values. When the late-season is short and the product goes to the table with its typical colour and tenderness, the end-season F_r is close to the mid-season value, as for table beets, carrots, celery, green and seed onions, parsnip, radish, rutabaga, and turnip. F_r decreases substantially for asparagus because only the harvestable spears are present at harvesting. A much lower F_r value results for the crops that have a long late-season

Table 6
Indicative K_{cb} and K_c for roots, tuber, bulb and stem vegetable crops and related A&P computation parameters obtained with a numerical search procedure.

Crop	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c		Standard K_{cb} and K_c from Pereira et al. (2021a)	
		h (m)	$f_{c\ eff}$	M_L	F_r	K_{cb}	K_c	K_{cb}	K_c
Asparagus (*Asparagus officinalis*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.80	0.70	2.00	0.93	0.90	0.95	0.90	0.95
	End (harvest)	0.25	0.20	2.00	0.68	0.20	0.30	0.20	0.30
Beets (table) (*Beta vulgaris*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.40	0.85	2.00	0.97	0.95	1.05	0.95	1.05
	End	0.40	0.80	2.00	0.95	0.90	1.00	0.90	1.00
Carrots (*Daucus carota*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.30	0.90	2.00	0.96	0.95	1.05	0.95	1.05
	End	0.30	0.90	2.00	0.86	0.85	0.95	0.85	0.95
Celery (*Apium graveolens*)	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.60	0.80	2.00	0.95	0.95	1.05	0.95	1.05
	End	0.60	0.80	2.00	0.88	0.90	1.00	0.90	1.00
Garlic (*Allium sativum*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.50	0.85	2.00	0.95	0.95	1.05	0.95	1.05
	End	0.45	0.80	2.00	0.62	0.60	0.70	0.60	0.70
Onion (*Allium cepa*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
Dry	Mid	0.45	0.75	2.00	1.00	0.95	1.05	0.95	1.05
	End	0.40	0.70	2.00	0.62	0.55	0.65	0.55	0.65
Green	Mid	0.45	0.75	2.00	1.00	0.95	1.05	0.95	1.05
	End	0.40	0.75	2.00	0.90	0.80	0.90	0.80	0.90
Seed	Mid	0.65	0.75	2.00	1.00	0.95	1.05	0.95	1.05
	End	0.65	0.60	2.00	0.85	0.70	0.80	0.70	0.80
Parsnip (*Pastinaca sativa*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.40	0.80	2.00	1.00	0.95	1.05	0.95	1.05
	End	0.40	0.80	2.00	0.95	0.90	1.00	0.90	1.00
Potato (*Solanum tuberosum*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.60	0.90	2.00	1.00	1.10	1.15	1.10	1.15
	End, short season	0.55	0.55	2.00	0.80	0.65	0.75	0.65	0.75
	End, long season	0.45	0.35	2.00	0.52	0.35	0.40	0.35	0.40
Radish (*Raphanus sativus*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.30	0.80	2.00	0.93	0.85	0.90	0.85	0.90
	End	0.30	0.80	2.00	0.81	0.75	0.85	0.75	0.85
Rutabaga (*Brassica napobrassica*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.60	0.85	2.00	0.97	1.00	1.10	1.00	1.10
	End	0.60	0.85	2.00	0.90	0.90	1.00	0.90	1.00
Sweet potato (*Ipomoea batatas*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.40	0.95	2.00	1.00	1.05	1.10	1.05	1.10
	End	0.40	0.85	2.00	0.50	0.50	0.60	0.50	0.60
Turnip (*Brassica rapa* var. *rapa*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.60	0.85	2.00	0.97	1.00	1.10	1.00	1.10
	End	0.60	0.85	2.00	0.88	0.90	1.00	0.90	1.00

Table 7
Indicative K_{cb} and K_c leaf and flower vegetable crops and related A&P computation parameters obtained with a numerical search procedure.

Crop	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c		Standard K_{cb} and K_c from Pereira et al. (2021a)	
		h (m)	$f_{c\ eff}$	M_L	F_r	K_{cb}	K_c	K_{cb}	K_c
Artichoke (*Cynara scolymus)* (1st year)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.80	0.75	2.00	0.94	0.95	1.00	0.95	1.00
	End	0.80	0.75	2.00	0.89	0.90	0.95	0.90	0.95
Broccoli (*Brassica oleracea* var. *italica)*	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.60	0.90	2.00	0.94	1.00	1.10	1.00	1.10
	End	0.60	0.90	2.00	0.94	1.00	1.10	1.00	1.10
Brussels sprout (*Brassica oleracea* var. *gemmifera*)	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.75	0.90	2.00	0.87	0.95	1.05	0.95	1.05
	End	0.75	0.90	2.00	0.87	0.95	1.05	0.95	1.05
Cabbage (*Brassica oleracea* var. *capitata)*	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.40	0.85	2.00	0.97	0.95	1.05	0.95	1.05
	End	0.40	0.85	2.00	0.92	0.90	1.00	0.90	1.00
Cauliflower (*Brassica oleracea* var. *botrytis*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.40	0.85	2.00	0.97	0.95	1.05	0.95	1.05
	End	0.40	0.85	2.00	0.92	0.90	1.00	0.90	1.00
Lettuce (*Lactuca sativa*)	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.35	0.80	2.00	1.00	0.93	0.98	0.95	1.00
	End	0.35	0.80	2.00	1.00	0.93	0.98	0.95	1.00
Spinach (*Spinacia oleracea*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.35	0.80	2.00	0.97	0.90	1.00	0.90	1.00
	End	0.35	0.80	2.00	0.97	0.90	1.00	0.90	1.00

Table 8
Indicative K_{cb} and K_c for fruit and pod vegetable crops and related A&P computation parameters obtained with a numerical search procedure.

Crop	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c		Standard K_{cb} and K_c from Pereira et al. (2021a)	
		h (m)	$f_{c\ eff}$	M_L	F_r	K_{cb}	K_c	K_{cb}	K_c
Bell pepper (*Capsicum annuum)*	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.70	0.90	2.00	1.00	1.03	1.08	1.05	1.10
	End	0.70	0.85	2.00	0.95	1.00	1.05	1.00	1.05
Chilli pepper (*Capsicum annuum*)	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.75	0.85	2.00	0.94	1.00	1.10	1.00	1.10
	End	0.75	0.80	2.00	0.72	0.75	0.80	0.75	0.80
Cucumber (*Cucumis sativus)*	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.30	0.90	2.00	1.00	0.99	1.04	1.00	1.05
	End, market	0.30	0.90	2.00	0.73	0.70	0.80	0.70	0.80
	End, processing	0.30	0.85	2.00	0.81	0.80	0.90	0.80	0.90
Eggplant (*Solanum melongena)*	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.80	0.75	2.00	1.00	1.00	1.05	1.00	1.05
	End	0.80	0.70	2.00	0.92	0.90	1.00	0.90	1.00
Melon (*Cucumis melo*)	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.30	0.95	2.00	0.93	0.95	1.05	0.95	1.05
	End	0.30	0.85	2.00	0.78	0.75	0.85	0.75	0.85
Melon, cantaloupe (*Cucumis melo*)	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.30	0.90	2.00	0.96	0.95	1.00	0.95	1.00
	End	0.30	0.85	2.00	0.73	0.70	0.80	0.70	0.80
Okra, green (*Abelmoschus esculentus)*	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.90	0.90	2.00	0.75	0.85	0.95	0.85	0.95
	End	0.90	0.85	2.00	0.73	0.80	0.90	0.80	0.90
Pumpkin (*Cucurbita pepo)*	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.40	0.85	2.00	0.97	0.95	1.00	0.95	1.00
	End	0.40	0.80	2.00	0.74	0.70	0.80	0.70	0.80
Squash, Zucchini (*Cucurbita pepo)*	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.30	0.90	2.00	0.96	0.95	1.00	0.95	1.00
	End	0.30	0.85	2.00	0.68	0.65	0.75	0.65	0.75
Strawberries (*Fragaria × ananassa)*	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.30	0.75	2.00	0.81	0.75	0.80	0.75	0.80
	End	0.30	0.70	2.00	0.75	0.65	0.75	0.65	0.75
Tomato (*Solanum lycopersicum)*	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.70	0.90	2.00	0.97	1.05	1.10	1.05	1.10
	End, processing	0.70	0.80	2.00	0.83	0.85	0.90	0.85	0.90
Watermelon (*Citrulus lanatus*)	Initial	0.10	0.05	0.40	1.00	0.15	–	0.15	–
	Mid	0.40	0.80	2.00	1.00	0.94	1.04	0.95	1.05
	End	0.40	0.75	2.00	0.65	0.60	0.70	0.60	0.70

and senesce before harvesting. This is typically the case for garlic, dry onion, long late season potato and sweet potato. Therefore, users should select the end season $F_r < 1.0$ for these crops, taking into consideration the possible occurrence of stress, which requires stomatal adjustment, and the duration of the late season, which is associated with crop senescence.

The computed values resulting from the A&P application show $K_{cb\ mid\ A\&P}$ and $K_{cb\ end\ A\&P}$ values equal to the tabulated ones reported by Pereira et al. (2021a). This is expected since the numerical search aimed at matching $K_{cb\ A\&P}$ with the $K_{cb\ TAB}$ values. The K_c values were estimated as $K_{c\ mid} = K_{cb\ mid} + 0.05$ for a few crops (asparagus, potato, radish, sweet potato and turnip), otherwise the additional term was 0.10. For $K_{c\ end}$, generally, it differed from $K_{cb\ end}$ by 0.10. Such differences are similar to those relative for roots, tuber, bulb and stem vegetable crops tabulated by Pereira et al. (2021a) based upon observed values published in the literature.

The A&P computation parameters used for leaves and flowers vegetable crops (Table 7) behave similarly to the roots, tuber, bulb and stem crops. M_L values were also 2.0 since the value for M_L did not influence the K_d value. In contrast, low values were used for the initial crop stage as reported earlier. It was assumed that these crops were not stressed because the related $K_{cb\ TAB}$ values are supposed to represent standard, near to the -pristine crop conditions. However, the numerical search procedure led to F_r values slightly below 1.0 with the exception of lettuce. Since the late-season is very short for these crops, the result was that $K_{cb\ end\ A\&P}$ values were close to $K_{cb\ mid\ A\&P}$ values, generally differing by 0.10 or 0.05, in agreement with the values tabulated by Pereira et al. (2021a). $K_{c\ mid\ A\&P}$ and $K_{c\ end\ A\&P}$ were computed from $K_{cb\ mid\ A\&P}$ and $K_{cb\ end\ A\&P}$ respectively, assuming a difference of 0.10 for all crops except artichoke and lettuce where that difference is 0.05, following the assumptions made in FAO56 and Pereira et al. (2021a). Moreover, it was observed that A&P computed K_c and K_{cb} values for leaves and flowers vegetable crops are equal to the values tabulated by Pereira et al. (2021a), which should be expected because the latter were used as target of the numerical search procedure used to find the best M_L and F_r parameters.

For most fruit and pod vegetable crops (Table 8), since the late season is short, h values do not change from the mid-season to the end-season while $f_{c\ eff}$ was considered to decrease by 0.05 from the mid-to the end-season in agreement with the information provided by Pereira et al. (2021a). However, because these crops are harvested early, no decreases were considered for cucumber and okra; in contrast, a decrease of 0.10 was assumed for squash and zucchini.

M_L values close to 2.0 were assumed for all crops at both the mid- and end-season because the M_L value does not influence the K_d results (Eq. (6)). As for the previously discussed vegetable crops, F_r was assumed to be close to 1.0 for all fruit and pod vegetable crops during the mid-season since the target $K_{cb\ TAB}$ values (Pereira et al., 2021a) are standard, not stressed and cultivated under nearly pristine conditions. In contrast, lower F_r values were considered at harvest for all crops of this type since they have a relatively long late season, especially chili pepper, melon, pumpkin, squash, and watermelon. The computed $K_{cb\ end\ A\&P}$ values are smaller than $K_{cb\ mid\ A\&P}$ values in all cases, but just slightly smaller in the case of produce that are consumed fresh, e.g., bell pepper, cucumber, eggplant, okra, strawberries and tomato.

When predicting crop coefficients for vegetable crops, users of the

Table 9
Indicative K_{cb} and K_c for grain legume crops and related A&P computation parameters obtained with a numerical search procedure.

Crop	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c		Standard K_{cb} and K_c from Pereira et al. (2021b)	
		h (m)	$f_{c\ eff}$	M_L	F_r	K_{cb}	K_c	K_{cb}	K_c
Beans (*Phaseolus vulgaris*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.70	0.80	2.00	0.98	1.00	1.05	1.00	1.05
green pods	End	0.70	0.80	2.00	0.83	0.85	0.95	0.85	0.95
dry grain	End	0.55	0.55	2.00	0.34	0.30	0.40	0.30	0.40
Black and green gram (*Vigna mungo*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.90	0.95	2.00	0.95	1.10	1.15	1.10	1.15
green pods	End	0.85	0.95	2.00	0.48	0.60	0.65	0.60	0.65
dry grain	End	0.55	0.65	2.00	0.31	0.30	0.35	0.30	0.35
Chickpea (*Cicer arietinum*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.70	0.90	2.00	0.97	1.05	1.10	1.05	1.10
	End	0.55	0.70	2.00	0.25	0.25	0.35	0.25	0.35
Cowpea (*Vigna unguiculate*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.80	0.80	2.00	1.00	1.04	1.09	1.05	1.10
	End	0.75	0.75	2.00	0.49	0.50	0.60	0.50	0.60
Fava bean (*Vicia faba*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.80	0.85	2.00	0.98	1.05	1.10	1.05	1.10
	End, fresh	0.80	0.85	2.00	0.88	0.95	1.05	0.95	1.05
	End, dry	0.70	0.60	2.00	0.31	0.30	0.40	0.30	0.40
Peanut (*Arachis hypogaea*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.50	0.90	2.00	1.00	1.04	1.09	1.05	1.10
	End	0.30	0.75	2.00	0.55	0.50	0.60	0.50	0.60
Lentil (*Lens culinaris*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.50	0.85	2.00	1.00	1.00	1.05	1.00	1.05
	End	0.40	0.65	2.00	0.20	0.20	0.30	0.20	0.30
Peas (*Pisum sativum*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.60	0.98	2.00	1.00	1.10	1.15	1.10	1.15
	End, processing	0.55	0.98	2.00	0.96	1.05	1.10	1.05	1.10
	End, dry	0.50	0.80	2.00	0.24	0.25	0.30	0.25	0.30
Soybean (*Glycine max*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.80	0.98	2.00	0.95	1.10	1.15	1.10	1.15
	End	0.70	0.75	2.00	0.24	0.25	0.35	0.25	0.35

Table 10
Indicative K_{cb} and K_c for fiber, oil and sugar crops and respective related A&P computation parameters obtained with a numerical search procedure.

Crop	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c		Standard K_{cb} and K_c from Pereira et al. (2021b)	
		h (m)	$f_{c\ eff}$	M_L	F_r	K_{cb}	K_c	K_{cb}	K_c
Fiber crops									
Cotton (*Gossypium hirsutum*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.20	0.90	2.00	0.98	1.05	1.10	1.05	1.10
	End	1.10	0.80	2.00	0.38	0.40	0.50	0.40	0.50
Flax (*Linum usitatissimum*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.00	0.85	2.00	0.97	1.00	1.05	1.00	1.05
	End	0.90	0.75	2.00	0.19	0.20	0.25	0.20	0.25
Oil crops									
Camelina (*Camelina sativa*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.80	0.95	2.00	1.00	1.05	1.10	1.05	1.10
	End	0.75	0.85	2.00	0.39	0.40	0.45	0.40	0.45
Canola (*Brassica napus*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.00	0.95	2.00	0.98	1.05	1.10	1.05	1.10
	End	0.90	0.90	2.00	0.23	0.25	0.35	0.25	0.35
Castor bean (*Ricinus communis*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.00	0.95	2.00	0.98	1.05	1.10	1.05	1.10
	End	0.85	0.85	2.00	0.43	0.45	0.55	0.45	0.55
Mustard (*Brassica juncea*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	2.00	0.95	2.00	0.93	1.10	1.15	1.10	1.15
	End	1.90	0.90	2.00	0.30	0.35	0.40	0.35	0.40
Safflower (*Carthamus tinctorius*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.10	0.90	2.00	1.00	1.05	1.10	1.05	1.10
	End	1.00	0.60	2.00	0.20	0.20	0.25	0.20	0.25
Sunflower (*Helianthus annuus*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	2.00	0.90	2.00	0.95	1.15	1.20	1.15	1.20
	End	1.95	0.80	2.00	0.22	0.25	0.30	0.25	0.30
Sugar crops									
Sugar beet (*Beta vulgaris*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.50	0.80	2.00	1.00	0.97	1.02	1.00	1.05
	End	0.50	0.75	2.00	0.69	0.65	0.75	0.65	0.75
Sugar cane (*Saccharum officinarum*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	4.00	0.95	2.00	0.96	1.15	1.20	1.15	1.20
	End	4.00	0.80	2.00	0.60	0.70	0.80	0.70	0.80

Table 11
Indicative K_{cb} and K_c for cereals and related A&P computation parameters obtained with a numerical search procedure.

Crop	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c		Standard K_{cb} and K_c from Pereira et al. (2021b)	
		h (m)	$f_{c\ eff}$	M_L	F_r	K_{cb}	K_c	K_{cb}	K_c
Barley (*Hordeum vulgare*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.90	0.90	2.00	0.96	1.00	1.05	1.00	1.05
	End	0.85	0.80	2.00	0.19	0.20	0.25	0.20	0.25
Oats (*Avena sativa*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.10	0.90	2.00	0.94	1.00	1.05	1.00	1.05
	End	1.00	0.80	2.00	0.19	0.20	0.25	0.20	0.25
Maize (*Zea mays*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
grain	Mid	3.50	0.95	2.00	0.97	1.15	1.20	1.15	1.20
	End, low m. g.	3.30	0.75	2.00	0.21	0.25	0.30	0.25	0.30
	End, high m. g.	3.40	0.85	2.00	0.51	0.60	0.65	0.60	0.65
silage	Mid	3.20	0.90	2.00	0.94	1.10	1.15	1.15	1.20
	End	3.10	0.85	2.00	0.73	0.85	0.95	0.85	0.95
sweet	Mid	2.50	0.85	2.00	0.95	1.10	1.15	1.10	1.15
	End	2.50	0.85	2.00	0.88	1.00	1.05	1.00	1.05
Millet (*Pennisetum glaucum*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	2.00	0.85	2.00	0.92	1.05	1.10	1.05	1.10
	End	1.85	0.70	2.00	0.22	0.25	0.35	0.25	0.35
Quinoa (*Chenopodium quinoa)*	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.20	0.80	2.00	1.00	1.03	1.08	1.05	1.10
	End	1.05	0.75	2.00	0.45	0.45	0.50	0.45	0.50
Rye (*Secale cereal*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.90	0.90	1.80	0.91	0.95	1.00	0.95	1.00
	End	0.80	0.80	1.50	0.30	0.30	0.35	0.30	0.35
Sorghum (*S. bicolor*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
grain	Mid	2.00	0.85	2.00	0.92	1.05	1.10	1.05	1.10
	End	1.90	0.75	2.00	0.31	0.35	0.45	0.35	0.45
silage	Mid	3.00	0.80	2.00	0.92	1.05	1.10	1.05	1.10
	End	3.00	0.75	2.00	0.75	0.85	0.90	0.85	0.90
sweet	Mid	4.00	0.95	2.00	0.92	1.10	1.15	1.10	1.15
	End	4.00	0.85	2.00	0.77	0.85	0.95	0.85	0.95
Teff (*Eragrotis tef*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.10	0.80	2.00	1.00	1.00	1.05	1.00	1.05
	End	1.00	0.70	2.00	0.19	0.20	0.25	0.20	0.25
Winter wheat (*Triticum aestivum*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.10	0.95	2.00	1.00	1.09	1.14	1.10	1.15
	End, low m. g.	1.00	0.75	2.00	0.19	0.20	0.25	0.20	0.25
	End, high m. g.	1.00	0.85	2.00	0.43	0.45	0.55	0.45	0.55
Spring wheat (*Triticum aestivum*)	Initial	0.05	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.10	0.95	2.00	1.00	1.10	1.15	1.10	1.15
	End, low m. g.	1.00	0.75	2.00	0.19	0.20	0.25	0.20	0.25
	End, high m. g.	1.00	0.85	2.00	0.38	0.40	0.45	0.40	0.45
Rice (*Oryza sativa*) Flooded	Initial	0.10	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.00	0.95	2.00	1.00	1.08	1.18	1.15	1.20
	End	1.00	0.90	2.00	0.85	0.90	1.05	0.90	1.05
dry seeding	Initial	0.10	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.00	0.95	2.00	1.00	1.15	1.20	1.15	1.20
	End	1.00	0.90	2.00	0.85	0.90	1.05	0.90	1.05
with cut-off	Initial	0.10	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	1.00	0.95	2.00	1.00	1.15	1.20	1.15	1.20
	End	0.90	0.75	2.00	0.72	0.70	0.80	0.70	0.80
Intermittent	Initial	0.10	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.80	0.95	2.00	1.00	1.05	1.20	1.05	1.20
	End	0.70	0.90	2.00	0.83	0.85	1.00	0.85	1.00
Aerobic, irrigated	Initial	0.10	0.05	0.30	1.00	0.15	–	0.15	–
	Mid	0.80	0.95	2.00	1.00	1.05	1.10	1.05	1.10
	End	0.75	0.95	2.00	0.81	0.85	0.95	0.85	0.95

Note: End, low m. g. or high m. g. refer respectively to harvesting at low or high grain moisture.

A&P approach should verify that the assumptions describe above are appropriate for their local environment, crop varieties and management, and, therefore, if the default values for the M_L and F_r parameters presented in this paper can be used as defaults in their computations with observed f_c and h. When the crops are stressed, the application of the A&P approach may also be performed using observed f_c and h and a reduced F_r value.

4.2. Field crops

Table 9 presents the results of the application of the A&P approach to grain legumes and includes the parameters used in the computations. In all cases, h values decreased from the mid-season to the end-season due to crop senescence but decreases in h values are small when grain pods are harvested green or fresh, as occurs for bean, grams and fava bean crops. $f_{c\ eff}$ by the end-season is always smaller than at the mid-season, particularly when grain legumes are harvested dry. Similar to the vegetable crops, M_L at the mid-season equals 2.0. F_r values are equal or near to 1.0 for all crops during the mid-season since it is assumed that the crops are not stressed and are cultivated in the pristine conditions represented by standard crop coefficients (Pereira et al. 2021b). F_r values at end season are close to 1.0 when the crop is cultivated for harvesting green as it happens for bean, black or green gram and fava bean when harvesting at the green pods stage, and to peas harvested for processing. In contrast, F_r is low when the crop is harvested with dry grains, which happens with most crops listed in Table 9.

All F_r values were obtained with a numerical search procedure targeting the $K_{cb\ mid\ TAB}$ and $K_{cb\ end\ TAB}$ values tabulated by Pereira et al. (2021b). Therefore, the adopted parameters M_L and F_r are those appropriate for predicting $K_{cb\ A\&P}$ of grain legume crops. In agreement with values tabulated by Pereira et al. (2021b), the $K_{c\ mid\ A\&P}$ values were estimated by adding 0.05 to the $K_{cb\ mid\ A\&P}$ values, and the $K_{c\ end\ A\&P}$ values were estimated by adding 0.10 to the $K_{cb\ end\ A\&P}$ values. Exceptions refer to the cases when the late season is very short such as peas harvested for processing. For dry grain production, $K_{cb\ A\&P}$ and $K_{c\ A\&P}$ values for the end season are much smaller than at mid-season.

Results for fiber, oil and sugar crops are reported in Table 10. The h values are assumed to slightly decrease after the mid-season, with the exception of sugar beet and sugar cane for which h values do not decrease, as per the information used by Pereira et al. (2021b). Similarly, slight decreases of $f_{c\ eff}$ are also assumed for all crops. M_L was assumed to equal 2.0 as for other field crops since K_d at the mid- and end-season does not change. Computed F_r values through the numerical search procedure revealed values that were equal or close to 1.0 at the mid-season. All but the sugar crops dry out in the field, and have a large late-season; therefore, F_r decreases to values below 0.40 for fiber and oil crops, down to values smaller than 0.25 in case of canola, safflower and sunflower. In contrast, F_r values at end season are larger for the sugar crops. Coherently, the $K_{cb\ end\ A\&P}$ values are much lower than $K_{cb\ mid\ A\&P}$ with the exception of the sugar crops, which are kept green until harvest and have $K_{cb\ end\ A\&P}$ values of 0.75 or higher. $K_{c\ A\&P}$ values were computed assuming a difference relative to $K_{cb\ A\&P}$ of 0.05 at the mid-season. For the end-season, that difference is 0.10 for cotton, canola, castor bean, sugar beet and sugar cane, in agreement with tabulated values in FAO56 and Pereira et al. (2021b).

Results for cereals (Table 11) show a similar behaviour among crops, however with large differences in the case of rice. The values for h are generally slightly smaller at the end-season after a long late season when senescence occurs. Similarly, $f_{c\ eff}$ also slightly decreases after the mid-season. M_L values of 2.0 were adopted for all crops and both the mid- and end-seasons since only very low values, not appropriate for the considered vegetable and field crops, would influence the computation of K_d. The numerical search procedure, which used as the target the $K_{cb\ TAB}$ values tabulated by Pereira et al. (2021b). Values for F_r in the mid-season are close or equal to 1.0, and much smaller F_r values at the end-season. The latter are quite small, around 0.20 when harvested with low moisture, and around 0.45 with high moisture since in that case the late-season is relatively short. F_r decreases much less when the crop is harvested for silage or is used as biomass for energy because the late-season is then short.

Following the tabulated values in FAO56 (Allen et al., 1998) and in the review paper by Pereira et al. (2021b), the $K_{c\ A\&P}$ values generally are just 0.05 higher than $K_{cb\ A\&P}$ for all cereals during the mid-season, and for most of them at the end-season (Table 11). Exceptions include maize for silage, grain and sweet sorghum, and wheat harvested with high moisture grain, whose $K_{c\ end\ A\&P}$ result from adding 0.10 to $K_{cb\ end\ A\&P}$, thus when the crop does not dry much before harvesting. As expected, the $K_{cb\ A\&P}$ and $K_{c\ A\&P}$ values from the numerical search procedure fully match the tabulated values in Pereira et al. (2021b) which favours the use M_L and F_r parameters as default parameters by any user of the A&P approach that intends to determine crop coefficients from observed values of f_c and h.

For flooded paddy rice (Table 11), regardless of use of dry seeding and adopting or not anticipated cut-off, for intermittently irrigated rice, and for aerobic irrigated rice, the M_L parameter behaves similarly to other cereals. In contrast to other cereals, $F_r = 1.0$ at the initial and through the crop season until the end of the mid-season, decreasing just a little from the mid-season to the end-season, which is likely due to the water regime of rice paddies. It results in a $K_{cb\ end\ A\&P}$ value generally equal to $K_{cb\ mid\ A\&P}$ except when the anticipated cut-off is adopted. $K_{c\ mid\ A\&P}$ is larger than $K_{cb\ mid\ A\&P}$ by a value varying from 0.05 to 0.15 depending upon the soil water regime, with the larger difference for the intermittent irrigation mode. Differences for the end-season are greater when anticipated cut-off or intermittent irrigation are adopted because a lower soil water content is then produced at harvesting. Aerobic irrigated rice shows a behaviour that is in between intermittently irrigated paddies and upland cereals like wheat.

4.3. Tree and vine crops

Indicative values for standard K_{cb} and K_c for tree and vine fruit crops computed with the A&P approach are presented in Table 12 for vines, Table 13 for evergreen trees, Table 14 for pome fruits and pomegranate, and Table 15 for stone fruits and nut deciduous trees. The crop parameters used for the computations are also tabulated to support applications by users.

The $K_{cb\ A\&P}$ and $K_{c\ A\&P}$ values refer only to the mid-season and end-season, and to cultivation under conditions with no ground cover. Computations do not refer to $K_{cb\ ini}$ or $K_{c\ ini}$ because the initial season is short, soil evaporation is dominant in the case of vines and deciduous trees during the initial season, and soil evaporation varies with the soil water, the frequency and amounts of wettings by rain and irrigation, and the soil hydrodynamic properties. In the case of evergreen crops, $K_{cb\ ini}$ and $K_{c\ ini}$ are tied with K_{cb} and K_c relative to the non-growing season, which varies with the climate. Crop coefficients for the end season are also tied with K_c and K_{cb} for the non-growing season, and are also largely dependent upon the local climate. Therefore, calculations refer to $K_{cb\ A\&P}$ and $K_{c\ A\&P}$ relative to the mid- and end-season, which are largely dependent upon the dynamics of transpiration. The option to disregard active ground cover is due to, on the one hand, the decreased trend in adoption of active ground cover in orchards and vineyards and, on the other hand, the fact that $K_{cb\ A\&P}$ calculation requires the use of a specific equation (Eq. (3)), and thus a different parameterization for active cover crops. However, the result is not far from that calculated without crop cover (e.g., Fandiño et al. 2012; Cancela et al., 2015).

Crop heights were defined from those tabulated in FAO56, in Table 2 of Allen and Pereira (2009) and in Tables 5–7 of Rallo et al. (2021) for vine crops, evergreen trees and deciduous trees respectively. However, h values were selected considering the current trends for high densities and vigour reducing rootstocks aimed to facilitate mechanized harvesting, which implies shorter crop heights. Changes in h from the mid-season to end-season were not considered. The values for $f_{c\ eff}$ resulted from combining the remote sensing observed f_c values tabulated in Table 5, those previously tabulated by Allen and Pereira (2009), and observed values reported in literature and tabulated by Rallo et al. (2021). M_L and F_r values were obtained through the numerical search aimed at matching the standard values tabulated by Rallo et al. (2021) considering crop density and training systems, as well as the selected f_c and h tabulated by these authors. Because K_{cb} values tabulated in Rallo et al. (2021) refer to a central value ± 10%, the numerical search was applied targeting two values, the central one, $K_{cb\ A\&P}$, and the upper one, $K_{cb\ A\&P} + 10\%$.

Computations for grapes (Table 12) were performed with consideration of training and f_c, given that $K_{cb\ A\&P}$ is influenced primely by training and f_c, and secondarily by h. These factors lead, generally, to larger f_c and h values for table grapes compared to wine grapes, resulting in larger $K_{cb\ A\&P}$ values for table grapes. For all vines, $K_{c\ mid\ A\&P}$ resulted from adding 0.05 to $K_{cb\ mid\ A\&P}$ in agreement with the simplified procedure used in FAO56 (Allen et al., 1998) and in Rallo et al. (2021). This approach results from the fact that drip irrigation systems are commonly used with vines, and thus only a small fraction of soil is wetted by irrigation. Most of the wetted soil area is under the shadow of the vine canopy, and thus only a limited amount of solar energy reaches the soil surface, also limiting the amount of soil water evaporation. In contrast, following Rallo et al. (2021), $K_{c\ end\ A\&P}$ values were obtained by adding

Table 12

Indicative K_c and K_{cb} of vine crops estimated with the A&P approach observed and calibrated computation parameters obtained with a numerical search procedure.

Crop	Management	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c (ranges)		Standard K_{cb} and K_c from Rallo et al. (2021)	
			h (m)	$f_{c\ eff}$	M_L	F_r (ranges)	K_{cb}	K_c	K_{cb}	K_c
Table grapes (*Vitis vinifera*)	Young	Mid	1.8	0.35	1.5	0.85	0.55	0.60	0.55	0.60
						0.94	0.60	0.65	0.60	0.65
		End	1.8	0.30	1.5	0.80	0.45	0.55	0.45	0.55
						0.89	0.50	0.60	0.50	0.60
	Overhead trellis	Mid	2.0	0.95	1.5	0.76	0.90	0.95	0.90	0.95
						0.85	1.00	1.05	1.00	1.05
		End	2.0	0.90	1.5	0.56	0.65	0.70	0.65	0.70
						0.60	0.70	0.75	0.70	0.75
	Horizontal trellis	Mid	1.8	0.70	1.5	0.81	0.85	0.90	0.85	0.90
						0.91	0.95	1.00	0.95	1.00
		End	1.8	0.65	1.5	0.68	0.70	0.80	0.70	0.80
						0.73	0.75	0.85	0.75	0.85
	T trellis	Mid	2.0	0.50	1.5	0.82	0.75	0.80	0.75	0.80
						0.93	0.85	0.90	0.85	0.90
		End	2.0	0.45	1.5	0.66	0.55	0.60	0.55	0.60
						0.72	0.60	0.65	0.60	0.65
	Y gable trellis	Mid	2.2	0.90	1.5	0.56	0.65	0.70	0.65	0.70
						0.60	0.70	0.75	0.70	0.75
		End	2.2	0.85	1.5	0.44	0.50	0.55	0.50	0.55
						0.48	0.55	0.60	0.55	0.60
Wine grapes (*Vitis vinifera*)	Young	Mid	1.5	0.30	1.3	0.82	0.40	0.45	0.40	0.45
						0.93	0.45	0.50	0.45	0.50
		End	1.5	0.25	1.2	0.76	0.30	0.40	0.30	0.40
						0.90	0.35	0.45	0.35	0.45
	Pergola trellis	Mid	2.0	0.60	1.5	0.59	0.60	0.65	0.60	0.65
						0.63	0.65	0.70	0.65	0.70
		End	2.0	0.55	1.5	0.45	0.45	0.50	0.45	0.50
						0.50	0.50	0.55	0.50	0.55
	Vertical shoot positioned trellis	Mid	2.0	0.45	1.5	0.78	0.65	0.70	0.65	0.70
						0.85	0.70	0.75	0.70	0.75
		End	2.0	0.40	1.5	0.53	0.40	0.45	0.40	0.45
						0.60	0.45	0.50	0.45	0.50
	Guyot trellis	Mid	2.0	0.50	1.5	0.49	0.45	0.50	0.45	0.50
						0.54	0.50	0.55	0.50	0.55
		End	2.0	0.45	1.5	0.41	0.35	0.40	0.35	0.40
						0.47	0.40	0.45	0.40	0.45
Kiwi (*Actinidia chinensis*)	Pergola, T bar trellis	Mid	2.0	0.90	1.6	0.77	0.89	0.94	0.90	0.95
						0.86	1.00	1.05	1.00	1.05
		End	2.0	0.85	1.5	0.70	0.80	0.90	0.80	0.90
						0.79	0.90	1.00	0.90	1.00

0.10 to $K_{cb\ end\ A\&P}$ when $f_c < 0.30$, and adding 0.05 when f_c is higher. The M_L values were based upon those of Table 2 used to initiate the numerical search procedure. In contrast, the F_r values vary considerably and indicate that stomatal adjustment is applied by the crop since a beneficial deficit irrigation is commonly practiced to limit the vegetative vigour of the plants. Larger F_r correspond to the larger K_{cb} target when the numerical search was applied. Larger F_r values for table grapes were observed for the young plants because the water deficits are then smaller, and when the training system was overhead, horizontal and T trellis.

For wine grapes, the highest F_r values are also associated with the young vineyards because less stress is then applied to the crop, and to the training system of vertical shoot positioned trellis systems. The variability of F_r values was expected after the test results reported in the companion paper (Pereira et al., 2020) and likely result from the variety of crop and irrigation management practices that influence the response of vineyards to various levels of stress.

$K_{cb\ A\&P}$ values for kiwi (Table 12) are not very high, but f_c is quite large likely because this vine is trained with pergola and T bar trellis systems; $K_{c\ A\&P}$ values differ by 0.05 from $K_{cb\ A\&P}$. Considering both high f_c and h it results in a relatively high value for F_r, larger for the mid-season and when the target K_{cb} value is larger.

For the evergreen fruit trees (Table 13), in agreement with Rallo et al. (2021), $K_{c\ mid\ A\&P}$ was computed when adding 0.05 to $K_{cb\ mid\ A\&P}$ while $K_{c\ end\ A\&P}$ was obtained by adding a diverse amount to $K_{cb\ end\ A\&P}$. That amount decreases when f_c increases, i.e., when the canopy shaded area is larger. For citrus trees, the added value ranged from 0.25 in the young orchards, where f_c is small ($f_c < 0.25$), to 0.10 in the high-density orchards with $f_c > 0.65$. Data for citrus (Table 13) was derived mainly from studies of orange trees but some information was also available for clementine and mandarin. All information was assembled and it has been possible to distinguish the densities of crops, f_c and h. The M_L parameter varies little (1.6–1.7) and, apparently, plays a minor role in the computations. The F_r values are higher for the young plants, since they are generally considered to be non-stressed, and to the orchards with taller trees and larger density, i.e., when vegetative vigour of plants is larger. Specific to citrus orchards is the fact that the end-season $K_{cb\ A\&P}$ is equal to $K_{cb\ mid\ A\&P}$ because senescence of leaves does not occur. Differently, $K_{c\ end\ A\&P}$ is higher than $K_{c\ mid\ A\&P}$ because fruits grow and mature in winter, when wetting events by precipitation are frequent.

Data collected for olive trees made it possible to perform the calculations (Table 13) in relation to the density of trees and the main training types: the traditional vase, hedge pruned olives, and hedgerow super-intensive modern orchards. The f_c values are generally not high (< 0.45) and change little among the various types of orchards; therefore the changes in K_{cb} are also small. The olive orchards have a larger

Table 13
Indicative K_c and K_{cb} of evergreen fruit trees estimated with the A&P approach and related observed and calibrated computation parameters obtained with a numerical search procedure.

Crop	Management	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c (ranges)		Standard K_{cb} and K_c from Rallo et al. (2021)	
			h (m)	$f_{c\ eff}$	M_L	F_r (ranges)	K_{cb}	K_c	K_{cb}	K_c
Citrus										
Orange (*Citrus sinensis*), **Mandarine** (*C. reticulata*), **Clementine** (*C. clementina*)	Young	Mid	1.5	0.20	1.6	0.85	0.35	0.40	0.35	0.40
						0.97	0.40	0.45	0.40	0.45
		End	1.5	0.20	1.6	0.85	0.35	0.60	0.35	0.60
						0.97	0.40	0.65	0.40	0.65
	Low density	Mid	4.5	0.40	1.7	0.60	0.50	0.55	0.50	0.55
						0.65	0.55	0.60	0.55	0.60
		End	4.5	0.40	1.7	0.60	0.50	0.65	0.50	0.65
						0.65	0.55	0.70	0.55	0.70
	Medium density, small trees	Mid	3.5	0.65	1.7	0.50	0.55	0.60	0.55	0.60
						0.55	0.60	0.65	0.60	0.65
		End	3.5	0.65	1.7	0.50	0.55	0.70	0.55	0.70
						0.55	0.60	0.75	0.60	0.75
	Medium density, tall trees	Mid	4.5	0.65	1.7	0.55	0.60	0.65	0.60	0.65
						0.58	0.65	0.70	0.65	0.70
		End	4.5	0.65	1.7	0.55	0.60	0.75	0.60	0.75
						0.58	0.65	0.80	0.65	0.80
	High density, small trees	Mid	3.5	0.70	1.7	0.58	0.65	0.70	0.65	0.70
						0.63	0.70	0.75	0.70	0.75
		End	3.5	0.70	1.7	0.58	0.65	0.80	0.65	0.80
						0.63	0.70	0.85	0.70	0.85
	High density, tall trees	Mid	4.5	0.70	1.7	0.75	0.85	0.90	0.85	0.90
						0.84	0.95	1.00	0.95	1.00
		End	4.5	0.70	1.7	0.75	0.85	0.95	0.85	0.95
						0.84	0.95	1.05	0.95	1.05
Olives (*Olea europaea*)	Low density/young	Mid	2.0	0.30	1.0	0.47	0.20	0.25	0.20	0.25
						0.60	0.25	0.30	0.25	0.30
		End	2.0	0.30	1.0	0.33	0.15	0.55	0.15	0.55
						0.45	0.20	0.60	0.20	0.60
	Traditional, medium density (vase)	Mid	3.5	0.35	1.5	0.60	0.40	0.45	0.40	0.45
						0.68	0.45	0.50	0.45	0.50
		End	3.5	0.35	1.5	0.52	0.35	0.70	0.30	0.65
						0.60	0.40	0.75	0.35	0.70
	Intensive (hedge prune)	Mid	3.5	0.40	1.5	0.53	0.40	0.45	0.40	0.45
						0.60	0.45	0.50	0.45	0.50
		End	3.5	0.40	1.5	0.46	0.35	0.70	0.35	0.70
						0.53	0.40	0.75	0.40	0.75
	Super-intensive (hedgerow), small trees	Mid	3.5	0.35	1.5	0.50	0.35	0.40	0.35	0.40
						0.60	0.40	0.45	0.40	0.45
		End	3.5	0.35	1.5	0.44	0.30	0.70	0.30	0.70
						0.51	0.35	0.75	0.35	0.75
	Super-intensive, tall trees	Mid	4.0	0.45	1.5	0.54	0.45	0.50	0.45	0.50
						0.60	0.50	0.55	0.50	0.55
		End	4.0	0.45	1.5	0.47	0.40	0.75	0.40	0.75
						0.53	0.45	0.80	0.45	0.80

$K_{c\ end\ A\&P}$, which is computed from the $K_{cb\ end\ A\&P}$ by adding 0.35–0.40, because the end-season, as well as the non-growing season, occur during the rainy period. The parameter M_L also plays a minor role and is approximately constant and equal to 1.5. Since f_c changes little among the considered types of orchards, the F_r values change little, around 0.55 ± 10%, with values indicating a strong stomatal adjustment, which is to be expected since pruning and training are designed to control the vigor of the trees while irrigation is practiced with application of limited volumes of water. To be noted that the numerical search procedure led to fully match the target standard $K_{cb\ TAB}$ values.

Computations for apple and pear trees were performed individually, in contrast to the approach used in Allen and Pereira (2009) and Jensen and Allen (2016), despite the fact that central leader type of systems are generally adopted for both crops (Table 14). Our approach was to group both crops with pomegranate trees, which commonly have similar training systems. The indicative $K_{c\ mid\ A\&P}$ values for pome fruit trees and pomegranate were calculated by adding 0.05 to the $K_{cb\ mid\ A\&P}$ value, while the $K_{c\ end\ A\&P}$ values were obtained by adding 0.10 or 0.05 according to the fraction of ground cover (larger when f_c is smaller ($f_c \leq 0.35$), i.e. for the young and low density orchards, where soil evaporation is larger). It was assumed that height and f_c are more often larger for apple and, due to the canopy opacity (Girona et al., 2011), apple orchards have a slightly higher M_L than pears. It resulted in quite similar values for K_d and $K_{cb\ full}$, therefore in K_{cb} values that are also quite similar. F_r values are larger for the young orchards, less stressed than the mature ones, and for medium to very high density central leader systems, when more vegetative vigour is allowed. Nevertheless, all F_r values denote stomatal adjustment since beneficial deficit irrigation is commonly practiced.

Differences among stone fruits and nut trees were reported in the reviewed literature (Table 4); however, the information on training was insufficient for all deciduous fruits, and both vase and central leader systems were mentioned. Thus, for all stone fruits and nut trees, it was only possible to tie the calculations to the crop densities (Table 15). The indicative $K_{c\ mid\ A\&P}$ values in for stone fruits and nut trees were computed by adding 0.05 to $K_{cb\ mid\ A\&P}$. The $K_{c\ end\ A\&P}$ values were obtained by adding 0.10 or 0.05 to $K_{cb\ end\ A\&P}$, with the highest added value for young, low and medium density orchards, i.e., when the canopy shadow at the end-season is reduced. Relative to stone fruits, crop heights are higher for apricot, cherry and plum orchards but f_c, M_L and F_r

Table 14
Indicative K_c and K_{cb} of pome fruit trees and pomegranate trees estimated with the A&P approach and related observed and calibrated computation parameters obtained with a numerical search procedure.

Crop	Management	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c (ranges)		Standard K_{cb} and K_c from Rallo et al. (2021)	
			h (m)	$f_{c\ eff}$	M_L	F_r (ranges)	K_{cb}	K_c	K_{cb}	K_c
Pome fruit trees										
Apples (*Malus domestica*)	Young	Mid	1.8	0.25	1.3	0.82 0.95	0.35 0.40	0.40 0.45	0.35 0.40	0.40 0.45
		End	1.8	0.25	1.1	0.65 0.80	0.25 0.30	0.35 0.40	0.25 0.30	0.35 0.40
	Low density	Mid	3.6	0.30	1.4	0.84 0.93	0.45 0.50	0.50 0.55	0.45 0.50	0.50 0.55
		End	3.6	0.30	1.3	0.58 0.68	0.30 0.35	0.40 0.45	0.30 0.35	0.40 0.45
	Medium density, central leader, or spindle bush	Mid	3.6	0.40	1.7	0.78 0.84	0.65 0.70	0.70 0.75	0.65 0.70	0.70 0.75
		End	3.6	0.35	1.6	0.64 0.71	0.45 0.50	0.55 0.60	0.45 0.50	0.55 0.60
	High density, central leader, or spindle bush	Mid	3.6	0.50	1.8	0.82 0.91	0.85 0.95	0.90 1.00	0.85 0.95	0.90 1.00
		End	3.6	0.45	1.7	0.48 0.53	0.45 0.50	0.50 0.55	0.45 0.50	0.50 0.55
	Very high density, central leader, or spindle bush	Mid	4.5	0.85	1.8	0.81 0.90	0.95 1.05	1.00 1.10	0.95 1.05	1.00 1.10
		End	4.5	0.75	1.7	0.52 0.56	0.60 0.65	0.65 0.70	0.60 0.65	0.65 0.70
Pears (*Pyrus communis*)	Young	Mid	1.5	0.25	1.3	0.85 0.97	0.35 0.40	0.40 0.45	0.35 0.40	0.40 0.45
		End	1.5	0.20	1.1	0.65 0.82	0.20 0.25	0.30 0.35	0.20 0.25	0.30 0.35
	Low density	Mid	3.0	0.35	1.3	0.87 0.95	0.50 0.55	0.55 0.60	0.50 0.55	0.55 0.60
		End	3.0	0.30	1.2	0.74 0.85	0.35 0.40	0.45 0.50	0.35 0.40	0.45 0.50
	Medium density, central leader	Mid	3.0	0.40	1.7	0.96 1.00	0.80 0.90	0.85 0.95	0.80 0.90	0.85 0.95
		End	3.0	0.35	1.6	0.86 0.94	0.60 0.65	0.65 0.70	0.60 0.65	0.65 0.70
	High density, central leader	Mid	3.0	0.50	1.7	0.93 1.00	0.95 1.00	1.00 1.05	0.95 1.05	1.00 1.10
		End	3.0	0.45	1.6	0.79 0.85	0.70 0.75	0.75 0.80	0.70 0.75	0.75 0.80
	Very high density, central leader	Mid	3.6	0.70	1.7	0.94 1.00	1.05 1.10	1.10 1.15	1.05 1.15	1.10 1.20
		End	3.6	0.65	1.6	0.73 0.82	0.80 0.90	0.85 0.90	0.80 0.90	0.85 0.90
Pomegranate (*Punica granatum*)	Young	Mid	3.0	0.25	1.1	0.80 0.95	0.30 0.35	0.35 0.40	0.30 0.35	0.35 0.40
		End	3.0	0.20	1.0	0.65 0.86	0.20 0.25	0.30 0.35	0.20 0.25	0.30 0.35
	Low density	Mid	3.5	0.35	1.4	0.72 0.80	0.45 0.50	0.50 0.55	0.45 0.50	0.50 0.55
		End	3.5	0.30	1.3	0.57 0.69	0.30 0.35	0.40 0.45	0.30 0.35	0.40 0.45
	Medium density	Mid	3.5	0.45	1.6	0.62 0.68	0.55 0.60	0.60 0.65	0.55 0.60	0.60 0.65
		End	3.5	0.40	1.5	0.53 0.60	0.40 0.45	0.45 0.50	0.40 0.45	0.45 0.50
	High density	Mid	3.5	0.50	1.7	0.76 0.85	0.80 0.90	0.85 0.95	0.80 0.90	0.85 0.95
		End	3.5	0.45	1.6	0.56 0.61	0.55 0.60	0.60 0.65	0.55 0.60	0.60 0.65

values were similar to those of peach. Nevertheless, the K_{cb} values calculated for these crops are quite similar but it is expected that differences in crop varieties and crop management practices will result in differences for $K_{cb\ A\&P}$.

Walnut trees are higher than pistachio trees and walnut orchards are likely denser than those of pistachio. Related crop training was not discussed in the reviewed literature. Therefore, following Rallo et al. (2021) larger f_c and h values were assumed for walnut orchards resulting in larger $K_{cb\ A\&P}$ values than for pistachio. The application of the numerical search procedure led to similar M_L values for the mentioned stone fruit and nut crops, with lower values for the less dense orchards. F_r values were higher for the mid-season and lower for the end-season, when stomatal adjustment is strong. Young orchards show higher F_r values because training and pruning, as well as irrigation, promote large vegetative vigour. Higher density orchards with tall trees also result in large F_r values.

Table 15

Indicative K_c and K_{cb} of stone fruits and nut trees estimated with the A&P approach and related observed and calibrated computation parameters obtained with a numerical search procedure.

Crop	Management	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c (ranges)		Standard K_{cb} and K_c from Rallo et al. (2021)	
			h (m)	$f_{c\ eff}$	M_L	F_r (ranges)	K_{cb}	K_c	K_{cb}	K_c
Stone fruits										
Apricots (*Prunus armeniaca*), **Cherry** (*P. avium*), and **Plums** (P. *salicina/domestica*)	Young	Mid	2.0	0.30	1.5	0.88	0.50	0.55	0.50	0.55
						0.97	0.55	0.60	0.55	0.60
		End	2.0	0.25	1.4	0.64	0.30	0.40	0.30	0.40
						0.75	0.35	0.45	0.35	0.45
	Low density	Mid	3.0	0.40	1.5	0.74	0.55	0.60	0.55	0.60
						0.81	0.60	0.65	0.60	0.65
		End	3.0	0.35	1.4	0.55	0.35	0.45	0.35	0.45
						0.63	0.40	0.50	0.40	0.50
	Medium density	Mid	3.5	0.50	1.6	0.77	0.75	0.80	0.75	0.80
						0.88	0.85	0.90	0.85	0.90
		End	3.5	0.45	1.5	0.60	0.50	0.55	0.50	0.55
						0.66	0.55	0.60	0.55	0.60
	High density, central leader	Mid	4.0	0.60	1.6	0.78	0.85	0.90	0.85	0.90
						0.87	0.95	1.00	0.95	1.00
		End	4.0	0.55	1.5	0.55	0.55	0.60	0.55	0.60
						0.60	0.60	0.65	0.60	0.65
	Very high density	Mid	5.0	0.70	1.6	0.88	1.00	1.05	1.00	1.05
						0.97	1.10	1.15	1.10	1.15
		End	5.0	0.65	1.5	0.58	0.65	0.70	0.65	0.70
						0.62	0.70	0.75	0.70	0.75
Peaches (*P. persica*)	Young	Mid	2.5	0.25	1.6	0.98	0.50	0.55	0.50	0.55
						1.00	0.51	0.56	0.55	0.60
		End	2.5	0.20	1.5	0.88	0.35	0.45	0.35	0.45
						1.00	0.40	0.50	0.40	0.50
	Low density	Mid	3.0	0.40	1.7	0.71	0.60	0.65	0.60	0.65
						0.78	0.65	0.70	0.65	0.70
		End	3.0	0.35	1.6	0.56	0.40	0.50	0.40	0.50
						0.63	0.45	0.55	0.45	0.55
	Medium density, central leader	Mid	3.5	0.60	1.7	0.79	0.85	0.90	0.85	0.90
						0.88	0.95	1.00	0.95	1.00
		End	3.5	0.55	1.6	0.57	0.61	0.66	0.60	0.65
						0.61	0.65	0.70	0.65	0.70
	Very high density, central leader	Mid	5.0	0.70	1.7	0.88	1.00	1.05	1.00	1.05
						0.97	1.10	1.15	1.10	1.15
		End	5.0	0.65	1.6	0.58	0.65	0.70	0.65	0.70
						0.62	0.70	0.75	0.70	0.75
Nut trees										
Almonds (*Prunus dulcis*)	Young	Mid	2.0	0.30	1.1	0.81	0.35	0.40	0.35	0.40
						0.92	0.40	0.45	0.40	0.45
		End	2.0	0.25	1.0	0.70	0.25	0.35	0.25	0.35
						0.86	0.30	0.40	0.30	0.40
	Low density	Mid	5.0	0.40	1.4	0.56	0.40	0.45	0.40	0.45
						0.62	0.45	0.50	0.45	0.50
		End	5.0	0.35	1.3	0.50	0.30	0.40	0.30	0.40
						0.55	0.35	0.45	0.35	0.45
	Medium density, central leader and vase	Mid	5.0	0.50	1.5	0.65	0.60	0.65	0.60	0.65
						0.71	0.65	0.70	0.65	0.70
		End	5.0	0.45	1.4	0.50	0.40	0.50	0.40	0.50
						0.57	0.45	0.55	0.45	0.55
	High density, central leader and vase	Mid	5.0	0.60	1.5	0.78	0.85	0.90	0.85	0.90
						0.88	0.96	1.01	0.95	1.00
		End	5.0	0.55	1.5	0.60	0.60	0.65	0.60	0.65
						0.65	0.65	0.70	0.65	0.70
	Very high density	Mid	5.5	0.70	1.5	0.88	1.00	1.05	1.00	1.05
						0.97	1.10	1.15	1.10	1.15
		End	5.5	0.65	1.5	0.62	0.70	0.75	0.70	0.75
						0.67	0.76	0.81	0.75	0.80
Pistachio (*Pistacia vera*)	Young	Mid	2.0	0.30	1.2	0.86	0.40	0.45	0.40	0.45
						0.96	0.45	0.50	0.45	0.50
		End	2.0	0.25	1.1	0.65	0.25	0.35	0.25	0.35
						0.80	0.30	0.40	0.30	0.40
	Low density	Mid	3.0	0.50	1.4	0.88	0.75	0.80	0.75	0.80
						0.99	0.85	0.90	0.85	0.90
		End	3.0	0.45	1.3	0.68	0.50	0.55	0.50	0.55
						0.76	0.55	0.60	0.55	0.60
	High density	Mid	3.0	0.70	2.0	0.82	0.90	0.95	0.90	0.95
						0.91	1.00	1.05	1.00	1.05
		End	3.0	0.65	2.0	0.55	0.60	0.65	0.60	0.65
						0.60	0.65	0.70	0.65	0.70

(*continued on next page*)

Table 15 (*continued*)

Crop	Management	Crop stages	Observed parameters		Calibrated parameters		A&P K_{cb} and K_c (ranges)		Standard K_{cb} and K_c from Rallo et al. (2021)	
			h (m)	$f_{c\ eff}$	M_L	F_r (ranges)	K_{cb}	K_c	K_{cb}	K_c
Walnut (*Juglans regia*)	Low density/young	Mid	2.0	0.30	1.3	0.90	0.45	0.50	0.45	0.50
						1.00	0.50	0.55	0.50	0.55
		End	2.0	0.25	1.2	0.60	0.25	0.45	0.25	0.45
						0.74	0.30	0.50	0.30	0.50
	Medium density	Mid	7.0	0.75	1.5	0.69	0.80	0.85	0.80	0.85
						0.78	0.90	0.95	0.90	0.95
		End	7.0	0.70	1.5	0.35	0.40	0.50	0.40	0.50
						0.39	0.45	0.55	0.45	0.55
	High density	Mid	7.0	0.85	1.5	0.77	0.91	0.96	0.90	0.95
						0.85	1.00	1.05	1.00	1.05
		End	7.0	0.80	1.5	0.43	0.50	0.55	0.50	0.55
						0.47	0.55	0.60	0.55	0.60
	Very high density	Mid	7.0	0.90	1.5	0.85	1.00	1.05	1.00	1.05
						0.94	1.10	1.15	1.10	1.15
		End	7.0	0.85	1.5	0.47	0.55	0.60	0.55	0.60
						0.51	0.60	0.65	0.60	0.65

4.4. *Cross validation of the M_L and F_r parameters. Usability of the A&P approach*

The results of the A&P computation are overall, excellent after the application of a numerical search procedure for estimating the best M_L and F_r parameters. That procedure aimed at finding the M_L and F_r parameters that led the $K_{cb\ A\&P}$ values to match the $K_{cb\ TAB}$ by Pereira et al. (2021a, 2021b), respectively for the vegetable and field crops, and by Rallo et al. (2021) for tree and vine crops. The close agreement may be observed in Tables 6–8 for vegetable crops, Tables 9–11 for field crops and Tables 12–15 for vines and trees, by comparing the tabulated $K_{cb\ A\&P}$ values in the 7th/8th column with the target $K_{cb\ TAB}$ values in the 10th/11th column. With these results, we could conclude that the M_L and F_r parameters are adequate to compute K_{cb} with the f_c and h data tabulated in the 3rd/4th column, i.e., the data collected from Pereira et al. (2021a, 2021b) and Rallo et al. (2021). However, there is the need for additional validation of these M_L and F_r parameters using independent data. Cross validation was therefore applied.

Data available for the cross validation includes already published data on f_c and h, which consist of input data for the application of the A&P approach, and $K_{cb\ OBS}$ data which are to be compared with the $K_{cb\ A\&P}$. For the comparison, a linear regression forced through the origin was adopted. Input data refer to the following:

- Vegetable and legume crops: onion (López-Urrea et al., 2009a, 2009b), pea (Paredes et al., 2017), soybean (Wei et al., 2015; Giménez et al., 2017), and tomato (Zheng et al., 2013).
- Field crops: Cereals - barley (Pereira et al., 2015a, 2015b), maize (Martins et al., 2013; Zhao et al., 2013; Paredes et al., 2014; Giménez et al., 2016; Miao et al., 2016), and wheat (Zhao et al., 2013; Sánchez et al., 2015; Miao et al., 2016). Oil and fiber crops - canola (Sánchez et al., 2014), sunflower (Miao et al., 2016), and cotton (Rosa et al., 2012).
- Vine and tree crops: wine grapes with bare soil (López-Urrea et al. 2012), peach (Paço et al. 2012), olives (Paço et al., 2019), and pear and lemon (Rosa, 2019).

The cross validation was performed using the parameters M_L and F_r obtained with the numerical search procedure to compute $K_{cb\ A\&P}$ using the observed f_c and h determined in the studies referred above (Tables 5–15) and then comparing the resulting $K_{cb\ A\&P}$ with the reported $K_{cb\ OBS}$. Results for the annual crops are presented in Fig. 1 and for trees and vines in Fig. 2. They show a quasi-equality between $K_{cb\ A\&P}$ and the reported $K_{cb\ OBS}$, with the regression coefficient (b_0) very close to 1.0 and the coefficient of determination (R^2) also not far from 1.0. Consequently, the root mean square errors (RMSE) are quite small, RMSE = 0.06 for the three sets of annual crops and RMSE = 0.07 for the tree and vine crops. These errors are less than 10% for most of the computed $K_{cb\ A\&P}$ values as well as the observed $K_{cb\ OBS}$.

The good statistical goodness of fit values for b_0, R^2 and RMSE allow us to conclude that the parameters M_L and F_r tabulated and presented here are appropriate for use with the A&P approach when a user seeks to estimate a K_{cb} value using local observations of f_c and h. For annual crops, the goodness of fit herein were obtained with selecting the F_r and M_L values relative to the considered crop but for tree and vine crops the computations were performed selecting the crop group having the pair f_c and h closer to the observed f_c and h. The results in Figs. 1 and 2 indicate that selecting F_r and M_L with that simplicity is appropriate. However, users may use some kind of interpolation/extrapolation of F_r (and secondly the M_L) considering the f_c value observed (and secondly the h value). This means that using the A&P approach adopting the tabulated parameters F_r and M_L is an adequate tool to estimate K_{cb} for the crops referred herein, thus for also estimating K_c using the same relations between K_c and K_{cb} referred above. Since K_{cb} and K_c decrease when a crop is water and/or salt stressed, the A&P approach is also usable when deficit irrigation or low-quality water are applied with observed f_c and height values reflecting the impacts of those stress conditions (e.g. Santos et al., 2012; Wu et al., 2015).

5. Conclusions and recommendations

The Allen and Pereira (2009) approach to estimate crop coefficients from the fraction of ground cover and crop height, following the review and application tests developed in the companion paper (Pereira et al., 2020), has been applied to a large variety of annual and perennial crops. Here, application of the A&P approach used f_c collected from both ground observations and remote sensing, supplemented by ground-observed h values. A numerical search procedure was used to specify M_L and F_r parameter values resulting in best match of $K_{cb\ A\&P}$ with the updated standard $K_{cb\ TAB}$ values of Pereira et al. (2021a, 2021b) and Rallo et al. (2021). The initial values of M_L and F_r were those already published in the literature. When those parameters were not available, initial values were based on those of similar crops. The numerical search facilitated the determination of optimal M_L and F_r values for all crops and showed excellent agreement with the updated K_{cb} values for each crop. Indicative K_{cb} and K_c were tabulated for the mid-and end-season,

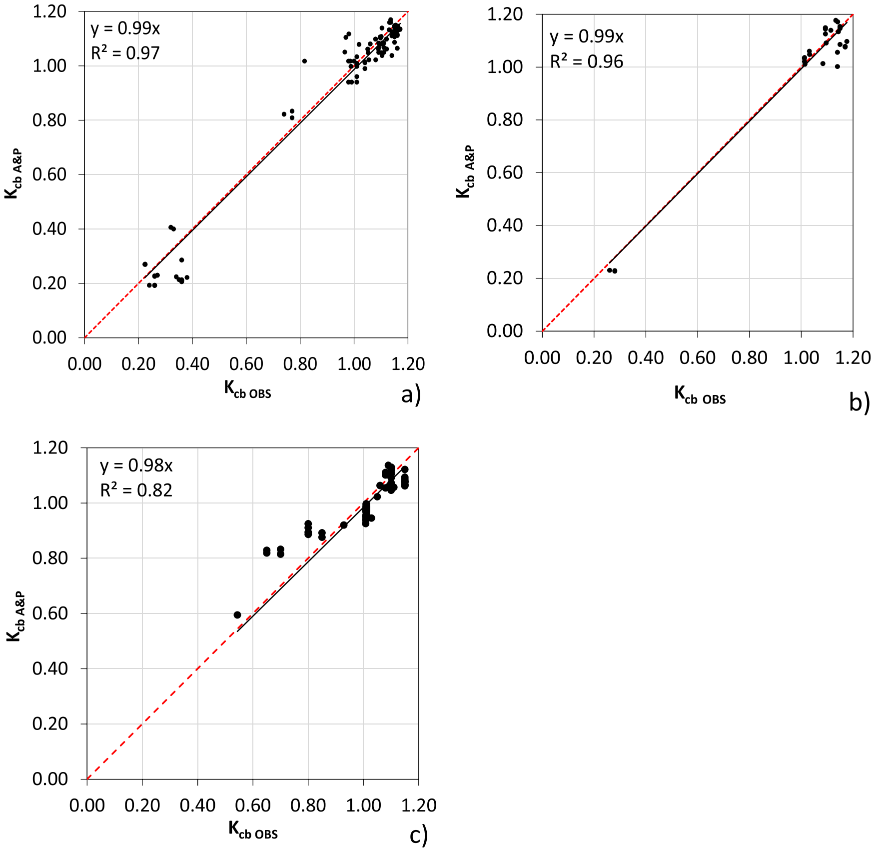

Fig. 1. Linear regression forced through the origin, comparing K_{cb} values computed with the A&P approach ($K_{cb\ A\&P}$) with those obtained from field research ($K_{cb\ OBS}$) for a) cereals, b) oil and fiber crops and c) vegetable and legume crops; also depicted is the 1:1 line (- - -).

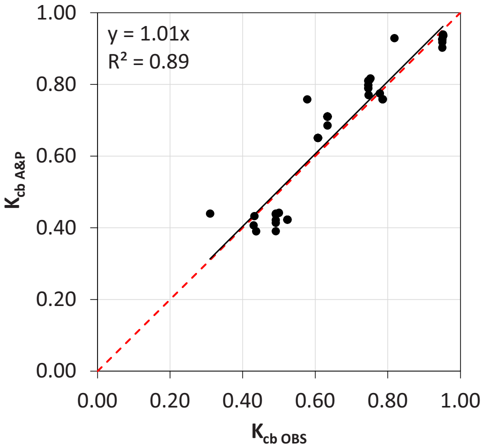

Fig. 2. Linear regression forced through the origin comparing K_{cb} values computed with the A&P approach ($K_{cb\ A\&P}$) with those obtained from field research ($K_{cb\ OBS}$) for vine and tree crops; also depicted the 1:1 line (- - -).

along with corresponding values of f_c and h, the respective optimized M_L and F_r values, and of the tabulated $K_{cb\ TAB}$ and $K_{c\ TAB}$ used as the target in the search procedure. To validate the accuracy of the approach, we evaluated the computations of K_{cb} against independent sets of observed data for a diverse set of vegetable, field, and fruit crops. A linear regression demonstrated a very good match between the observed/measured K_{cb} and the K_{cb} derived by the A&P approach using the optimized M_L and F_r parameters. These results support adoption of the tabulated M_L and F_r parameters values by field practitioners in the field when using f_c and h observations to calculate $K_{cb\ A\&P}$.

The application of the A&P approach, using observations of f_c and h, with the tabulated M_L and F_r parameters, provides for the estimation of appropriate values for local, actual crop coefficients, including when water and salt stresses occur. The approach developed and summarized here is more practical and cost-effective than estimating crop coefficients using field ET observations by Bowen Ratio Energy Balance (BREB), eddy covariance instrumentation (EC), soil water balance (SWB), sap-flow approaches, or weighing lysimeters. The predicted values calculated through use of the A&P approach may be more accurate and representative of local conditions than estimating actual K_c or K_{cb} values from the tabulated standard crop coefficients. However, particular attention must be paid to the field evaluation of f_c and h.

Practical use of the A&P approach is primarily intended to support irrigation scheduling and planning, as well as to advance the use of water conservation practices which are essential responses to the challenges and pressures of global climatic changes. Implementation of the A&P approach coupled with satellite-based f_c measurements within the fully automated SIMS framework (Melton et al., 2012, 2020) demonstrate the potential to reduce the effort required to calculate K_{cb} values and increase access to accurate data for ET-based irrigation management. Continued development of the A&P approach should proceed in parallel with additional research where actual ET is observed through use of BREB, EC, SWB, sap-flow or remote sensing and related approaches. Such complementary research continues to be a high priority in order to progressively refine the FAO56 methodologies. Development of practical approaches such as A&P are particularly important in the context of challenges imposed on irrigated agriculture by global change, and the growing importance of assuring long-term sustainability of agricultural water supplies.

Declaration of Competing Interest

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

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